Interrelationships of Load and Displacement of Barrette Piles for Various Interpretation Criteria Subjected to Uplift Loading

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Abstract. This paper evaluates various interpretation criteria for barrette piles subjected to uplift loading conditions. Eight load test results were gathered and employed for the analysis in order to determine the application of these interpretation criteria to barrette piles. The database was divided into drained and undrained soil conditions. Analysis of each of the interpretation criteria was performed in relation to the displacement ranges of each of the interpreted capacities. It was found out that the interpretation criteria L_1 provided the initial linear elastic stage or the serviceability design at mean displacements of 4.1 mm and 7.3 mm, respectively, for drained and undrained soil conditions. On the other hand, the interpretation criteria of DeBeer, van der Veen, Terzaghi and Peck, Davisson, L_2, and slope tangent fell on the same ranges of interpreted capacities with mean displacements ranging from 15 to 25 mm for drained and from 21 to 34 mm for undrained soil conditions. Finally, the interpretation criteria of DIN4026, Fuller and Hoy, and Chin all over-estimate the capacity with mean displacement exceeding 40 mm for drained and 53 mm for undrained soil conditions. In addition, the interrelationships of the load and the displacement for each of the interpretation criteria were further analyzed. A normalized load-displacement curve was determined in order to assess the corresponding mean displacements at which each of these interpretation criterion's loads are mobilizing along the curve. Statistical analysis was also applied to determine the consistency and reliability of each of the interpretation criteria. Normalized load-displacement equations for barrette piles subjected to uplift loading condition were also calculated for both drained and undrained soil conditions to be utilized and recommended for engineering practice and design of barrette piles for uplift loading.

Keywords: Uplift loading · Barrette piles · Displacement · Interpretation criteria · Load test

1 Introduction

Various conditions of a pile foundations can lead into various load (Q) – displacement (ρ) curve types that is gathered from axial load tests on such foundations. These varieties may exhibit any one of three shapes, A, B, or C, as shown in Fig. 1. But due to the

E. Strauss (Ed.): ICOCE 2022, LNCE 276, pp. 98–107, 2023.
https://doi.org/10.1007/978-981-19-3983-9_9

requirements of structures that can only withstand a range of displacements, most of the load-displacement curves that are gathered from load test results resemble that of curve C. This may pose a dilemma as the capacity of the pile is not clearly visible on such condition of the load-displacement curve. Therefore, the capacity almost always needs to be interpreted from the load test results. Interpretation criteria (e.g., [1–10]) have been proposed over the years for interpreting such failure load. Table 1 defines nine representative criteria for the interpreted failure load based on a variety of assumptions, individual judgments, extrapolations, and others from the measured load–displacement curve. As found in practice, these interpretation criteria will give different results that can vary substantially.

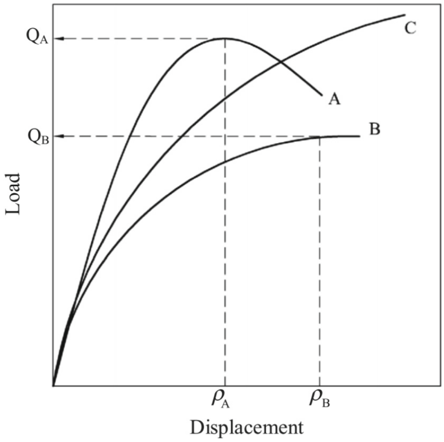


Fig. 1. Typical load–displacement curves for pile foundations

With these uncertainties in the interpretation of the capacity of a foundation, it is of utmost importance to analyze the application of these interpretation on various conditions and pile types. These load test data may provide vital information in determining the effects of different loading conditions to various soil and pile properties. Various researchers have also compiled relational databases of axial load test on different types of piles [11–16]. And since the 1980s, Kulhawy and co-workers have examined this issue in detail for drilled foundations. Their research [9, 10] and [17–20] mainly focused on the L_1 (elastic limit) – L_2 (failure threshold) method. Later, Chen and co-authors ([13, 16] and [21–24]) performed a more extensive evaluation to cover the existing representative uplift and compression interpretation criteria for various soil and pile types. What lacked in these analyses is a detailed comparison of various interpretation criteria when they are applied to barrette piles under uplift loading conditions.

Therefore, in this paper, nine representative uplift interpretation methods are examined in detail to assess their relative merits and their interrelationships. A database consisting of axial uplift load tests for barrette piles under drained and undrained soil conditions is used for this purpose. The results are compared statistically and graphically, and conclusions are reached for consistent use in practice.

Table 1. Definitions of representative uplift interpretation criteria for pile foundations

Method	Classification	Definition of interpreted capacity, Q
van der Veen (1953)	Mathematical modeling	Value of Q_{ult} which is the ultimate load that gives a straight line when log $(1\text{-}Q/Q_{ult})$ is plotted versus total settlement.
Chin (1970)	Mathematical modeling	Load is equal to inverse slope, $\frac{1}{m}$, of line $\frac{s}{Q} = ms + c$ with Q = load and s = total settlement.
Terzaghi and Peck (1967)	Settlement limitation	Load occurs at 1.0 in (25.4 mm) total settlement.
DeBeer (1970)	Settlement limitation	Load occurs at which change in slope on log-log total settlement curve.
Fuller and Hoy (1970)	Settlement limitation	Minimum load occurs at a rate of plastic settlement of 0.05 in per ton (0.14 mm/kN).
DIN4026 (1975)	Settlement limitation	Load corresponds to displacement at 2.5% B.
Davisson (1972)	Graphical construction	Load occurs at a displacement equal to the pile elastic compression line, $\frac{QD}{AE}$, plus 0.15 in (3.8 mm) + B (in inch or mm)/120, in which Q = load, D = depth, A = area, E = Young's modulus, B = pile diameter.
slope tangent (1985)	Graphical construction	Load occurs at a displacement equal to the initial slope of the load-displacement curve plus 0.15 in (3.8 mm) + B (in inch or mm)/120.
L_1 - L_2 (1989, 2002)	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.

2 Database

The database that was utilized in this study consisted of eight (8) load test results of barrette piles under uplift loading conditions. These load tests were done both in drained and undrained soil conditions, thus, the database was further divided into the said soil conditions, respectively. Division of the database into drained and undrained groups is governed by the prominent soil type along the pile length of each load test. Table 2 shows the soil and pile parameters that have been utilized in the study for its analysis. It can also be calculated in the table that the average equivalent diameter of the database is at 1.98 m while average pile length is at 41.7 m ranging from 3.5 to 57.5 m.

3 Interpreted Axial Uplift Capacity

As discussed, nine different criteria were used to analyze the interpreted capacity, as given in Table 1. These criteria were selected because they represent various displacement ranges and may represent the distribution of the interpreted results from the lower, middle and higher ranges as seen in past researches. Table 3 shows the results of each of the interpreted capacities (Q) based on each of the methods and represents different ranges of the capacities. However, during extrapolation, some load tests were terminated before achieving the available interpolated values. Following the conclusions of Phoon and Tang [25], bias is deemed inside a reasonable range for extrapolation from a load test terminated at 75% or higher of the actual Davisson capacity which is around 133% or lower of the final terminated load from any load test. Thus, these interpreted results were denoted as greater than (>) the value of 133% of the terminated load.

In addition to the results of the interpreted capacities, the relative displacements (ρ) are also determined in order to assess the location of each of the interpreted capacities

Table 2. Soil and pile information for barrette piles

Shaft No.	Test location	Soil layer description	Soil condition	Width, W (m)	Side, S (m)	Equivalent diameter B (m)	Pile length L (m)	L/B
TPU1	Taipei, Taiwan	Clay, sand and rock	Undrained	1.20	2.70	2.03	34.50	17.0
TPU2	Taipei, Taiwan	Clay, sand and rock	Undrained	1.20	2.70	2.03	50.30	24.8
TPU3	Taipei, Taiwan	Clay and silty gravels	Drained	1.30	2.70	2.11	52.00	24.6
TPU4	Taipei, Taiwan	Silt sand, silt clay	Drained	1.20	2.70	2.03	51.40	25.3
TPU5	Bangkok, Thailand	Soft and hard clay and dense to very dense sand	Undrained	1.50	3.00	2.40	57.50	24.0
TPU6	Taipei, Taiwan	Silty clay, sandy silt, and gravel	Drained	0.8	2.7	1.66	45.3	27.3
TPU7	Taipei, Taiwan	Silty clay, sandy silt, and gravel	Drained	0.80	2.60	1.63	39.50	24.2
TPU8	Zurich, Switzerland	Loose to dense moraine	Drained	1.00	3.00	1.95	3.50	1.8

Table 3. Interpreted uplift capacities utilizing various interpretation criteria

Shaft no.	Soil condition	Interpreted capacity, Q(kN)									
		L_1	L_2	DAV*	ST*	T&P*	DeBeer	DIN*	F&H*	VDV*	Chin
TPU3	Drained	12500	20000	22700	22400	22482	20400	24297	24600	21000	26259
TPU4		8000	15000	>15656	15400	>15656	13200	>15656	>15656	13000	>15656
TPU6		12500	20800	21000	20300	20549	20000	22300	23000	17000	25771
TPU7		8000	12000	12200	12100	12473	12500	13304	13600	11000	>14352
TPU8		9800	14000	15700	15600	15798	12700	>15960	13800	12000	>15656
TPU1	Undrained	20000	30000	32400	31200	31093	25000	33699	34000	26000	36785
TPU2		15000	29700	26400	26400	25302	25100	30549	32000	28000	38550
TPU5		35250	61500	62100	66700	57773	60500	69525	69000	60000	>71820

Note: *: DAV – Davisson, ST – Slope-tangent, T&P – Terzaghi and Peck, DIN – DIN4026, F&H – Fuller and Hoy, VDV – van der Veen

and their distribution along the load-displacement curve as seen in Table 4. Furthermore, comparison between each of the interpreted capacities was done in order to assess where each of the interpretation methods are distributed along the normalized load displacement curve. In order to assess this, a normalizing interpretation method must be determined in order to check each of the other methods' location in the curve in relation to the normalizing method. the L_2 method was used as the normalizing criterion. This graphical method interprets the capacity as the start of the load–displacement curve's final linear region. This method is effective for load–displacement curves resembling that of curves B and C with the application of a hyperbolic extension.

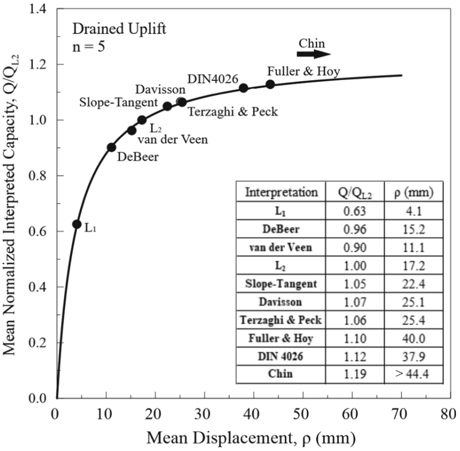
After normalizing the interpreted capacities and calculating the mean values for both drained and undrained soil conditions, it can be found that the interpreted load of the L_1 provided the initial linear elastic stage of the developed normalized load–displacement curve. It may be used to predict the serviceability load that can be resisted by barrette piles or designs that require displacements that do not exceed mean displacements of 4.1 mm and 7.3 mm, respectively for drained and undrained soil conditions.

Table 4. Relative displacements utilizing various interpretation criteria

Shaft no.	Soil condition	Relative displacement, ρ (mm)									
		L_1	L_2	DAV*	ST*	T&P*	DeBeer	DIN*	F&H*	VDV*	Chin
TPU3	Drained	3.9	13.6	27.2	24.8	25.4	14.9	52.9	63.3	17.0	>63.3
TPU4		2.1	16.5	24.6	20.7	25.4	8.0	24.6	24.6	7.5	>24.6
TPU6		6.1	27.0	28.4	23.9	25.4	22.4	41.5	53.6	12.5	>53.6
TPU7		5.8	20.5	22.4	21.4	25.4	25.7	40.7	50.6	14.1	>50.6
TPU8		2.4	8.5	23.1	21.2	25.4	5.3	30.1	7.8	4.3	>30.1
TPU1	Undrained	5.5	20.6	34.4	26.0	25.4	9.9	50.8	56.8	11.2	>56.8
TPU2		8.5	44.6	28.9	28.9	25.4	24.8	50.8	65.0	35.3	>65.0
TPU5		8.0	32.0	33.3	46.7	25.4	30.0	59.8	57.0	29.1	>76.0

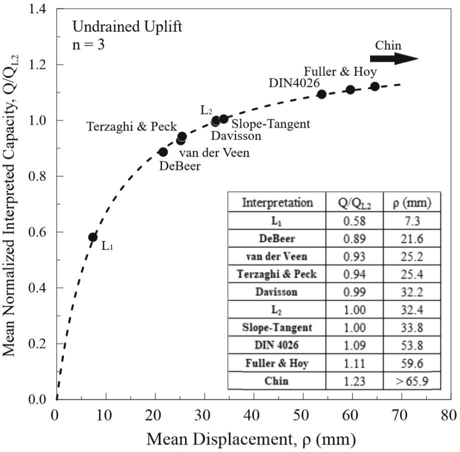
Note: *: DAV – Davisson, ST – slope-tangent, T&P – Terzaghi and Peck, DIN – DIN4026, F&H – Fuller and Hoy, VDV – van der Veen

Most of the interpretation criteria fell on the transition region of the normalized load–displacement curve with the methods of L_2, Davisson, slope-tangent, Terzaghi and Peck, van der Veen, and DeBeer. These interpretation criteria provided good estimates of the capacity of barrette piles and are effective for designs that require mean displacements that do not exceed a range from 15 to 25 mm for drained and from 21 to 34 mm for undrained soil conditions. Lastly, the methods of Fuller and Hoy, DIN4026, and Chin had overestimated capacities and thus were un-conservative in interpreting the capacity of barrette piles for both drained and undrained soil conditions with mean displacements exceeding 40 mm for drained and 53 mm for undrained soil conditions. Graphical representation of the location for these methods on the normalized load-displacement curve can be seen in Figs. 2 and 3 for drained and undrained soil conditions, respectively.



Interpretation	Q/Q_{L2}	ρ (mm)
L_1	0.63	4.1
DeBeer	0.96	15.2
van der Veen	0.90	11.1
L_2	1.00	17.2
Slope-Tangent	1.05	22.4
Davisson	1.07	25.1
Terzaghi & Peck	1.06	25.4
Fuller & Hoy	1.10	40.0
DIN 4026	1.12	37.9
Chin	1.19	> 44.4

Fig. 2. Normalized load displacement curve for barrette piles in drained soils



Interpretation	Q/Q_{L2}	ρ (mm)
L_1	0.58	7.3
DeBeer	0.89	21.6
van der Veen	0.93	25.2
Terzaghi & Peck	0.94	25.4
Davisson	0.99	32.2
L_2	1.00	32.4
Slope-Tangent	1.00	33.8
DIN 4026	1.09	53.8
Fuller & Hoy	1.11	59.6
Chin	1.23	> 65.9

Fig. 3. Normalized load displacement curve for barrette piles in undrained soils

It can also be seen in the calculated results that the drained soils mobilize capacity at a lower displacement values in comparison to the undrained soil conditions. This means that lower capacities can be expected from sandy soils at lower displacements in comparison to clayey soils at slightly higher displacements.

Normalized load-displacement curve equations are also computed based on the data that were interpreted for both drained and undrained soil conditions. These equations may help in simplifying the analysis of each interpreted capacities in relation to that of the normalizing method that is L_2. The equations are listed below for drained and undrained soil conditions, respectively.

$$\frac{Q}{Q_{L2}} = \frac{\rho}{3.21 + 0.82\rho} \quad \text{for drained soils} \left(r^2 = 0.99\right) \tag{1}$$

$$\frac{Q}{Q_{L2}} = \frac{\rho}{7.09 + 0.78\rho} \quad \text{for undrained soils} \left(\mathrm{r}^2 = 0.99\right) \tag{2}$$

Furthermore, the results of this preliminary analysis may be able to shed light on the behaviour of each of the interpretation criteria when applied to barrette piles under uplift loading conditions. In order to increase the reliability and decrease the uncertainty of the results of the analysis, additional load tests should be employed to the database. It is therefore recommended for future expansion of the study the addition of load test data, in order to increase the range of pile and soil properties included in the analysis. Also, analysis of the behaviour of the interpretation criteria to the side and tip resistances is advised in order to present a more robust comparison between the interpretation methods that are being studied.

4 Summary and Conclusions

Axial uplift load test data were used to evaluate the capacity of barrette piles in various soil conditions. The database included 8 field uplift load tests, including 5 drained and 3 undrained soil conditions. Nine representative interpretation criteria were utilized to evaluate the available data. From these analyses, the following results were drawn:

1. L_1 method provided the initial linear elastic stage or the serviceability region of the developed normalized load–displacement curve with mean displacements that do not exceed 4.1 mm and 7.3 mm, respectively, for drained and undrained soil conditions.
2. The methods of L_2, Davisson, slope-tangent, Terzaghi and Peck, van der Veen, and DeBeer are located at the transition region to the initial stage of the final linear region of the curve. These interpretations yielded at mean displacements that do not exceed a range from 15 to 25 mm for drained soil conditions.
3. For undrained soil conditions, the methods of L_2, Davisson, slope-tangent, Terzaghi and Peck, van der Veen, and DeBeer yielded at mean displacements ranging from 21 to 34 mm.
4. The methods of Fuller and Hoy, DIN4026, and Chin have overestimated capacities and thus were un-conservative in interpreting the capacity of barrette piles for both drained and undrained soil conditions. These methods have mean displacements exceeding 40 mm and 53 mm for drained and undrained soil conditions, respectively.
5. Normalized load-displacement curves and their respective equations have been presented to be utilized for future designs of barrette piles in different soil conditions. Drained soil conditions yielded an equation of $\frac{Q}{Q_{L2}} = \frac{\rho}{3.21+0.82\rho}$ with an $r^2 = 0.99$; while undrained soil conditions yielded an equation of $\frac{Q}{Q_{L2}} = \frac{\rho}{7.09+0.78\rho}$ with an $r^2 = 0.99$.
6. In order to increase the reliability of the analysis, additional load test data is necessary for the analysis.

Acknowledgements. This study was supported by the Ministry of Science and Technology of Taiwan under the contract number MOST 110–2221-E-033–010-MY2 and the John Su Foundation.

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