Research on application of O-Cell test in diaphragm foundation

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Abstract. O-Cell method with high safety and low cost has been widely applied in many projects compared with the conventional static load test, especially for high bearing capacity deep foundation. It has been applied in building, bridge, offshore wind power foundation, etc. The load-displacement curve of O-Cell test could be well converted into conventional pile top load-displacement curve. Based on different deep foundation styles, the load cell could be manufactured into circle type, rectangle type, bar-type, “L” type, etc. This paper introduces an application of O-Cell test in diaphragm, and the bearing capacity tested is the largest in the world at present with the maximum bearing capacity arriving at 313998kN. The O-Cell method is convenient to obtain maximum bearing capacity of large and deep foundation, and is helpful for designers to design the deep foundation reasonably and economically.

1. Introduction

The conventional static load test method is difficult to test in high capacity of large and deep foundation as it can't provide enough reaction force. O-Cell test method can be used in projects where traditional methods cannot be used\textsuperscript{[1]}. O-Cell test method is applied in engineering of building foundation, bridge foundation and offshore pile foundation around the world. Many researchers introduced the O-Cell method and the specific engineering test since proposed by Osterberg\textsuperscript{[2-9]}. For a long time, the load cell is just installed on the bottom of test pile to obtain the end resistance. After many projects used by O-Cell test method, the load cell could also be installed at a specified place (called balanced point) above the bottom of the test pile.

A patent of a new style of load cell is proposed by Dr. Wei-ming Gong and Dr. Guo-liang Dai in China\textsuperscript{[10-11]}. The load cell has been widely applied in many projects in China and other countries including Vietnam, Cambodia, Singapore, Brunei, Mozambique, Malaysia, etc. It has successfully obtained the bearing capacity of large dimension bored and steel pipe pile foundation, bar-type diaphragm foundation, “L” type diaphragm foundation, etc. The maximum bearing capacity has reached 313998kN by the specified load cell patent. Therefore, it is an effective method to test the bearing capacity of diaphragm wall.

2. Methods

The O-Cell method of pile load test is that piles are loaded by the embedded load cell. To determine the position of the load cell, soil investigation report has to be studied to calculate the balanced point. The load cell is a loading equipment specially designed using hydraulic jacks. Pressure is applied to
the load cell by high pressure hydraulic oil pump on the ground through the flexible oil hose embedded in the pile. The pressure in the load cell can be measured by manometer, and the displacements of the top & bottom plates can be measured by means of displacement transducers, which are located at the top of the telltale which sit on the respective load cell plates. When loaded, the load cell expands, pushing the upper shaft upwards and the lower shaft downwards, which would mobilize the side resistance and base resistance of the upward and downward pile shaft. According to relationship between the movement and the applied loads, the $Q-S$ curve can be obtained. From the two $Q-S$ curves and their corresponding $S-lgQ$ and $S-lgQ$ curves, bearing capacities of both upper and lower part of the pile can be determined. Adding up the modified side resistance of upward pile shaft and the base resistance of downward pile shaft makes up the total ultimate bearing capacity of the pile.

The equipment used for the load cell method is shown in Figure 1.

![Figure 1. Sketch of O-cell test method](image)

![Figure 2. Sketch of the Equivalent Conversion](image)

The formula for calculation of bearing capacity is shown as following, which is related to the test upward displacement and downward displacement.

$$Q_u = \frac{Q_{ua} - W}{\gamma} + Q_{ub}$$

(1)

Where, $Q_u$ is the ultimate bearing capacity, $Q_{ua}$ is the tested ultimate bearing capacity of pile part above load cell, $Q_{ub}$ is the tested ultimate bearing capacity of pile part below load cell, $W$ is the effective deadweight of pile segment above load cell, $\gamma$ is the correction coefficient of frictional resistance of upper pile shaft.

The test results of the O-Cell method can be converted to the conventional pile top load-displacement curve of static load test using the formulas based on mechanical analysis of the two test methods as follows.

$$Q = Q^+ + K(Q^+ - W)$$

(2)

$$S = S^- + \Delta S$$

(3)

Where, $Q$ is the converted pile top load, $S$ is the converted pile top displacement, $Q^+$ is the upward load value, $Q^-$ is the value of downward load, $\Delta S$ is the pile compression, $S^-$ is the downward displacement, $K$ is the conversion coefficient.

Compression of upward pile shaft $\Delta S$ is equal to flexible deformation of upward pile caused by the load of the lower and upper pile segments, that is:
\begin{equation}
\Delta S = \Delta S_1 + \Delta S_2
\end{equation}

Where, \( \Delta S_1 \) is the flexible deformation of upward pile segment caused by downward load, \( \Delta S_2 \) is the flexible deformation of upward pile segment caused by upward load.

\begin{equation}
\Delta S_1 = \frac{Q' \cdot L}{E_p \cdot A_p}
\end{equation}

\begin{equation}
\Delta S_2 = \frac{(Q' - W) \cdot L}{2E_p \cdot A_p}'
\end{equation}

According to O-Cell method, the upward load and downward load both generated by every load grade is equal, but the corresponding displacement is not equal. Therefore, \( Q' \) should be the upward load corresponding to the upper pile displacement absolute value of \( S \) in \( Q'-S' \) curve of O-Cell method. Then convert the tested upward and downward \( Q-S \) curve into equivalent \( Q-S \) curve of top-loaded pile. The corresponding displacement of the pile head also can be acquired. The sketch of the equivalent conversion is shown in Figure 2.

3. Application

Three pieces of diaphragm were chose to conduct O-Cell load test in Nanjing jinmao plaza phase II project, Nanjing city, China, the layout plan of test wall is shown in Figure 3. The height of the structure is about 285m, including 69 floors above ground and 5 floors below ground. The building is so high that it needs to choose a high bearing capacity foundation. Therefore, the diaphragm foundation with high bearing capacity is a relative reasonable foundation. It also could be regard as supporting structure. According to the design requirement, the top of diaphragm foundation is the elevation of the bottom of the basement, about -25.3m. The three pieces of test diaphragm were named as \( SQ-1 \), \( SQ2-1 \) and \( SQ2-2 \), respectively. The test diaphragm of \( SQ-1 \) was “L” shape, and \( SQ2-1 \) and \( SQ2-2 \) were bar-type. All the load cells were installed on the 7m position above the bottom of the test diaphragm. The detail parameters of test diaphragm were shown in Table 1.

![Figure 3. Layout plan of test wall](image)

| Name   | Thickness/mm | Length/m | Bearing layer | Type  | Estimated load value (kNm⁻¹) | The maximum load value of load cell (kN) |
|--------|--------------|----------|---------------|-------|-----------------------------|----------------------------------------|
| SQ-1   | 1000         | 56.261   | ⑥2a          | “L”   | 56160                       | 300000                                 |
| SQ2-1  | 1200         | 56.435   | ⑥2           | “一”   | 56160                       | 350000                                 |
| SQ2-2  | 1200         | 56.905   | ⑥2           | “一”   | 56160                       | 350000                                 |
According to the comprehensive analysis of drilling, in-situ test and indoor test, the surface layer ① of the site is artificial fill, and the lower part is Quaternary Holocene \((Q_4)\) newly deposited silty clay mixed with silt, silty sand, muddy silty clay and silty clay; the lower part is upper Pleistocene \((Q_3)\) deposited silty clay and silty clay mixed with gravel; the bottom bedrock is Jurassic Longwangshan formation \((J_3)\) tuff. Within the survey depth, the geotechnical layer of the site can be divided into five engineering geological layers and thirteen sub layers. The specific physical and mechanical parameters of the soil layer are shown in Table 2, where ②₁ is silty clay mixed with silt and silty sand, ②₂ is muddy silty clay, ③₁, ③₂, ③₃ are silty clay, ④ is silty clay and mixed gravel, ⑤₁ is strongly weathered tuff, ⑤₂ is broken moderately weathered tuff, ⑤₂₂ is moderately weathered tuff, \(\gamma\) is the bulk density, \(C_q\) is the cohesion force, \(\phi_q\) is the internal friction angle, \(f_a\) and \(f_{ak}\) the Characteristic value of bearing capacity, \(e\) is the void ratio, \(I_l\) is the liquid index, \(w\) is the moisture content, \(N\) is the standard penetration number, \(f_{ak}\) is the standard value of uniaxial compressive strength.

| Layer code | \(\gamma\) \((\text{kN} \cdot \text{m}^{-3})\) | \(C_q\) \((\text{kPa})\) | \(\phi_q\) \(^{(\circ)}\) | \(f_a\) \((\text{kPa})\) | \(e\) | \(I_l/w\) | \(f_{ak}\) \((\text{kPa})\) | \(N\) | \(f_{ak}\) \((\text{kPa})\) |
|------------|----------------|----------------|----------------|----------------|--------|---------------|----------------|--------|----------------|
| ②₁        | 19.6           | 4.8            | 25.0           | 94             | 0.746  | 0.91          | 140            | 7.4    | 160            |
| ②₂        | 18.4           | 15.9           | 10.0           | 86             | 1.044  | 1.06          | 60             | 2.4    | 50             |
| ②₃        | 19.8           | 44.7           | 13.2           | 233            | 0.746  | 0.41          | 200            | 7.0    | 150            |
| ③₁        | 19.9           | 52.1           | 14.1           | 275            | 0.739  | 0.24          | 250            | 10.8   | 220            |
| ③₂        | 19.7           | 35.7           | 12.1           | 184            | 0.733  | 0.66          | 220            | 7.8    | 170            |
| ③₃        | 19.4           | 35.4           | 11.7           | 180            | 0.811  | 0.67          | 210            | 7.0    | 150            |
| ④         | /              | /              | /              | /              | /      | /             | /              | 17.3   | 280            |
| ⑤₁        | /              | /              | /              | /              | /      | /             | /              | /      | 45.8           |
| ⑤₂₂       | /              | /              | /              | /              | /      | /             | /              | /      | 45.8           |
| ⑤₂        | /              | /              | /              | /              | /      | /             | /              | /      | /              |

The underground diaphragm wall load cell is shown in Figure 4, the welding and hoisting of load cell is shown in Figure 5 and the field test facilities is shown in Figure 6. According to the test result, the upward displacement and downward displacement of each test diaphragm under each load grade are shown in Figure 7, Figure 8 and Figure 9. Before conduct load test, each test diaphragm was grouted at the bottom. All the curves of load to displacement showed a similar varying pattern. The downward movement changed gradually, while the upward movement appeared abruptly. Therefore, the maximum bearing capacity of the upper foundation part above load cell of SQ₁, SQ₂₁, SQ₂₂ was 100000kN, 145200kN and 145200kN, respectively, the corresponding upward movement being
15.14mm, 14.28mm, 11.89mm, respectively. At the same time, the maximum bearing capacity of the lower foundation part below load cell of SQ-1, SQ2-1, SQ2-2 was 110000kN, 158400kN and 158400kN, respectively, the corresponding downward movement being 7.74mm, 11.38mm, 8.58mm, respectively.

Figure 7. The curve of load to displacement of SQ-1 diaphragm
Figure 8. The curve of load to displacement of SQ2-1 diaphragm
Figure 9. The curve of load to displacement of SQ2-2 diaphragm
Figure 10. The equivalent Q-S curve of each test diaphragm

In terms of equivalent conversion method, the equivalent traditional load to displacement curves were shown in Figure 10.

According to the equivalent Q-S result, it showed that the bar-type diaphragm of SQ2-1 and SQ2-2 displayed much higher bearing capacity than the “L” type diaphragm of SQ-1. The maximum bearing capacity of SQ2-1 and SQ2-2 was 313998kN and 313944kN, respectively, the corresponding settlement being 49.43mm and 47.36mm, respectively. While the maximum bearing capacity of SQ-1 was 217143kN, with the corresponding settlement of 50.06mm. Therefore, the bar-type diaphragm has a higher bearing capacity than “L” type diaphragm.

4. Conclusions
The O-Cell method obtains two load-movement curves, which could been converted into an equivalent top-load displacement curve with sufficient accuracy for most engineering applications by equivalent conversion method. Different types of foundations could be well tested by O-Cell method, including circle type, rectangle type, bar-type, “L” type, etc. The maximum bearing capacity of foundation came up to 313998kN. They have been tested successfully by O-Cell method. The techniques of shaft construction play an important part in subsequent shaft capacity. Improper load cell balance point, failure to roughen side walls, poor bottom cleaning technique, etc. could seriously reduce capacity.
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