Model Experimental Study on Support Structure of Double-row Piles in Deep Foundation Pit

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Abstract: The model experiment was designed to analyse the bending moment of pile body and earth pressure of double-row piles. The study finds that the influence of different loading conditions on pile bending moment and earth pressure is uniform. With the increase of pile spacing, the positive peak value of pile bending moment increases gradually. The average increment is about 27%. The trend of change coincides with power function. The positive peak value of earth pressure increases first and then stabilizes. The average increment is 11%. The trend of change accords with the quadratic function of one variable. With the increase of row spacing, the positive peak values of soil pressure and pile bending moment first decrease and then increase. The change relation is in accordance with the quadratic function of one variable. The minimum appears between 5.0d and 5.25d. It can be seen that when the row spacing is small, it can be regarded as a single row of piles. With the increase of row spacing, the two rows of piles share the load together. The structure tends to be reasonable. When the minimum earth pressure occurs, the retaining effect of the structure is the best.

1. Introduction

Foundation pit engineering is an increasingly important part of foundation engineering. This area is involved in large-scale civil engineering especially without exception. Foundation pit support is a comprehensive geotechnical engineering and the study of earth pressure is one of the most concerned problems among researchers. Zeng Xiaoxin[1] simulated the influence of the spacing of isolation piles on the deformation of foundation pit with the ABAQUS finite element software. Xu Xun[2] discussed the limit state of passive earth pressure through the curve of top beam displacement and pile bending moment varying with load by model test. Xia Xiong[3~4] summarized the displacement characteristics of double-row pile structure in foundation pit through indoor model test research. On the other hand, foreign scholars who studied on the pit model started earlier. K. Terzaghi[5] is the first scholar to use model test to study foundation pit engineering problems. As early as the 1930s, they did a series of model tests, which used sand as model soil and simulated the earth pressure distribution of rigid retaining wall under six different displacement modes. Nina H. and David J. [6~7] carried out experimental research on the stress distribution and working mechanism of transversely loaded piles and obtained some useful conclusions. It can be seen that the research on double-row pile structure is not perfect at present, and its mechanical characteristics need to be further explored.
2. Experimental design
The geometric similarity ratio of the model test was 1:30. The model condition included 6 kinds: 3, 6, 9 meters of excavation and loading 20, 30, 40kPa which was based on the similarity theory.

The data of pile bending moment and earth pressure were collected through monitoring the excavation and loading conditions. Through the analysis of the test results, the parameters of pile spacing were optimized. The parameters of the model test of pile: The pile spacing was 3.5d, 4.7d, 5.5d, and the row spacing was 4d, 4.7d, 6d. (d was pile diameter)

(1) The calculation formula of the bending moment of pile:
\[ M = \frac{E \cdot I \cdot \varepsilon}{y} \]

In formula, M is the bending moment of each measuring point of pile body. The unit is N·m; \( \varepsilon \) is the strain value measured at each measuring point; y is the distance from the outer edge of the pile to the neutral axis. The unit is m. EI is the bending stiffness of aluminium alloy tubes. The unit is N·m².

(2) The calculation formula of soil pressure:
\[ P = \mu \cdot \varepsilon \cdot K \]

In formula, P is the value of earth pressure. The unit is kPa; \( \mu \) is a strain; K is the calibration coefficient. The unit is kPa/\( \varepsilon \).

In this experiment, the retaining effects of different parameters of double-row piles are compared according to measured bending moment and earth pressure data. Furthermore, the size of pile arrangement is optimized.

3. The influence of pile spacing

3.1 Pile Spacing & Bending Moment
Compare the relationship between the bending moment of double-row piles and pile spacing at first. The maximum positive bending moment under different pile spacing is selected and compared, which is shown in table 1.

| Pile Spacing | Excavation | Loading |
|--------------|------------|---------|
|              | 3m         | 6m      | 9m      | 20kPa | 30kPa | 40kPa |
| 3.5d         | 6.1        | 10.7    | 35.7    | 51.3  | 58.9  | 67.2  |
| 4.7d         | 9.9        | 18.5    | 55.9    | 65.7  | 72.2  | 87.7  |
| 5.5d         | 12.6       | 25.2    | 63.7    | 75.8  | 89.1  | 104.3 |

\( \omega \) is the average incremental percentage of the bending moment of the latter working condition and the former working condition.

Table 1 shows, the increments of pile bending moment are respectively 87% and 196% when excavating 6m and 9m. The increment of bending moment is about 10%~20% when loading 20, 30, 40kPa. It can be seen that the influence of loading conditions at all levels on the bending moment of pile body is uniform. But it is worth noting that the influence of foundation pit excavation on the bending moment of double-row piles is remarkable.

On the other hand, the bending moment of pile body increases gradually when pile spacing increases from 3.5 times pile diameter to 5.5 times pile diameter, which the average increment is about 27%. It is because the amount of retaining soil shared by single row piles increases when the pile spacing increases, which resulting in larger bending moment.

3.2 Pile Spacing & Soil Pressure
The maximum earth pressure peak value under different pile spacing is selected and compared, which is shown in table 2.
Table 2. The relationship between soil pressure and pile spacing. (Unit: kPa)

| Pile Spacing | Excavation Loading |
|--------------|--------------------|
|              | 3m     | 6m     | 9m     | 20kPa  | 30kPa  | 40kPa  |
| 3.5d         | 1.3    | 3.8    | 23.1   | 28.2   | 33.3   | 40.6   |
| 4.7d         | 2.8    | 8.9    | 32.0   | 38.0   | 44.1   | 53.1   |
| 5.5d         | 2.2    | 7.7    | 30.3   | 36.3   | 41.2   | 49.4   |

ω is the average incremental percentage of soil pressure of the latter working condition and the former working condition.

Table 2 shows, the increments of soil pressure are respectively 220%、354% when excavating 6m and 9m. The increment of bending moment is about 15%~25% when loading 20, 30, 40kPa. It can be seen that the influence of loading conditions at all levels on soil pressure is uniform. But it is worth noting that the influence of foundation pit excavation on soil pressure of double-row piles is remarkable.

On the other hand, the double-row pile soil pressure increases first and then stabilizes when the pile spacing is increased from 3.5 times the pile diameter to 5.5 times, and the average increment of soil pressure is 11%. It conforms to the calculation principle of single pile soil reaction force in the foundation pit specification. Soil reaction on single supporting pile is affected by pile spacing according to Technical specification for retaining and protecting of building foundation excavation (JGJ 120-2012). When the pile spacing increases, the earth pressure shared by a single pile is weakened by the influence of pile spacing when the pile spacing increases to a certain range.

4. The influence of row spacing

4.1 Row Spacing & Bending Moment

Compare the relationship between the bending moment of double-row piles and row spacing at first. The maximum positive bending moment under different row spacing is selected and compared, which is shown in Table 3.

Table 3. The relationship between peak positive moment and row spacing. (Unit: kN•m)

| Row Spacing | Excavation Loading |
|-------------|--------------------|
|              | 3m     | 6m     | 9m     | 20kPa  | 30kPa  | 40kPa  |
| 4d          | 9.9    | 18.5   | 55.9   | 65.7   | 72.2   | 87.7   |
| 4.7d        | 4.1    | 15.3   | 47.6   | 56.5   | 62.5   | 76.6   |
| 6d          | 8.1    | 16.5   | 56.2   | 65.3   | 76.1   | 96.5   |

ω is the average incremental percentage of the bending moment of the latter working condition and the former working condition.

Table 3 shows, the increments of pile bending moment are respectively 155%、218% when excavating 6m and 9m. The increment of bending moment is about 15%~20% when loading 20, 30, 40kPa. It can be seen that the influence of loading conditions at all levels on the bending moment of pile body is uniform. But it is worth noting that the influence of foundation pit excavation on the bending moment of double-row piles is remarkable.

On the other hand, the bending moment of pile body decreased first and then increased when row spacing increases, which the minimum is approximately between 5.0d and 5.5d. The soil between piles has obvious influence on the force of front and rear piles according to He Yihua's deformation theory of double-row piles[9]. When row spacing is small, the effect of soil between piles is not obvious, which can be regarded as single row pile support. With the increase of row spacing, the soil between piles gradually plays a role which makes the force of pile body more reasonable. When the row
spacing exceeds a certain range, the soil between piles will no longer play an active role. Therefore, 4.75d ~ 5.25d is a reasonable displacement value for double-row piles.

4.2 Row Spacing & Soil Pressure

The maximum earth pressure peak value under different row spacing is selected and compared, which is shown in table 4.

| Row Spacing | Excavation Loading |
|-------------|--------------------|
|             | 3m | 6m | 9m | 20kPa | 30kPa | 40kPa |
| 4d          | 2.8 | 8.9 | 32.0 | 38.0 | 44.1 | 53.1 |
| 4.7d        | 1.2 | 4.2 | 25.0 | 34.1 | 42.8 | 47.6 |
| 6d          | 3.0 | 8.6 | 29.0 | 37.0 | 46.3 | 53.9 |
| ω           | /   | 218%| 331%| 28%   | 22%   | 16%   |

ω is the average incremental percentage of soil pressure of the latter working condition and the former working condition.

Table 4 shows, the increments of soil pressure are respectively 218%, 331% when excavating 6m and 9m. The increment of bending moment is about 16%~28% when loading 20, 30, 40kPa. It can be seen that the influence of loading conditions at all levels on soil pressure is uniform. But it is worth noting that the influence of foundation pit excavation on soil pressure of double-row piles is remarkable.

On the other hand, soil pressure decreased first and then increased when row spacing increases, which the minimum is approximately between 4.75d and 5.25d. The earth pressure behind the pile is shared by the front and rear piles respectively according to Tang Fen's sharing theory of earth pressure [10]. The proportion of front row piles is gradually increasing as the row spacing increasing, which is still not fully utilized. The optimal soil pressure shared by front and rear piles appears at a certain row distance, which soil pressure behind the pile reaches the minimum value. Therefore, 4.75d ~ 5.25d is the most reasonable row spacing value of earth pressure considering the force.

5. Conclusion

(1) The bending moment of pile body increases gradually when pile spacing increases from 3.5 times pile diameter to 5.5 times pile diameter as 9m excavated and 40kPa loaded, which the average increment is about 27%. At the same time, the soil pressure increases first and then stabilizes. And the average increment of soil pressure is about 11%.

(2) The bending moment of pile body and soil pressure decreased first and then increased when row spacing increases from 4 times pile diameter to 6 times pile diameter, which the minimum is approximately between 5.0d and 5.25d. It shows that when row spacing is small, the proportion of soil pressure shared by front row piles is small. The effect of soil between piles is not obvious, which can be regarded as single row pile support. With the increase of row spacing, the soil between piles gradually plays a role which makes the force of pile body more reasonable. When the distance reaches 5.0d - 5.25d, the support effect of the structure is optimal.

(3) The smaller pile spacing and suitable row spacing which is 4.75-5.5d are conducive to improving the stability of foundation pit.

References

[1] Zeng XX, Ding WX, Peng L, et al. (2018) Effects of pile spacing on the displacement of subway tunnel during excavation[J]. China Science paper, 13: 17-22

[2] Xu X. (2012) Model experimental study of the combination of miniature steel pile structure working mechanism[D]. Chengdu University of Technology.

[3] Wang YB, Xia X, Li LL, et al. (2017) Model Test Research of Double Hollow Pipe Piles based on Displacement of Foundation[J]. Journal of Changzhou University(Natural Science Edition), 29: 78-85
[4] Xia X. (2014) Double Row Hollow Pipe Pile Structure for Assembled Foundation Pit Support: China, CN201420250691.6 [P].
[5] Terzaghi K. (1943) Theoretical Soil Mechanics[M]. New York: John Wiley and Sons.
[6] Nina H. Levy, Itai Einav, Mark F. Randolph. (2007) Effect of recent load history on laterally loaded piles in normally consolidated clay[J]. International Journal of Geomechanics, 7: 277-286.
[7] David J. White, Mark J. Thompson, Muhannad T. Suleiman, et al. (2008) Behavior of slender piles subject to free-field lateral soil movement[J]. Journal of Geotechnical and Geoenvironmental Engineering, 134: 428-436.
[8] JGJ120-2012, (2012) Technical Specification for Retaining and Protection of Building Foundation Excavations[S]. Beijing: China Architecture & Building Press.
[9] He YH, Yang B, Jin BS. (1996) Study on Test and Calculation of Double Row Slope Retaining Piles[J]. Journal of building structures, 17: 58-66.
[10] Tang F, Zheng YR, Yang B. (2010) Thrust Share Ratios and Optimization Design for Two-Row Anti-Slide Piles. Chinese Journal of Rock Mechanics and Engineering,29: 3162-3168.