

BEHAVIOR OF DISPLACEMENT CONCRETE PILE UNDER COMPRESSIVE LOADS

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ABSTRACT: This paper provides the research of displacement precast piles through performing compressive Static Load Tests (SLTs). A total number of 40 piles which contain square solid pile and pipe pile with various pile lengths were tested. It is concluded that, because of the soil layers' difference among driven locations, the piles with various lengths presents different maximum settlements. Furthermore, it is discovered that the load-settlement curves obtained from the same type of concrete pile are relatively parallel during unloading stages. For the solid pile, the interpretations which are based on Double Tangent and Chin's method are used for capacity determination, and these results are compare to the designed ultimate capacity. It can be found that the Double Tangent method is conservative, and Chin's method overestimate the pile capacity. The increase and reduction factors are proposed and then the modified Double Tangent and Chin's interpretations are determined. Due to most of the SLTs being the Proof Tests (PTs), it is expected that this paper can provide practical information for geotechnical engineers to determine the ultimate bearing capacity of pile foundation from these PT results.

Keywords: Displacement concrete pile, Static load test, Proof Test, Test interpretation

1. INTRODUCTION

Pile foundation is a long structural element that cooperates with soil to resist the loading transferred from the upper structure. It can be primarily categorized into bored pile and precast pile foundation based on the construction method. Precast pile can resist more loading comparing to the shallow foundation and cost less since it does not need pre-driving as the bored pile does. Mostly, the precast pile foundation is considered as displacement pile because the precast pile will compact soil layers during driving. Based on the configuration, it can be categorized into small or large displacement piles.

For the precast concrete square piles (large displacement piles), these sizes can be ranging from 250mm to 450mm in diameter and 12m to 25m in length, and the working loads which can be resisted vary from 200kN to 900kN [1]. These piles can be a normally reinforced structure or be a prestressed structure. Past studies were focused on the pile tests illustration [2], types of soil profiles [3,4], drivability [5-7], load transfer mechanism [8,9] and configurations of piles and strength of concrete [10].

Recently, there has been intensive investigations aimed to research the materials effect on concrete pile. For example, due to a lack of data using Illinois PCC bottom ash in concrete structure, full-size tests were performed on concrete piles with Illinois PCC

bottom ash, and these piles were compared to the traditional reinforced concrete pile with fly ash admixture [11].

The behavior of open-ended piles is more complicated because the Soil Plug Effect (SPE) which created inside the pile should be considered when investigating the open-ended piles. Recently, a new CPT-based HKU method was proposed for base capacity estimation of the open-ended pipe piles with mechanical consideration of annulus resistance and plug resistance [12]. Detailed reviews of these precast piles were provided with consideration of soil profiles, methods of driven technique and configurations of precast piles [13]. Furthermore, another aspect that associates with precast pile in clay is the 'setup' or 'freeze' of the foundation, which is a normal phenomenon of pile capacity increases with the increment of time. Recent research has commenced to determine the amount of setup time of precast piles by performing dynamic load tests, statnamic load tests and static load tests [14,15].

Because of the process of driving pile into soil layers is relatively similar to some tests like standard penetration test, dynamic load tests etc., numerous studies have been focused on the relationships between bearing capacity with penetration tests' parameters [16,17]. The real capacity is actually accepted after the field tests being conducted and hence there are a lot of field tests research performed. Practically, if static load

tests are selected to be conducted, the PT is preferred because it only apply twice the allowable load instead of failing it. Then, there are many different extrapolation methods proposed to determine the ultimate bearing pile capacity. Marcos, Chen and Kulhawy (2013) reviewed 8 interpretation criteria based on the database of 72 sites with 152 filed compression load tests. These tested piles included round and square shape, and the soil profile was categorized in to drained and undrained condition. It is concluded the Davisson and slope tangent methods give a lower interpreted failure load by 10%-15%, and Chin's method gives the upper bound solution.

This paper provides the behavior research on pile foundation respected to square solid pile as well as pipe pile. It also provides the designed capacity calculation as well as interpretation based on Double Tangent and Chin's method. The modified Double Tangent and Chin's method is proposed. It is expected that this paper can provide practical information for geotechnical engineers to determine the ultimate bearing capacity of pile foundation from these PTs.

2. SUBSURFACE CONDITION

This construction project aimed to construct 28-levels apartment. The driven location of these tested piles was in Shandong Province, China. From the construction site, all the precast piles were driven into the soil. As shown in Fig. 1, the piles from three areas were tested by compressive SLTs. Areas A and B were the locations of tested concrete pipe piles, and area C was the location of tested solid square piles. The solid square pile driven in area C was used for resisting the loads transferred from upper building.



Fig. 1 Location of tested piles (not to Scale)

The subsurface exploration was discovered through laboratory and in-situ tests. The In-situ tests of standard penetration tests (SPT) and laboratory tests of consolidation tests, direct shear tests and triaxial tests were conducted based on the Chinese Code of Standard for Soil Tests Method (GB/T 50123-1999, 1999) [18], Standard for Test Methods

of Engineering Rock Mass (GB/T 50266-2013, 2013) [19] and Code for Investigation of Geotechnical Engineering (GB 50021-2001, 2001) [20] respectively. Based on the borehole logs, the soil layers were discovered as follows:

1) Planting Soil (Q^{4ml}), yellowish brown, loose and wet, contains clay, partially contains plant roots, average thickness 0.75m; 1-1) Miscellaneous Fill (Q^{4ml}), loose, partially contains gravel and rubble, diameter ranging from 2.0-7.0mm, the average thickness of this layer is 1.22m; 2) Silty Clay (Q^{4al+pl}), medium stiff, yellowish with low plasticity, average thickness is 3.91m; 3) Silty Clay (Q^{4m}), grey to ash black, liquid-plastic state, contains fine sand, partially contains clayey silt, average thickness is 4.92m; 3-1) Fine Sand (Q^{4m}), grey and cinereous, loose, saturated, average thickness is 2.01m 4) Silty Clay (Q^{4al+pl}), grey to yellowish grey, medium stiff, low plasticity with average depth of 2.57m; 5) Silty Clay (Q^{4al+pl}), yellowish brown, plastic state, partially contains medium to dense sand, average thickness of 2.57m; 5-1) Medium Sand (Q^{4al+pl}), yellowish brown, medium dense, loose and saturated, average thickness of 4.08m; 5-2) Coarse Gravel Sand (Q^{4al+pl}), yellowish brown, medium to dense, saturated, average thickness of 4.19m; 6) Angular Gravel (Q^{4p1+dl}), yellowish brown, medium dense, saturated, particle size ranges from 2-50mm, maximum to 100mm, highly weathered, average thickness 5.66mm; 7) Highly Weathered Mica Schist (Pt), yellowish brown to grey, highly weathered, thickness of 4.52m; 8) Medium Weathered Mica Schist (Pt), grey, medium hard.

3. PILE DESCRIPTION

For the tested precast open-ended pipe piles, the diameter is 400mm and the length varies from 20m to 26m. In area A, one 20m pile, seven 21m piles, seven 22m piles, two 23m piles and five 24m piles are tested. In area B, one 23m pile and two 26m piles are tested. For precast solid square piles, the cross section is 400mm×400mm. All these square piles are tested in area C. These tested piles consist of two 22m piles, two 25m pile, one 26m pile, four 27m piles and six 28m piles The concrete strength of these tested piles is 30MPa, 50MPa and 40MPa from area A, B and C, respectively. The tested pile information is summarized in Table 1.

As shown in Fig. 2 (a) and (b), all piles are driven into the required location by drop hammers. As illustrated in Table 1, the maximum allowable load of pile reaches to 2440kN so the maximum applied load can be up to 4880kN. Because the projects only requires 650kN capacity of the piles from area A and 1570kN from area B, all these piles were tested with maximum loading of 1300kN and 3140kN, respectively.



Fig. 2 (a) Open-end concrete pipe pile; (b) Precast square pile

4. TEST SET UP

The weighted platform (Fig. 3) is used instead of using the reaction beams and anchoring piles. Due to the designed capacity of these piles being relatively small compared to the traditional bored piles, the reaction system is only needed to provide small reaction loads, the use of weighted platform is less time consuming and economic. Furthermore, numerous piles are required to be tested, it would be very expensive if casting reaction piles. This weighted platform is more practical to be selected when a large number of tests is required because the transfer of the platform is much cheaper.



Fig. 3 Weighted platform system

To perform compressive SLTs, as shown in Fig. 4, hydraulic jacks are used for providing loads and the dial gauges are symmetrically installed on reference bar to measure the vertical displacement of pile head. Maintained loads with increment of 130kN are applied on the precast pipe pile until maximum loads of 1300kN in area A is reached, and for the pipe pile in area B, the increment of 314kN is applied until maximum loads of 3140kN is achieved. For the square concrete pile, maintained loads with increment of 488kN is applied on most of piles (the maximum load is 4880kN) except for three piles which are applied increment loads of 360kN (the maximum load is 3240kN). These three pile results are used for data comparison.

Table 1 Information of tested pile foundation

No. of Pile	Label	Pile Length (m)	Max. Load (kN)	No. of Pile	Label	Pile Length (m)	Max. Load (kN)
1	P24	22	3600	21	P1165	21	1300
2	P41	22	3600	22	P1175	21	1300
3	P1	25	4880	23	P1470	21	1300
4	P106	25	3600	24	P643	22	1300
5	P91	26	4880	25	P630	22	1300
6	P238	27	4880	26	P1473	22	1300
7	P124	27	4880	27	P1475	22	1300
8	P137	27	4880	28	P1485	22	1300
9	P173	27	4880	29	P1509	22	1300
10	P147	28	4880	30	P1580	22	1300
11	P93	28	4880	31	P639	23	1300
12	P85	28	4880	32	P1481	23	1300
13	P48	28	4880	33	P1275	24	1300
14	P16	28	4880	34	P1287	24	1300
15	P4	28	4880	35	P1299	24	1300
16	P1172	20	1300	36	P1453	24	1300
17	P976	21	1300	37	P1465	24	1300
18	P991	21	1300	38	S126	23	3140
19	P995	21	1300	39	S73	26	3140
20	P1163	21	1300	40	S103	26	3140

Note: No. 1-15: Location C, Square configuration, concrete strength of 40MPa; No. 16-37: Location A, Pipe configuration, concrete strength of 30MPa; No. 38-40: Location B, Pipe configuration, concrete strength of 50MPa.



Fig. 4 Equipment underneath platform

5. RESULTS AND DISCUSSION

5.1 Load Settlement Results

5.1.1 Square pile

The Load-settlement curves (Q-s curve) of 27m square piles is presented in Fig. 5. It illustrates that the total average settlement is discovered of 23mm, and the average permanent settlement is discovered as 12mm. As shown in Fig. 6, for the 28m piles, the Q-s curves illustrate that the total average settlement is discovered of 22mm, and the average permanent settlement is discovered as 12mm. It can also be seen that, during loading stages, the maximum settlements among these piles are different, and from unloading stages, the curves are parallel (Figs. 5 and 6).

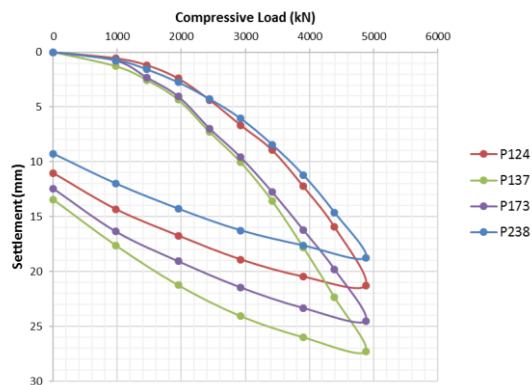


Fig. 5 27m square piles

As shown in Fig. 7, two piles with the same dimension and concrete strength (distance between piles are 5m) are tested but the load increment are different, it can also be seen that, from unloading stages, these two curves are parallel. Fig. 8 present square piles' behavior with various pile lengths, the results show that the total average settlement is around 24mm, and the average permanent settlement is discovered as 12mm. Similar to the previous results, it is discovered that during

unloading stages, these curves are relatively parallel, and the gradients are close with each other.

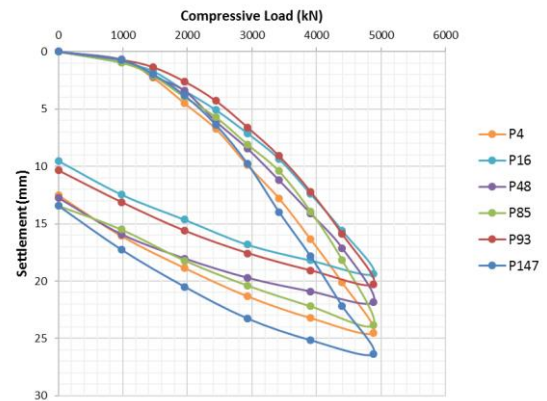


Fig. 6 28m square piles

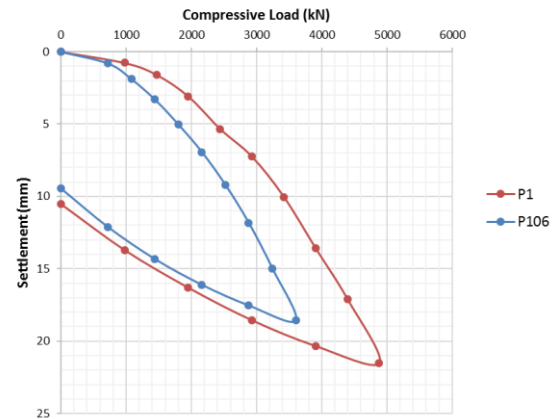


Fig. 7 Same type piles with different load increments

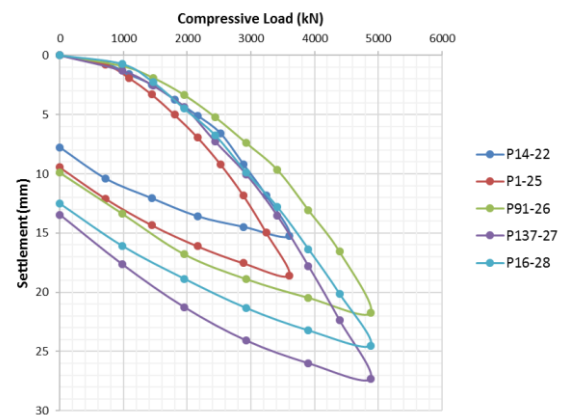


Fig. 8 Piles with different pile lengths

5.1.2 Pipe Pile

As shown in Fig. 9, the Q-s curves of 21m pipe pile shows similar behavior. The total settlement of these 21m piles is averagely discovered as 19mm and after the loading released, the average permanent settlement is discovered as 10mm. It can also be discovered that the curves after loading released are parallel with each other.

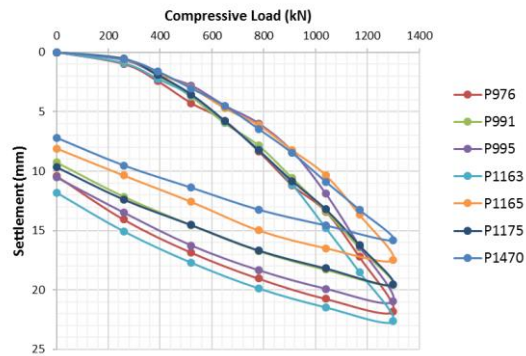


Fig. 9 21m pipe piles

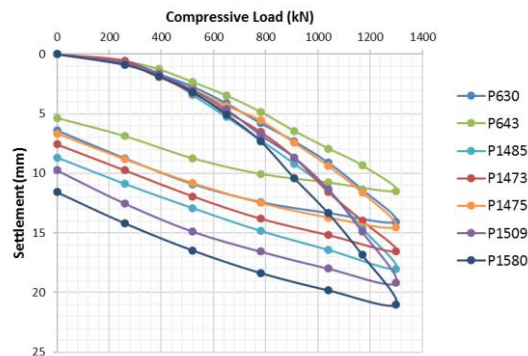


Fig. 10 22m pipe piles

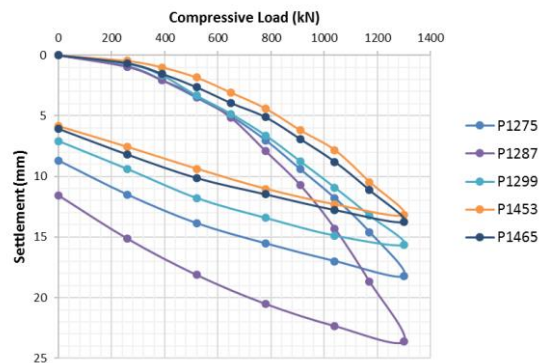


Fig. 11 24m square piles

The Q-s curves of 22m piles are presented in Fig. 10, it can be found that the total settlement of the 22m piles is averagely discovered as 15mm and after the loading released, the average settlement is discovered as 8mm. Similar to 21m piles, the curves among the tested piles are parallel (during unloading stages). The Q-s curves of 24m piles are provided in Fig. 11, the behavior of P1287 is relatively different to the other piles, which needs further discussion. The other 24m piles show a similar behavior, and the total settlement is discovered as 15mm and after the loading released, the average settlement is discovered as 7mm.

The Q-s curves of piles with different lengths are provided in Fig. 12, it can be found that the total average settlement is 21mm, and the permanent average displacement is 10mm. The curves of tested piles during unloading stages are parallel with each other. The Q-s curves of tested pile located at area B is provided in Fig. 13, similar to piles behaviors tested at area A, the total average settlement is discovered of 18mm, and the average permanent settlement is discovered as 8mm. The curves of these tested pile during unloading is also found to be parallel, and the gradient is similar to the piles tested from area A.

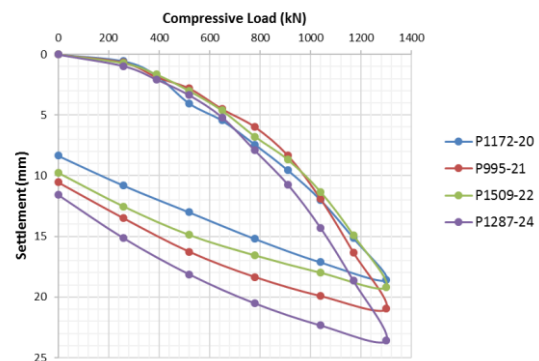


Fig. 12 Pipe piles with different lengths in area A

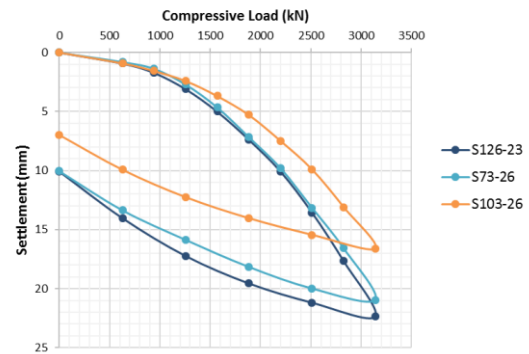


Fig. 13 Pipe piles with different lengths in area B

5.2 Designed Capacity

The ultimate bearing capacity of a pile foundation can be determined via calculating the shaft and end capacity. Based on the Technical Code for Building Pile Foundations JGJ94-2008 [21], the capacity of the precast square piles and the pipe piles can be determined as follows:

For solid square piles:

$$Q_{uk} = Q_{sk} + Q_{pk} = u \sum q_{sik} l_i + q_{pk} A_p \quad (1)$$

For pipe piles:

$$Q_{uk} = Q_{sk} + Q_{pk} = u \sum q_{sik} l_i + q_{pk} (A_j + \lambda_p A_{p1}) \quad (2)$$

$$\lambda_p = 0.16 h_b / d \quad \text{When } h_b / d < 5$$

$$\lambda_p = 0.8 \quad \text{When } h_b / d \geq 5$$

Table 2 Shaft and total capacity of tested piles

Pile Label	Shaft Capacity (kN)	Total Capacity (kN)	Pile Label	Shaft Capacity (kN)	Total Capacity (kN)
P1	2256.00	3776.00	P1172	1333.37	2329.24
P106	2447.36	3967.36	P1470	1358.87	2354.74
P24	1977.28	3497.28	P976	1451.94	2447.81
P41	1799.04	3319.04	P991	1373.94	2369.81
P91	2495.2	4015.2	P995	1460.48	2456.35
P48	2667.36	4187.36	P1163	1441.39	2437.26
P147	2761.6	4281.6	P1165	1393.66	2389.53
P124	2634.88	4154.88	P1175	1343.92	2339.79
P238	2224.64	3744.64	P639	1490.12	2485.99
P173	2683.2	4203.2	P1275	1708.16	2704.03
P137	2611.36	4131.36	P1287	1714.44	2710.31
P4	2638.4	4158.4	P1299	1729.39	2725.26
P16	2651.36	4171.36	P1453	1727.13	2723.00
P85	2748.8	4268.8	P630	1412.25	2408.12
P93	2693.12	4213.12	P1473	1432.34	2428.22
P643	1496.65	2492.52	P1509	1531.44	2527.32
P1485	1411.87	2407.74	P1580	1542.74	2538.62
P1475	1483.21	2479.08	P1481	1478.19	2474.06
P1465	1706.02	2701.90	S73	1653.40	2649.27
S103	1653.15	2649.02	S126	1633.30	2629.18

Where:

Q_{uk} =Ultimate bearing capacity of piles;

Q_{sk} =Shaft capacity of piles

Q_{pk} =End capacity of piles;

u = Cross section perimeter of pile;

q_{sik} =Shaft resistance;

l_i = Thickness of i^{th} soil;

q_{pk} =End resistance;

A_p =Area from pile toe;

A_j =Effective area of pile toe and $A_j = \frac{\pi}{4} (d^2 - d_1^2)$;

λ_p = Plug effect coefficient;

A_{p1} =Hollow area of pile toe;

h_b = Embedment depth of pile in bearing stratum;

d =External diameter of pipe pile.

The shaft resistance q_{sik} and end resistance q_{pk} can be determined through JGJ94-2008 based on the parameters obtained from borehole logs and laboratory test results. The pile capacity should be based on the nearest borehole information instead of the average soil thickness. The shaft and total bearing capacity of tested piles are summarized in Table 2.

5.3 Capacity Discussion

Based on the Double Tangent method, the ultimate bearing capacities of the tested concrete square piles are determined. By plotting the interpreted capacity versus the calculated ultimate bearing capacity (Eq. (1)), as shown in Fig. 14, it can be seen that, all the points are located from the lower part, which illustrates the Double Tangent

method is conservative to determine the ultimate bearing capacity when using the un-plunging load-settlement data. The ultimate bearing capacity obtained from the Double tangent interpretation can be modified by multiplying a factor. In this case, the factor η_D is determined as 1.83. Via plotting the designed capacity versus the modified Double Tangent interpretation as shown in Fig. 15, it can be seen that the modified Double Tangent interpretation can provide a good prediction of ultimate bearing capacity.

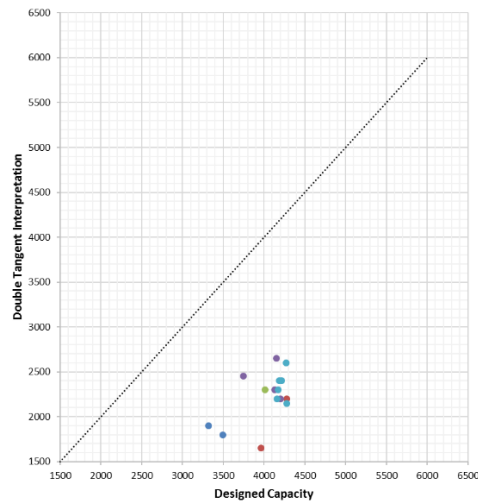


Fig. 14 Designed capacity versus Double Tangent Interpretation

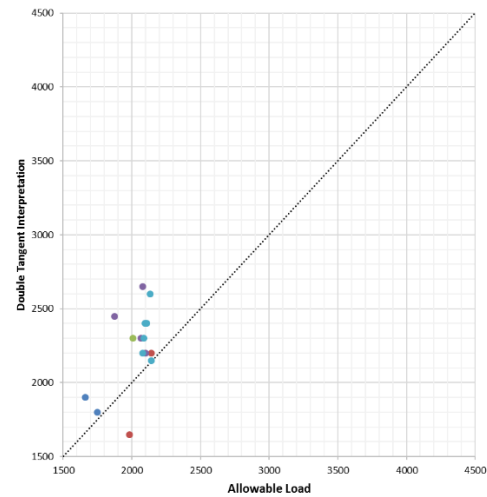


Fig. 16 Allowable load versus Double Tangent interpretation

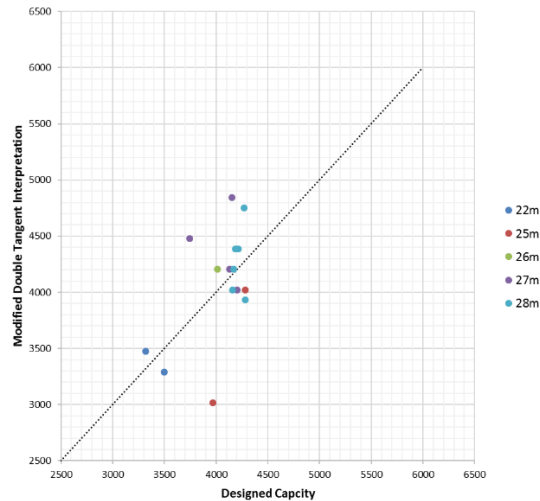


Fig. 15 Designed capacity versus modified Double Tangent interpretation

Traditionally, the allowable loading Q_a is equal to the calculated ultimate bearing capacity divided by the safety factor of 2. By plotting the allowable load versus the capacity result using the Double tangent method, as shown in Fig. 16, it can be seen that, the Double tangent method can appropriately predict the allowable loads.

Compared to the Double Tangent method, the Chin's method overestimates the ultimate bearing capacity. Reduction factor (η_{Ch}) of 1.35 for the pile which length is less than 25m, and of 1.2 for the pile that length is over 25m are recommended. As shown in Fig. 17, based on the proposed reduction factor, by plotting the modified Chin's interpretation versus the calculated capacity, all points assemble to angle bisector in the first quartile.

For the precast pipe piles, the calculated ultimate bearing capacity based on Eq. (2) is averagely 2500kN, the allowable load of a single pile is 1250kN (safety factor is 2). However, this project actually only requires the pile with capacity of 650kN, the PTs then applied with maximum loading of 1040kN (twice the required load: $2 \times 650\text{kN}$). Thus further research of precast pipe pile with more loading applications is required.

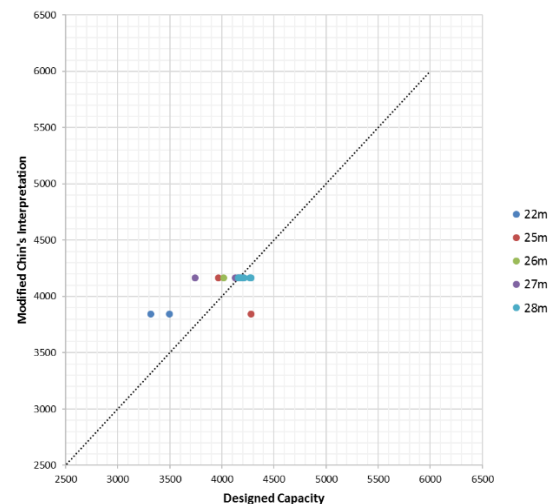


Fig. 17 Designed capacity versus Chin's interpretation

5.4 Settlement Discussion

The reason that leading to the settlement difference (even though these piles are driven adjacent to each other) is that the thickness of soil layers are different. If dividing the pile into small segment with length equals to the soil layer thickness, the reduction from each pile segment will be different when friction force is different.

Because the pile toe reaches the bearing stratum of angular gravel or brecciated gravel, and these SLTs are PTs where the applied maximum loading is relatively small, the force transferred to the bearing stratum is small and the deformation of this stratum is small. Hence the settlement of pile foundation is mostly the vertical compress of concrete pile element. This is also the reason that why the curves are parallel during unloading stages. If these piles are made of the same concrete with the same moduli, once the loading is released, the shortened pile will expand back in the same rate (Δ settlement/ Δ load, unit of mm/kN).

Define a expand settlement ratio R_{E-S} governed by Eq. (3), the R_{E-S} of small displacement pipe piles are averagely determined as 52.2% in area A (strength of concrete is 30Mpa), 54.9% in area B (strength of concrete is 50Mpa) and for the large displacement square piles, the R_{E-S} is determined as 49.0%, (strength of concrete is 40Mpa). It can be seen that the expansion settlement ratio of small displacement piles is greater than large displacement piles, however, this is not a general outcome since there is a lot of uncertainty such as concrete strength.

$$R_{E-S} = \frac{s_{max} - s_p}{s_{max}} \times 100 \quad (3)$$

Where:

R_{E-S} = Expansion settlement ratio;

s_{max} =Settlement under maximum applied load;

s_p =Permanent settlement after releasing load;

6. CONCLUSIONS &RECOMMENDATIONS

For the precast displacement piles, a total number of 40 piles were selected. 22 piles with various lengths are tested in area A, 3 piles with various lengths are tested in area B and 15 piles with various pile length are tested in area C. By defining the expansion settlement ratio R_{E-S} , it can be found that:

- 1) The R_{E-S} from all piles with concrete strength of 30Mpa are close to 52.2%, and Q-s curves from unloading stages are parallel with each other in area A;
- 2) The R_{E-S} from all piles with concrete strength of 50Mpa are close to 54.9%, and Q-s curves from unloading stages are parallel with each other in area B;
- 3) The R_{E-S} from all piles with concrete strength of 40Mpa are close to 49.0%, and Q-s curves from unloading stages are parallel with each other in area C;
- 4) For the PT result, if using Double Tangent method, the ultimate bearing capacity is the interpreted value multiplying by a factor η_D . If using Chin's method, the ultimate bearing capacity is the interpreted value dividing by a reduction factor η_{Ch} .

In the case of the project in China, $\eta_D=1.83$, $\eta_{Ch}=1.35$ ($L<25$) and $\eta_{Ch}=1.2$ ($L>25$) are recommended.

5) If in one area, these Q-s curves from unloading stages are not parallel and very complicated, this represents that the soil layers may change dramatically between piles or the pile is damaged. Thus more boreholes are recommended and Low Stain Integrity Test is suggested to perform.

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