Proc. of the 8th International Symposium on Geotechnical Safety and Risk (ISGSR)
Edited by Jinsong Huang, D.V. Griffiths, Shui-Hua Jiang, Anna Giacomini and Richard Kelly
 Published by Research Publishing, Singapore.
doi: 10.3850/978-981-18-5182-7_13-003-cd

ISGSR 2022

Database-Based Analysis of Various Interpretation Criteria for Barrette Piles in Drained Soils

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Abstract: An evaluation of various compression interpretation criteria for barrette piles under drained soil conditions was done in this study, together with the comparison of the results with previous researches. In order to achieve the objectives, a total of 18 load test results of barrette piles under drained soil conditions were collected and stored in a database for keen evaluation. These interpreted capacities were analysed by comparing each of the criterion with a set specific interpretation method, thus shedding light on the interrelationships of each interpretation criteria to the set standard. Upon normalizing the interpreted capacities with that of the results of the L_2 method, it was found out that the interpreted values of $L_1$is at 48% of the L_2 interpretation and can be utilized for serviceability design with displacements under 7 mm. DeBeer, Terzaghi and Peck, van der Veen, and slope tangent interpretations are all in the transition region of the normalized load-displacement curve with displacements ranging from 17 to 31 mm. Davisson method yielded almost the same mean normalized value as the L_2 interpretation with mean displacements at 43.4 mm. DIN 4026 is recommended for designs under 47 mm mean displacement while Fuller and Hoy and Chin methods are un-conservative methods which always over-estimate the capacity with displacements exceeding 104.8 mm.Finally, specific recommendations to guide the design of barrette piles under drained conditions are provided.

Keywords: Barrette Piles; Foundations; Drained Soils; Interpretation Criteria.

1 Introduction

Over the past decades, barrette piles are becoming more commonly used in high-rise buildings, elevated expressways, and subway stations. Due to its slender rectangular shape, barrette piles are also often called rectangular piles, wall-type piles, or diaphragm walls. In fact, an isolated barrette pile is actually built using the trenching method used to construct diaphragm walls(Hsu et al. 2017). One of the advantages of barrette piles is that it can resist large superstructure loads as compared to the drilled shafts (conventional circular piles)in addition to it being able to produce lesser deformations (Liao et al. 2013;Lin et al. 2014).

One of the most important factors in the design of any foundation is its capacity. These capacities are utilized in the design and ultimately affect the pile's properties. Therefore, it is of great importance to predict the capacity of barrette piles in a given site condition as accurately as possible. This is done by conducting on-site load tests. These load tests lessen the uncertainties in the design and provide the designers ample information for the design. The results of these load tests are load-displacement curves. These curves are often used to estimate the capacity of the pile given the soil condition on-site. These load-displacement curves may produce any of the three scenarios shown in Figure 1 which can be interpreted in multiple ways. Curve A shows a clear peak followed by the loss of capacity as displacement continuously increase thus providing a clearly defined capacity. On the other hand, it can be seen that there is no clear peak on curve B, but there is a linear region near the end of the curve that can be used to interpret the capacity. Lastly, it can be seen that curve C doesn't have either a clear peak or a final linear region. When determining the ultimate capacity of these kinds of curves, uncertainty is much higher. However, this curve type resembles most of the load test data results in the field.Therefore, in order to minimize such uncertainties, applicability of specific interpretation criteria to each load test should be properly determined.

Different interpretation criteria are used in practice to interpret pile capacity based on various assumptions (Chen and Fang 2009). Figure 2 represents one of the many ways to interpret the load-displacement curve to determine the capacity of piles. Different regions in the load-displacement curve such as initial or elastic, transition, and final linear regions are seen. It can be seen that the L_1 can be found at the end of the initial linear region and is usually used to interpret serviceability loads. On the other hand, the L_2 capacity can be interpreted at the start of the final linear region, where ultimate capacities are averagely located. Between the initial and final linear regions is the transition region. These interpretation methods are important to properly assess the most applicable method of interpretation that can be applied for barrette piles under drained loading conditions.

In this study, various load test data results were gathered and examined to explore the applicability and interrelationships of different interpretation criteria to barrette piles in drained soil conditions. After comparing the results of each interpretation methods, the study was further analysed by comparing in to the results of other pile types in different soil conditions that were done in previous researches (Chen and Fang 2009; Chu 2009;

Marcos et al. 2011; Chen et al. 2013; Marcos et al. 2013; Chen et al. 2021; Topacio et al. 2022). The results of the comparison are also presented statistically and graphically, along with recommendations for the design of barrette piles in drained soil conditions.

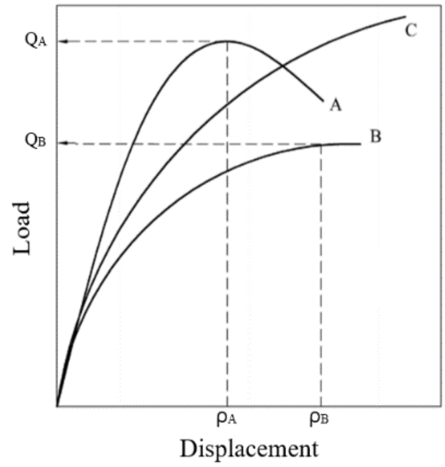

Figure 1. Typical load-displacement curves for pile foundations

2 Database

Currently, 18 load test data were collected from published papers and site reports under drained compression loading. The load test data was categorized as having drained conditions according to the predominant soil condition along the shaft length. The statistical results are listed in Table 1 with ranges of statistical properties, mean values, standard deviation (SD), and coefficient of variation (COV) for foundation geometry and aspect ratio, respectively. As seen in Table 1, the width and side dimensions range from 0.6 to 1.7 m, and from 1.8 to 3.2 m, respectively. The lengths of the piles range from 9.5 to 75.0 m. Equivalent diameters range from 1.2 to 2.5 m while aspect ratios range from 3.9 to 42.2.

Table 1. Statistical results of pile properties of the database

Statistics	Wide, W (m)	Side, S (m)	Pile length, L (m)	Equivalent pile diameter, D (m)	Aspect ratio L/D
n	18	18	18	18	18
Range	0.6 – 1.7	1.8 – 3.2	9.5 – 75.0	1.2 – 2.5	3.9 – 42.2
Mean	1.04	2.72	40.34	1.88	22.19
SD	0.31	0.26	22.18	0.32	12.48
COV	0.30	0.10	0.55	0.17	0.56

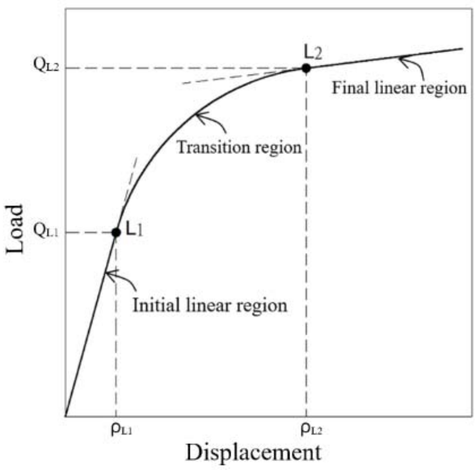

Figure 2. Regions of the load-displacement curve

3 Interpretation Criteria

As discussed previously, load-displacement curves were used in this paper to interpret the capacities by applying various interpretation methods. Nine interpretation criteria with varying specific methods were used to estimate the interpreted capacity of each load test results in the created database. All interpretation methods and their respective procedures are listed in Table 2. The methods can be divided into three categories: Graphical construction, settlement limitation, and mathematical modelling. Graphical construction methodsinclude the L_1 - L_2 method (Hirany and Kulhawy 1988), the slope-tangent method (O'Rourke and Kulhawy 1985), and the Davisson (1972) method. Settlement limitation is composed of DeBeer (1970),DIN 4026 (1975), Terzaghi and Peck (1967), and Fuller and Hoy (1970) methods, which utilized the pile equivalent diameters (D) in interpreting the capacities in this paper. Finally, mathematical modelling methods include the van der Veen (1953) and Chin (1970) methods. These methods were chosen for their usability and consistency. And as discussed, previous studies also examined these interpretation methods and their applicability to various pile types in different soil conditions (Chen and Fang 2009; Chu2009; Marcos et al. 2014; Chen et al. 2021) thus proving the need to assess their applicability to barrette piles in drained soils.

Table 2. Representative compression interpretation criteria for barrette piles

Method	Classification	Definition of interpreted capacity, Q
L_1 - L_2 (Hirany and Kulhawy, 1988)	Graphical Construction	L_1 and L_2 designate the elastic limit and failure threshold, respectively. Failure is defined qualitatively as the load beyond which a small increase in load produces a significant increase in displacement.
Slope-tangent (O'Rourke and Kulhawy, 1985)		Load occurs at a displacement equal to the initial slope of the load-displacement plus 0.15 in (3.8 mm) + *D* (in mm)/120, in which *D* = equilibrium diameter.
Davisson (1972)		Load occurs at a displacement equal to the pile elastic compression line, *PL/AE*, plus 0.15 in. (3.8mm) + *D*(in. or mm)/120, in which *P* = load, *L*= depth, *A* = area, *E* = young's modulus, *D*=equilibrium diameter,
DeBeer (1970)	Settlement Limitation	Load occurs at which change in slope on log-log total settlement curve.
DIN 4026 (1975)		The load that occurs at specific settlements is based on the percentage of the equilibrium diameter of the pile, D.
Terzaghi and Peck (1967)		Load occurs at 1.0 in (=25.4 mm) of the total settlement.
Fuller and Hoy (1970)		Minimum load occurs at a rate of plastic settlement of 0.05 in/ton (0.14 mm/kN)
van der Veen (1953)	Mathematical Modeling	The value of Q_{VDV} which gives a straight line when log ($1-Q/Q_{VDV}$) is plotted versus total settlement.
Chin (1970)		Load is equal to inverse slope, $\frac{1}{m}$, of line $\frac{s}{p} = ms + c$ with p = load and s = total settlement.

4 Interpreted Results

4.1 Results of variousinterpretation methods

Table 3 presents the statistics of all the load test data that were examined by applying thenine interpretation methods. According to the results, the L_1 method can be found in the lower bound with a mean capacity of 16560kN, a standard deviation (SD) of 7013kN, and a COV value of 0.42. This is in contrast with the Chin method which presents a higher mean valuewhichalways falls on the asymptote of the extension curve in the load-displacement curve with a mean capacity of 47858kN, a standard deviation (SD) of 23017kN, and COV of 0.48. However, the DeBeer, slope-tangent, Terzaghi and Peck, van der Veen, and L_2methods are seen as the methods that fall in the median and in between the initial and final linear region in the load-displacement curve with mean capacities ranging from 27123 to 36383kN, withstandard deviations (SD) and COVs ranging from 13843 kN to 17100 kN and 0.46 to 0.51, respectively. The remaining methods which arethe DIN 4026, Davisson, and Fuller and Hoy methods fall in the final linear region with mean capacities ranging from 37277 to 42956kN, standard deviations (SD) from 17668 kN to 20172 kN, and COVs from 0.47 to 0.54.

Table 3. Statistics of the interpreted results for barrette piles under drained compression

Statistics	Interpreted capacity, Q (kN)									
	Q_{L1}^*	Q_{L2}^*	Q_{DB}^*	Q_{VDV}^*	$Q_{T\&P}^*$	Q_{STC}^*	Q_{DA}^*	Q_{DIN}^*	$Q_{F\&H}^*$	Q_{CHIN}^*
n	18	18	18	18	18	18	18	18	18	18
Mean	16560	36383	27123	31278	31963	34591	37426	37277	42956	47858
SD	7013	17100	13843	14379	15407	16654	20065	17668	20172	23017
COV	0.42	0.47	0.51	0.46	0.48	0.48	0.54	0.47	0.47	0.48

Note:*:Q_{L1} – L_1 method; Q_{L2} – L_2 method; Q_{DB} – DeBeer method; Q_{VDV} – van der Veen method; $Q_{T\&P}$ – Terzaghi and Peck method; Q_{STC} – slope-tangent method; Q_{DA} = Davisson; Q_{DIN} = DIN4026 method; $Q_{F\&H}$ – Fuller and Hoy method; Q_{CHIN} – Chin method.

4.2 Normalized interpreted results

In order to compare each interpretation methods in a relative level, it is important to normalize the results using a standard value. This normalization provides a standard measure, thus providing a more accurate comparison results. For this paper, the standard interpretation method utilized is the L_2 method because of its flexibility in interpreting the load-displacement curve as seen in previous studies (Chen et al. 2021; and Topacio et al. 2022). The statistical results of the normalized interpreted methods are shown in Table 4 and their corresponding displacements in Table 5. Mean, SDs and COVs are still the statistical measures utilized in this comparison. Finally, to clearly distinguish each interpretation methods from each other, Figure 3 shows the mean normalized load-displacement curve where the interpretation methods are plotted to clearly see their location and range. An equation was also calculated and shown to define any normalized load at any given displacement.

Table 4. Statistics of the normalized interpreted values for barrette piles under drained compression

Statistics	Q/Q_{L2}								
	Q_{L1}^*	Q_{DB}^*	Q_{VDV}^*	$Q_{T\&P}^*$	Q_{STC}^*	Q_{DA}^*	Q_{DIN}^*	$Q_{F\&H}^*$	Q_{CHIN}^*
n	18	18	18	18	18	18	18	18	18
Mean	0.48	0.75	0.87	0.90	0.96	1.00	1.03	1.18	1.31
SD	0.08	0.16	0.06	0.14	0.10	0.14	0.10	0.08	0.12
COV	0.17	0.22	0.07	0.15	0.10	0.14	0.09	0.07	0.09

Note: *:Q_{L1} – L_1 method; Q_{DB} – DeBeer method; Q_{VDV} – van der Veen method; $Q_{T\&P}$ – Terzaghi and Peck method; Q_{STC} – slope-tangentmethod; Q_{DA} = Davisson; Q_{DIN} = DIN4026 method; $Q_{F\&H}$ – Fuller and Hoy method; Q_{CHIN} – Chin method.

Based on the statistical results of the normalization, the L_1 method still fell on the lower bounds and can be recommended for serviceability with a mean value of 0.48with mean displacement at 7 mm. DeBeer method fell near the center of the transition region of the load-displacement curve with a mean normalized value of 0.75with its mean displacement at17 mm. van der Veen, Terzaghi and Peck, and slope-tangent methods all fell along the transition curve with mean normalized values ranging from 0.87 to 0.96anddisplacementsfrom 24 to 31 mm. Davisson method's mean value yielded the same value as that of the standard method, with its SD and COV values both equal to 0.14.Meanwhile, DIN 4026 and Fuller and Hoy methods fell on the final linear region with mean normalized values ranging from 1.03to 1.18 and mean displacements at 47and 105 mm, respectively. It can be seen that they both over-estimate the capacity in relation to the interpreted capacities of L_2. Finally, Chin method always fell at the higher bounds with a mean normalized value of 1.31 and displacement greater than 105 mm. This method is not recommended for design as it tends to over-estimate the capacity.

Table 5. Statistics of interpreted displacements for barrette piles under drained compression

Statistics	Relative displacement of interpreted criteria ρ (mm)									
	ρ_{L1}^*	ρ_{L2}^*	ρ_{DB}^*	ρ_{VDV}^*	$\rho_{T\&P}^*$	ρ_{STC}^*	ρ_{DA}^*	ρ_{DIN}^*	$\rho_{F\&H}^*$	ρ_{CHIN}^*
n	18	18	18	18	18	18	18	18	18	18
Mean	7.0	40.1	17.0	24.3	25.4	31.0	43.4	47.0	104.8	>104.8
SD	3.98	22.69	9.72	15.41	0.00	7.09	21.64	7.88	51.61	51.61
COV	0.57	0.57	0.57	0.64	0.00	0.23	0.50	0.17	0.49	0.49

Note: *:ρ_{L1} – L_1 method; ρ_{L2} – L_2 method; ρ_{DB} – DeBeer method; ρ_{VDV} – van der Veen method; $\rho_{T\&P}$ – Terzaghi and Peck method; ρ_{STC} – slope-tangent method; ρ_{DA} = Davisson; ρ_{DIN} = DIN4026 method;$\rho_{F\&H}$ – Fuller and Hoy method; ρ_{CHIN} – Chin method.

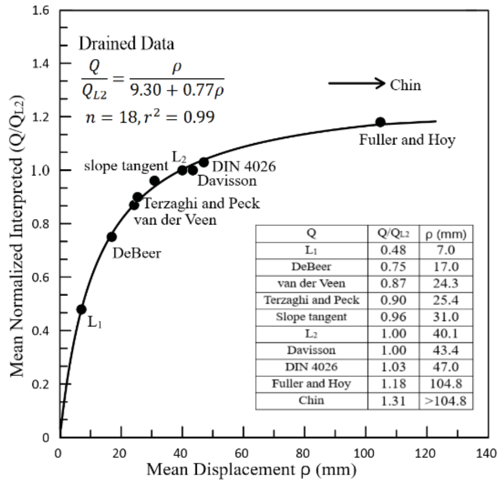

Figure3. Mean normalized load-displacement curve (Q/Q_{L2}) under drained compression loading

5 Comparison with Different PilesandSoil Conditions

To further assess the results of this paper, the created normalized load-displacement curve was then compared to the normalized load-displacement curves of other piles under a variety of soil conditions. This comparison can be seen in Figure 4.The current study was graphed side-by-side with other curves which include curves for: drilled shafts in drained soil (Curve B), gravel (Curve C), tip-grouted in drained soil (Curve G), and rock (Curve F) (Chen and Fang 2009; Chu 2009; Chen et al. 2021; and Topacio et al. 2022); driven precast concrete pile in drained soils (Curve D) (Marcos et al. 2013); and pre-bored precast concrete piles in drained soil conditions (Curve E) (Marcos et al. 2011;Chen et al. 2013).

It can be evaluated in Figure 4 that various pile types behave in various soil and rock conditions. It can also be seen that the curve behaviour of the current study is in comparable range with that of drilled shafts under drained soil conditions. However, differences can be seen at higher displacement values which were calculated for barrette piles. This can be attributed to the actual service area of the barrette piles being higher compared to that of drilled shafts. However, it can be seen that compared to tip-grouted piles in drained soils, the displacements of barrette piles are still quite small at the same normalized load, as the latter tend to mimic rock conditions to increase the capacity thus closing its displacement with that of drilled shafts in rock. In comparison with the other remaining studies, the barrette piles can be seen to mobilize the capacities at larger displacements, but with higher mean interpreted values.

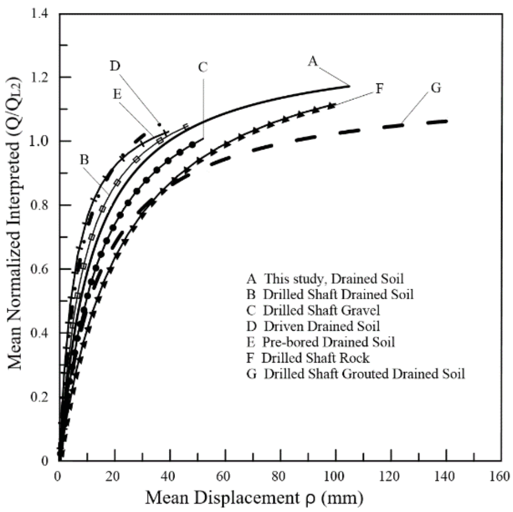

Figure 4. Comparisons of the normalized load-displacement curve of barrette piles in drained soil to other studies

6 Conclusions and Recommendations

A collection of load test results were compiled in this paper and were analysed with the application of different interpretation methods. Upon comparing each interpretation method results, the following design recommendations are drawn:

1. L_1 method can be utilized in the serviceability design with mean interpreted and normalized value of 16560kN and 0.48, respectively and at displacements not exceeding 7 mm.DeBeer, Terzaghi and Peck, van der

Veen, and slope tangent interpretations are all in the transition region of the normalized load-displacement curve with normalized values ranging from 0.75 to 0.96andare recommended for designs not exceeding displacements ranging from 17 to 31 mm.

2. Davissonand L_2 methods are recommended in the design as these interpretations closely estimated the capacities the same mean normalized value. These are recommended for designs not exceeding displacements of43 mm. DIN 4026 over-estimates in relation to L_2. This can be recommended for designs under47 mm

3. Fuller and Hoy and Chin methods are un-conservative methods which always over-estimate the capacity with displacements exceeding 104.8 mm.

4. In the comparison of barrette piles to different pile types, the currentstudy was found to be in comparable range with that of drilled shafts in drained soil conditions but with seemingly higher displacement.

7 Acknowledgements

This study was supported by the Ministry of Science and Technology (MOST), Taiwan, under Contract No: MOST 110-2221-E-033-010-MY2 and John Su Foundation.

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