樁基礎受壓載重之詮釋法評估
Evaluation of Interpretation Criteria for Piles under Compression Loading

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摘要

本研究用打擊式 PC 樁、預鑽孔植入式 PC 樁以及場鑄樁之靜載重試驗資料，評估樁基礎受軸向壓載之詮釋法。各種基樁在排水及不排水情況下，以不同的詮釋法檢驗各類基樁的載重位移曲線及行為關係。依分析結果，於各不同種類的基樁，每一種詮釋法所呈現之趨勢大致上相同。所有分析亦顯示 DeBeer 法之詮釋結果較低，可作為各詮釋法之低限值；而 Chin 法之值永遠大於量測結果，則可作為上限值之標準。經分析各載重-位移曲線，場鑄樁於卵礫石層之曲線呈現高度的韌性，打擊樁在排水土層則有較高的勁度。最後，本研究建立各種基樁於不同土層之正規化載重-位移曲線，同時顯現各詮釋法間之相互關係。

關鍵詞：詮釋法，打擊樁，預鑽孔植入式 PC 樁，場鑄樁，排水土層，不排水土層，礫石層

Abstract

This paper presents an evaluation of interpretation criteria for deep foundations under axial compression loading. Static load test data on driven PC pile, pre-bored PC pile, and drilled shaft under drained and undrained conditions were subjected to various interpretation criteria and used to examine the relationships of load-displacement behavior of different pile types. The general trend of each interpretation method demonstrates similarity for all pile types. In all events, DeBeer method is the lower bound criterion and Chin method is the upper bound and is always above the measured data. The normalized load-displacement curve of drilled shaft in gravelly soils shows great ductility whereas the curve of driven pile in drained soils exhibits a stiffer response. Based on these analyses, the interrelationships of these criteria for different pile types under drained and undrained soils are established in terms of normalized capacity and displacement.

Keywords: interpretation criteria, driven piles, pre-bored PC piles, drilled shafts, drained soils, undrained soils, gravelly soils

I. INTRODUCTION

Pile capacity is often verified by performing a load test to overcome many uncertainties in geotechnical parameters, installation issues, analysis models, and other factors. In practice, when selecting a pile suitable for a specific project is a critical issue, load tests on different pile types are permitted resulting to additional project cost. The load-displacement curves obtained from axial load tests can be distinct for different pile types because of the different installation methods. Drilled shaft, driven pile and pre-bored pile are among the most commonly used pile foundations worldwide. They mainly differ from the way they are installed into the ground. And these differences in construction procedures can significantly affect the pile capacity.

Numerous interpretation criteria [1-8] have been proposed to interpret the failure load of pile foundations from axial compression test data. Table 1 lists eight representative interpretation criteria and their definitions of compression capacity. As indicated, different failure definitions are suggested by these methods leading to different design recommendations.

To examine the relationships of load-displacement behavior of different pile types subjected to an analysis using common interpretation criteria, a comparative study is worthwhile. Results of the evaluation can provide guidance in selecting the most appropriate interpretation criterion to adopt in pile design and the suitable pile type for a proposed project.

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Table 1 Definition of representative compression interpretation criteria for deep foundations

Method	Category	Definition of interpreted capacity, Q
van der Veen [1]	Mathematical model	Q_{VDV} is P_{ult} that gives a straight line when log (1-P/P_{ult}) is plotted versus total settlement.
Chin [2]	Mathematical model	Q_{CHIN} is the inverse slope (1/m) of a line s/p = ms+c, where p = load and s = total settlement.
Fuller and Hoy [3]	Settlement limit	$Q_{F\&H}$ is the minimum load that occurs at a rate of total settlement of 0.05 in. per ton (0.14 mm/kN)
Terzaghi and Peck [4]	Settlement limit	$Q_{T\&P}$ is the load that occurs at 1.0 in. (25.4 mm) total settlement.
DeBeer [5]	Settlement limit	Q_{DB} is the load at the change in slope on a log-log load-settlement curve.
Davisson [6]	Graphical construction	Q_{DAV} occurs at a displacement equal to the pile elastic compression line (PD/AE) offset by 0.15 in. (3.8 mm) + B/120, where P = load, D = depth, A = area, E = Young's modulus, B = dia.
Slope tangent [7]	Graphical construction	Q_{ST} occurs at a displacement equal to the initial slope of the load-displacement curve offset by 0.15 in. (3.8 mm) + B (in. or mm)/120.
L_1 - L_2 [8]	Graphical construction	Q_{L1} and Q_{L2} correspond to elastic limit and failure threshold loads, respectively.

Table 2 Range of geometry for different pile types

Loading condition	Pile type	Number of tests	Statistics	Pile geometry (m)		D/B	Interpreted capacity, Q_{L2} (kN)
				Depth, D	Diameter, B		
Drained	Driven PC	75	Range	6.0-48.5	0.27-0.91	11.4-133.3	189-7295
			Mean	19.0	0.44	45.1	2390
			COV	0.49	0.33	0.49	0.68
	Pre-bored PC	50	Range	10.0-40.0	0.5-0.8	20.0-64.0	813-8193
			Mean	26.8	0.59	45.9	4236
			COV	0.27	0.14	0.26	0.53
	Drilled	55	Range	4.7-68.5	0.24-2.0	5.1-73.3	180-34970
			Mean	22.4	0.96	24.0	7100
			COV	0.67	0.44	0.52	0.98
	Drilled-gravelly	48	Range	4.7-30.0	0.59-1.52	6.2-30.0	2800-39230
			Mean	13.7	1.0	13.5	12636
			COV	0.43	0.26	0.39	0.62
Undrained	Driven PC	42	Range	4.4-57.5	0.18-1.4	6.0-142	63.2-11300
			Mean	21.0	0.5	47.5	2977
			COV	0.56	0.53	0.55	1.0
	Drilled	78	Range	1.8-60.0	0.20-1.8	3.4-55.0	65-24464
			Mean	20.6	0.87	21.9	5293
			COV	0.87	0.38	0.65	0.88

II. SOURCES OF LOAD TEST DATA

Three pile types are considered for the analysis: (1) driven precast concrete pile, (2) pre-bored precast concrete pile, and (3) drilled shaft. A load test database is developed for driven PC pile [9] and utilized for this purpose. The pre-bored PC pile data are from Marcos *et al.* [10] and Chen *et al.* [11], while the drilled shaft data are from Chen and Fang [12]. Static axial compression load test data were collected for the analysis. These tests were conducted in various sites around the world at different points in time. The soil profile is categorized herein as drained or undrained, based on the predominant soil conditions along the pile depth. For additional drilled shaft data, load tests in gravelly soils are included to assess the influence of gravels on pile capacity. Data for gravelly soils are referred from the study by Chu [13].

The piles are grouped into six categories, four belong to drained condition and two belong to undrained condition. For the drained condition; driven PC has 33 sites with 75 field tests; pre-bored PC has 18 sites with 50 tests; drilled has 34 sites with 55 tests; and drilled-gravelly has 25 sites with 48 tests. For undrained condition; driven PC has 25 sites with 42 tests; and drilled has 38 sites with 78 tests. Based on the case history descriptions, these piles appear to be of high quality. Therefore, these load tests should be representative of common field situations.

For convenience, the ranges of foundation geometry, compression capacity, and their statistics, are summarized in Table 2. The basic information and interpreted capacities are far lengthy to list herein but they are presented elsewhere [14]. The ranges of geometry are broad and the pile dimensions and capacities for driven and pre-bored PC pile for drained condition and driven and drilled shafts for undrained condition are somewhat comparable.

III. INTERPRETATION OF LOAD TESTS

Eight interpretation criteria listed in Table 1 were used to evaluate the interpreted failure load or capacity (Q)

Table 3 Summary comparison of interpreted capacities and displacements for drained soils

Drained data	Q_{L1}/Q_{L2}	δ (mm)	Q_{DB}/Q_{L2}	δ (mm)	Q_{ST}/Q_{L2}	δ (mm)	Q_{DAV}/Q_{L2}	δ (mm)	$Q_{T\&P}/Q_{L2}$	δ (mm)
Driven (n = 75)	0.44	4.2	0.81	11.5	0.87	14.1	0.92	19.2	0.99	25.4
Pre-bored (n = 50)	0.35	3.4	0.80	16.3	0.79	16.0	0.93	27.4	0.92	25.4
Drilled (n = 55)	0.43	3.4	0.58	7.2	0.86	18.9	0.86	18.5	0.94	25.4
Drilled-gravelly (n = 48)	0.41	7.2	0.79	23.1	0.83	26.5	0.75	20.4	0.82	25.4
range	0.35-0.44	3.4-7.2	0.58-0.81	7.2-23.1	0.83-0.87	14.1-26.5	0.75-0.93	18.5-27.4	0.82-0.99	-
mean	0.41	4.5	0.75	14.5	0.84	18.9	0.87	21.4	0.92	25.4
SD	0.04	1.81	0.11	6.81	0.04	5.46	0.08	4.09	0.07	-
COV	0.10	0.40	0.15	0.47	0.04	0.29	0.10	0.19	0.08	-
Drained data	Q_{L2}/Q_{L2}	δ (mm)	Q_{FH}/Q_{L2}	δ (mm)	Q_{VDV}/Q_{L2}	δ (mm)	Q_{CHIN}/Q_{L2}	δ (mm)		
Driven (n = 75)	1.00	25.9	1.01	28.8	1.08	41.1	1.29	>41.1		
Pre-bored (n = 50)	1.00	35.6	1.03	37.3	1.04	46.6	1.27	>64.6		
Drilled (n = 55)	1.00	34.9	1.04	44.7	0.88	23.4	1.34	>63.2		
Drilled-gravelly (n = 48)	1.00	52.1	-	-	0.89	32.4	1.27	>71.3		
range	-	25.9-52.1	1.01-1.04	28.8-44.7	0.89-1.08	23.4-46.6	1.27-1.34	>42->71.3		
mean	1.00	37.1	1.03	36.9	0.97	35.9	1.29	>60.1		
SD	-	10.90	0.02	7.97	0.10	10.16	0.03	12.69		
COV	-	0.29	0.01	0.22	0.11	0.28	0.03	0.21		

Table 4 Summary comparison of interpreted capacities and displacements for undrained soils

Undrained data	Q_{L1}/Q_{L2}	δ (mm)	Q_{DB}/Q_{L2}	δ (mm)	Q_{ST}/Q_{L2}	δ (mm)	Q_{DAV}/Q_{L2}	δ (mm)	$Q_{T\&P}/Q_{L2}$	δ (mm)
Driven (n = 42)	0.46	4.5	0.83	13.5	0.90	16.6	0.90	19.2	0.99	25.4
Drilled (n = 78)	0.50	3.2	0.66	7.4	0.88	15.8	0.89	16.4	0.96	25.4
range	0.46-0.50	3.2-4.5	0.66-0.83	7.4-13.5	0.88-0.90	15.8-16.6	0.89-0.90	16.4-19.2	0.96-0.99	-
mean	0.48	3.9	0.75	10.5	0.89	16.2	0.90	17.8	0.98	25.4
SD	0.03	0.94	0.12	4.31	0.01	0.56	0.01	1.94	0.02	-
COV	0.06	0.24	0.16	0.41	0.02	0.03	0.01	0.11	0.02	-
Undrained data	Q_{L2}/Q_{L2}	δ (mm)	Q_{FH}/Q_{L2}	δ (mm)	Q_{VDV}/Q_{L2}	δ (mm)	Q_{CHIN}/Q_{L2}	δ (mm)		
Driven (n = 42)	1.00	28.2	1.00	31.6	1.08	39.4	1.36	>42		
Drilled (n = 78)	1.00	30.9	1.04	39.6	0.85	15.4	1.28	>61.1		
range	-	28.2-30.9	1.00-1.04	31.6-39.6	0.85-1.08	15.4-39.4	1.28-1.36	>42->61.1		
mean	1.00	29.6	1.02	35.6	0.97	27.4	1.32	>51.55		
SD	-	1.88	0.03	5.66	0.16	16.96	0.06	13.51		
COV	-	0.06	0.03	0.16	0.17	0.62	0.04	0.26		

from the load-displacement curve of each pile case. These criteria were selected because they represent a wide distribution of interpreted results from the lower, middle, and higher bounds as found in practice. In addition, various definitions of failure load are employed, as noted in Table 1.

The mean normalized capacity and displacement that correspond to each interpretation criterion are presented in Tables 3 and 4 for drained and undrained conditions, respectively. The standard deviation (SD) and coefficient of variation (COV) values are likewise noted in the tables. The mean normalized load-displacement curves for the different piles are illustrated in Figs. 1 through 4 where the corresponding mean ratio of each interpretation method to Q_{L2} (interpreted capacity by L_2 method) is plotted against the mean displacement. Figs. 1 to 4 are referred from the previous studies [9, 11-13].

IV. COMPRASION OF INTERPRETATION CRITERIA

The summary comparisons for drained and undrianed conditions in Tables 3 and 4 show that, in general, most criteria exhibit the same general behavior for the interpreted results. However, some methods demonstrate unique behavior for every pile type. To compare and assess the relative merits of these criteria to different piles, each criterion is examined for both conditions.

For drained condition, the elastic limit Q_{L1} has a mean load ratio of 0.41 and a COV of 0.10. The elastic limits fordriven, prebored, and drilled are comparable. However,

at an early stage of loading, a siginificant increase of displacement is observed for drilled-gravelly. The Q_{DB} has a mean ratio of 0.75 with a COV of 0.15, the largest COV among the criteria. However, except for drilled group, Q_{DB} is consistent. Therefore, if it is a database issue or possible subjective judgement of the failure definition, is not clear.

In contrast, Q_{ST} presents a small COV of 0.04 having a mean load ratio of 0.84. The Q_{DAV} has a mean load ratio of 0.87 with a COV of 0.10. Interestingly, Q_{DAV} can be reached faster if applied to drilled shafts, especially in gravelly soils. By definition, Davisson method is based on the elastic compression of the pile and the excessive ductility of the load-displacement curve induced by the properties of gravelly soils is likely to underestimate the Q_{DAV}. The $Q_{T\&P}$ has a mean ratio of 0.92 and a COV of 0.08. However, it can be observed that for driven piles, $Q_{T\&P}$ is nearly at Q_{L2} with comparable displacements, while relatively larger displacements are needed for other piles to reach the initiation of final linear region (point L_2).

The result of $Q_{F\&H}$ has a mean load ratio of 1.03 and a COV of 0.01, the lowest COV among the methods which demonstrates that Fuller and Hoy method is a competent criterion. However, it failed to interpret load test cases in gravelly soils. This is possibly due to a very large displacement required to reach $Q_{F\&H}$ in gravelly soils. Meanwhile, different trends for Q_{VDV} are observed for the different piles. For PC pile, Q_{VDV} occurs after point L_2 and within the final region of the curve, while for drilled shaft, it happens between the L_1 and L_2 transition region of the load-displacement curves. This is likely that van der Veen method is conforming more to the plunging failure in PC pile than in drilled shafts.

Finally, Q_{CHIN} provides the highest interpreted capacity. The method of Chin is extrapolated from measured load-displacement curve, so it is always above the maximum measured value. Therefore, it should be noted that the interpreted result of Chin method could overestimate the bearing capacity. The mean compression

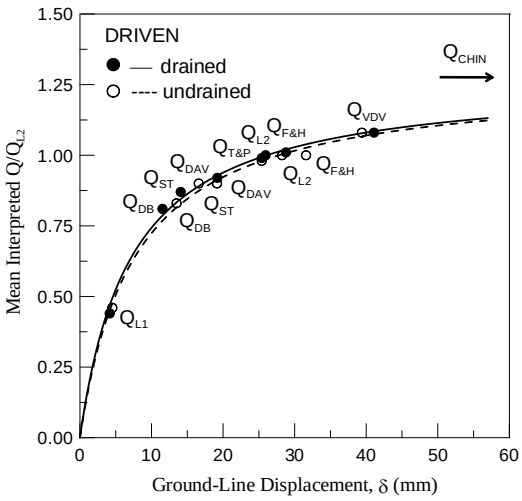

Fig. 1 Mean load-displacement curves for driven PC pile [9]

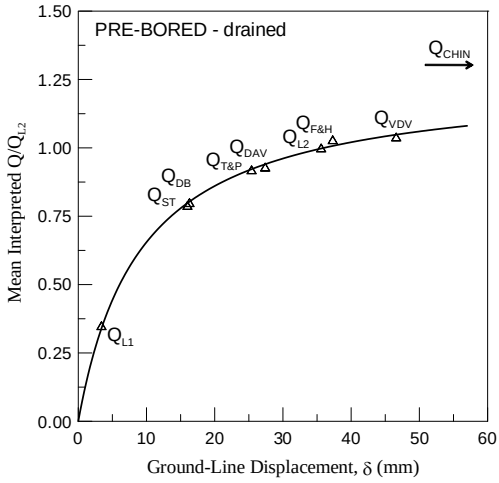

Fig. 2 Mean load-displacement curve for pre-bored PC pile in drained soils [11]

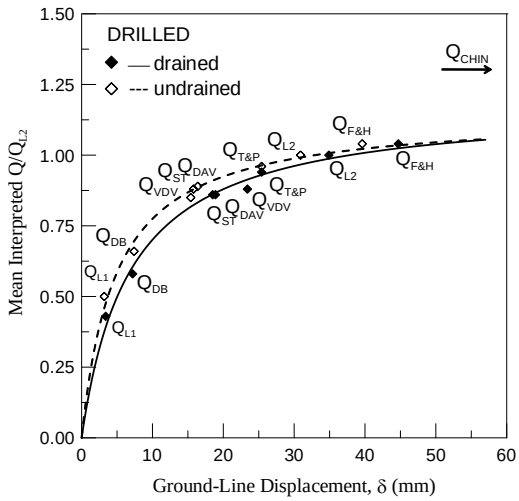

Fig. 3 Mean load-displacement curves for drilled shaft [12]

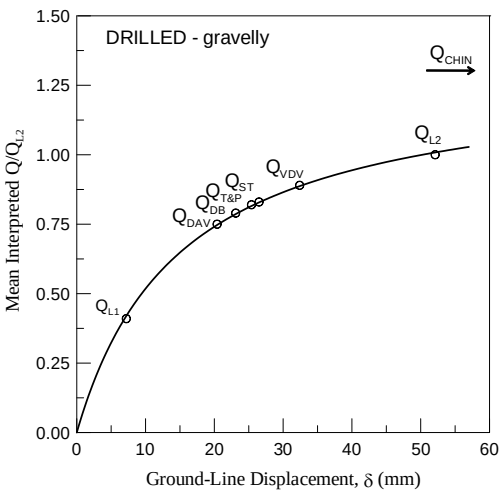

Fig. 4 Mean load-displacement curve for drilled shaft in gravelly soils [13]

displacements for the different piles is also shown in Table 3 which follow the same order as the capacities.

The summary comparison for undrained condition is illustrated in Table 4. The same methodology for the drained condition is employed to evaluate the undrained condition. Only two type piles are available for comparison; driven PC pile and drilled shaft. As in drained condition, most criteria exhibit the same general behavior for the interpreted results. The criteria are quite comparable for the two piles as reflected from the COV values of the mean load ratios. The elastic limit Q_{L1} has a mean ratio of 0.48 and a COV of 0.06.

Among the criteria that have relatively same behaviors for both piles are, Q_{ST}, Q_{DAV}, $Q_{T\&P}$, $Q_{F\&H}$, Q_{CHIN}, with mean load ratios of 0.89, 0.9, 0.98, 1.02, and 1.32, respectively. The COV values for these results are very small ranging from 0.01-0.04. The Q_{DB} is among the more variable criterion, with a mean ratio of 0.75 and a COV of 0.16. Same variability is seen from Q_{VDV} as in drained condition. The obvious differences in behavior of the two latter criteria may be attributed to the subjective judgement of the failure definition or possible database issue. The mean compression displacements for the different piles are also shown in Table 3 which basically follow the same order as the capacities.

V. COMPRASION OF DIFFERENT PILE TYPES

For direct comparisons, the normalized load-displacement curves for the different piles are combined in Figs. 5 and 6 for drained and undrained conditions, respectively. For drained condition, significant variations of load-displacement behavior from these piles are observed. First, among all piles drilled shaft in gravelly soils develops the largest displacements. This indicates that large settlement is required to fully mobilize pile capacity in gravelly soils.

The extremely great ductility of load-displacement curve can be attributed to the more dilative behavior of gravel which partially regains its shear strength under loading leading to its ability to attain larger settlement prior to failure. In contrast, the capacity of driven PC pile in drained soils can be reached at smaller displacements than either pre-bored pile or drilled shaft. This is likely brought about by the densification of soil surrounding the pile during driving resulting to a stiffer pile response. A relatively comparable behavior is demonstrated by pre-bored PC pile and drilled shaft in drained soils which may be due to their somewhat similar installation procedures. Another remarkable point of comparison in pile behavior is noted at the initiation of the final linear region (point L_2) which shows an increasing displacement from driven pile (25.9 mm), to drilled shaft in drained soils (34.9 mm), to pre-bored PC pile (35.6 mm), and to drilled shaft in gravelly soils (52.1 mm). This phenomenon indicates that the choice of pile type greatly depends on the allowable or design settlement.

For undrained condition in Fig. 6, the load-displacement curve of drilled shaft shows a somewhat stiffer response until the last portion of the transition region of the curve. This may be attributed to the more disturbances in undrained soils for driven pile during driving. However, in general, the curves are relatively in good agreement. For drilled shaft, the final linear region starts at a mean displacement of δ_{L2} = 30.9 mm and δ_{L2} = 28.2 mm for driven PC pile.

VI. CONCLUSIONS

1. The general trends of interpretation criteria for all pile types are comparable for both drained and undrained soils. DeBeer method is considered the lower bound criterion while Chin is the upper bound and always above the measured data.

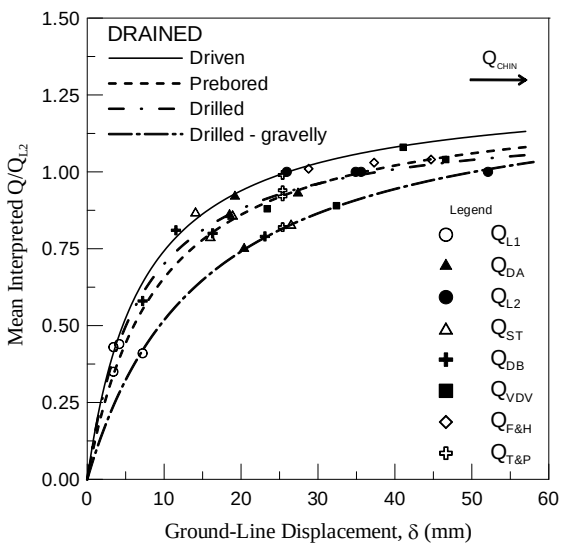

Fig. 5 Mean load-displacement curves for different piles in drained soils

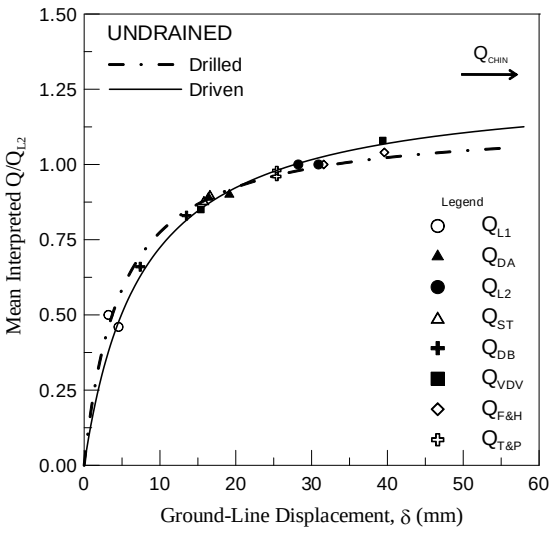

Fig. 6 Mean load-displacement curves for different piles in undrained soils

2. Among the different pile types, drilled shaft in gravelly soils develops the largest displacement to failure and exhibit great ductility.

3. Driven PC pile in drained soils produces the smallest displacement at failure and shows significant stiffness behavior.

4. Relatively comparable load-displacement behaviors are displayed by pre-bored PC pile and drilled shaft in drained soils, while the same is observed for driven PC pile and drilled shaft in undrained soils.

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