CHEMICAL ENGINEERING TRANSACTIONS
VOL. 62, 2017
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Fei Song, Haibo Wang, Fang He

ISBN 978-88-95608- 60-0; **ISSN** 2283-9216
DOI: 10.3303/CET1762175

The Experimental Study on Influence of the Plate Space on Uplift Failure Mechanism of the Concrete Expanded-Plate Pile under Vertical Tension in Undisturbed Soil

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Based on the existing theories about the concrete expanded-plate pile and through small-scale model test with undisturbed soil, this article studies the influence of plate space on the uplift failure mechanism of the soil surrounding the concrete expanded-plate pile, and after analysis by the finite element software, the conclusions were compared with those of experimental research. which provides a reliable theoretical basis for design, calculation and engineering application of the bearing capacity of the concrete expanded-plate pile, thus laying a good foundation for its application.

1. INTRODUCTION

Being adaptable, the concrete expanded-plate pile can be used in different soil layers and is not limited by underground water level. Its single pile has high bearing capacity, and its body has good stability and good uplift resistance. Therefore, nowadays this new type of variable cross-section pile technology is experiencing rapid development in China. Its theoretical research has made significant progress and has formed a basic calculation formula of single pile’s bearing capacity (Qian et al., 2015; Qian et al., 2015; Tian, 2014). However, some factors of the formula are still not definite, mainly those about the impact of plate parameters on the bearing capacity of single concrete expanded-plate pile, and lack of research on these unknown factors confines the development of the concrete expanded-plate pile (Qian, 2009). Therefore, it is urgent to solve these problems to promote this type of pile (Xu, 2014). Based on the existing research, this paper will further explore the influence of plate space on uplift failure mechanism of soil around the concrete expanded-plate pile under the vertical tension (Qian et al., 2015). Up till now, finite element simulation has been completed about the impact, but test is still lacking (Yan, 2006). This paper has conducted small-scale model test in undisturbed soil which can better reflect the actual situation of the interaction between the pile and soil and compared the results with those of finite element analysis so as to get a reasonable range of the plate space. Study in this paper will provide a reliable basis for design and application of the concrete expanded-plate pile (Haskell et al., 2012; Qian, 2004).

2. Test Program

2.1 Test Devices

The test devices mainly included three parts: model pile, loading platform and soil geotome. Specimen specifications are as shown in Table 1.
In the test, the steel pile was used instead of concrete pile, because it was a simulation of pile-soil interaction in which the pile body is generally not damaged (Ren, 2012). Because it was to study the influence of plate space on the uplift bearing capacity, two bearing plates were set up and the other specific parameters were determined on the basis of previous studies (Qian et al., 2003; Qian et al., 2003; He and Shen, 2001). As such parameters as diameter of the main pile body, plate diameter, plate height and the plate space influence each other (Qian and Zhai, 2015). Sizes of the six model piles are shown in Table1 (length unit: mm; slope toe unit: °) and picture of the model piles is shown in Figure 1.

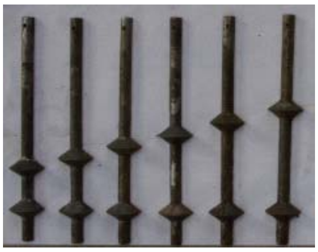
Please cite this article as: Yongmei Qian, Xiaozhou Li, Rongzheng Zhai, 2017, The experimental study on influence of the plate space on uplift failure mechanism of the concrete expanded-plate pile under vertical tension in undisturbed soil, Chemical Engineering Transactions, 62, 1045-1050 DOI:10.3303/CET1762175

The loading platform was designed independently, its design drawing and true chart are shown in Figure 2.

Table 1: Small scale and semi-section model pile size parameter value

P / No.	MPD	PD	PH	ST	PL	PDF	PS	PQ
1	10	30	15	37	300	20	20	2
2	10	30	15	37	300	20	30	2
3	10	30	15	37	300	20	40	2
4	10	30	15	37	300	20	50	2
5	10	30	15	37	300	20	60	2
6	10	30	15	37	300	20	70	2

(Note: P: parameter; MPD: main pile diameter; PD: plate diameter; PH: plate height; ST: slope toe; PL: plate length; DBF: The distance from the bottom of the pile to the first plate; PS: Plate space; PQ: Plate quantity.)



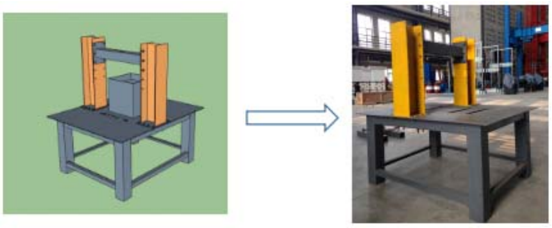


Figure 1: Small scale model pile with semi-circle section   *Figure 2: The platform for Loading*

2.2 Take Undisturbed Soil on Site and Bury the Pile

According to the geological survey report, the undisturbed soil to be taken is at the construction site of the Economic and Technological Development Zone of Changchun. Then the soil geotome that took the undisturbed soil were transported to the laboratory and laid up for some time, finally the model piles were buried with it. The main steps of taking soil and burying piles are shown in Figure 3.

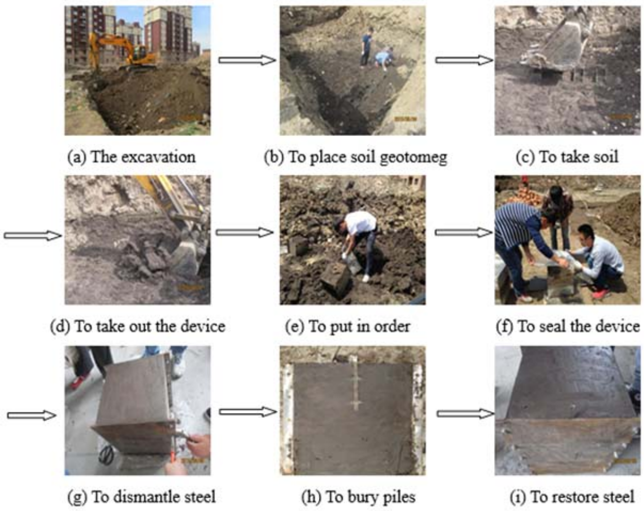


Figure 3: The process of taking soil and burying model piles

3. Results and Discussion

3.1 Results Interpretation

In steps above the tests were completed. And numerous and complex test images were collected from it. In order to facilitate results analysis, Fig.5 shows the failure conditions of model piles No.1 to No.6.
The following conclusions can be obtained from analysis of the images in Figure 4:

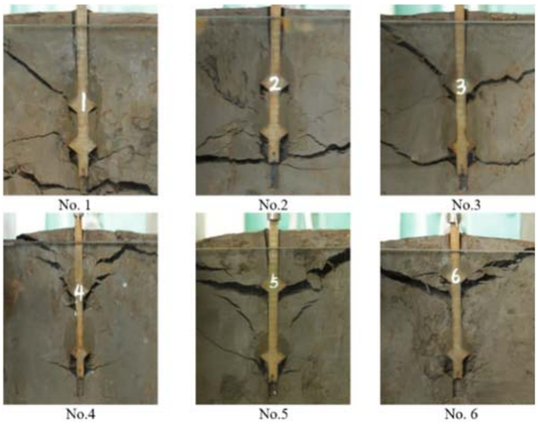


Figure 4: Images of different plate space models loaded to the failure

(1) When the model piles are loaded to failure, there are sliding failure on the upper of the plates, leaving obvious arc-shaped watermarks. In this test they were obvious on the upper plates of model No.1 & No.2 and the lower plates of model No.5 & No.6 while on both upper and lower plates of model No.3 & No.4. As the space is smaller between the upper and lower plates of model No.1 & No.2, failure of the lower plate was affected by that of the upper one, thus making a difference on the failure curve. The distance was close between the upper bearing plate and the top surface of soil body for model No.5 & No.6, and there are punching failure but no sliding failure on the upper plate. For model No.3 & No.4, the space was reasonable between the plates and between the upper plate and the top surface of soil body, hence bringing about obvious and complete failure behavior of the soil by both the upper and lower plates.
(2) It can be seen from failure behavior in images of model No.1 and No.2 that, the watermarks between the two bearing plates connected the soil region between them as the space was small between them. And the soil in this region generated a common shearing failure along with the movement of the plates. At this time the bearing capacity of each plate can not be fully realized. However, for model No.3 to No.6, the soil region between two plates was not connected under tension, so the two plates can fully exert their uplift bearing capacity independently in their own region. It shows the reasonable plate space is N≥3.
(3) From the failure behavior in images of model No.5 and No.6 it can be seen that, the soil on top of the upper plates was damaged by punching as the distance was too close between the bearing plate and the top surface of soil body, which led to punching failure to the soil. It would affect the uplift bearing capacity of the concrete expanded-plate pile. So it can be concluded that the thickness of soil on top of the plate is a very important factor in designing bearing plates of the concrete expanded-plate piles (Finno et al., 2005). And there's need to ensure not only a reasonable distance between the upper plate and the top surface of soil, but also a reasonable plate space. The plate space of the bearing plates should not be too large, or the pile length have to be increased. Usually the plate space should be N≤5. Based on the above, the reasonable plate space range should be N=3~5.

3.2 Comparative Analysis of Test Results

The results of analysis are shows as the curves of Figure 5 and Figure 6:

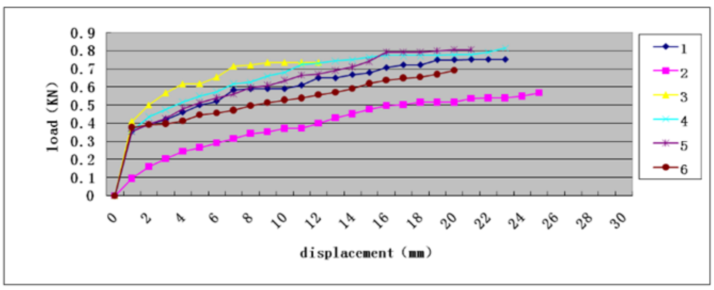


Figure 5: Load- displacement curves of different plate space models in the test

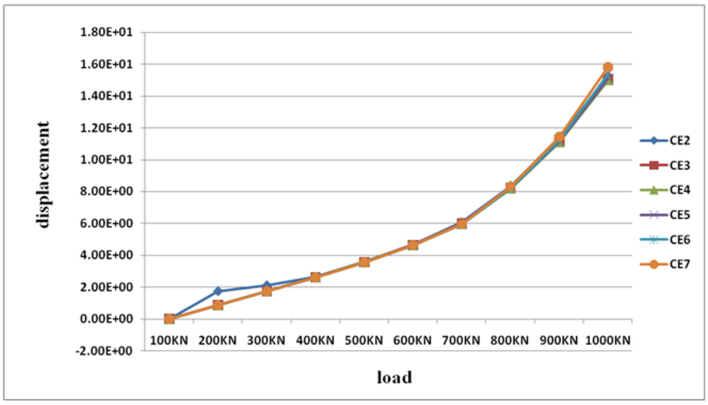


Figure 6: Displacement-load curves of different plate space models in the FEA

Figure 5 shows the load-displacement data collected during the model test and Figure 6 shows the load-displacement curves obtained from the corresponding finite element analysis, in which N=2-7 models indicate respectively No.1 to No.6 piles. The piles CE2 to CE7 in the finite element analysis (FEA) represents No.1 to No.6 models in the undisturbed soil test.

The following conclusions can be drawn from Figure 5:

(1) Through comparison of the displacement-load curves of No.1, No.4, No.5 and No.6 piles, it can be seen that, when they were lifted upward the same distance under tension, the tension increased successively from No.6, No.1, No.4 to No.5 piles. This indicates their uplift bearing capacity increased in the same sequence.

(2)The bearing capacity of No.6 pile was the smallest because the space was too large between the top bearing plate and the surface of soil, causing punching failure to the soil at top of the plate a total at a very early stage. In this reason the bearing plate lost uplift resistance, so the uplift bearing capacity of No.6 pile was smaller, this result is consistent with that of the finite element model. The bearing capacity of No.1, No.4 and No.5 piles grew gradually because the plate space of No.1 pile was small and that of No.4 and No.5 piles was reasonable. The test results are also consistent with those in the finite element model.

The following conclusions can be drawn from Figure 6:

(1) The displacements of the piles increased with the increase of load, change rate of the displacement was small at the beginning, and then increased with the increase of the load.

(2) The change rate of CE2 model was slightly higher than that of CE3 and CE4 models, but was basically consistent with that of the CE5 model. It shows that for the model with smaller plate space its displacement has a slightly higher growth rate with the increase of the load than that of the model with larger plate space. Moreover, it can be seen from Figure 6 that the displacement of each model was basically consistent at 900KN, but at 1000KN the growth rate of CE7 model was significantly higher than that of the others, because the distance between its bearing plate and the surface of soil was so close that there was punching failure on top of the plate which resulted in a sudden increase of displacement.

4. Finite Element Analysis

4.1 Construction of Finite Element Model

In order to be compared with experimental research, the finite element analysis model is constructed following below principles:

Tabel 2: Values of plate space S0

NO.	CE2	CE3	CE4	CE5	CE6	CE7
The times of plate space	2	3	4	5	6	7
The plate space (mm)	1000	1500	2000	2500	3000	3500

Table 3: Attribute value of the material

Material	Density (t/mm^2)	Modulus of elasticity (Mpa)	Poisson's ratio μ	Cohesion (Kpa)	Angle of friction (°)	Friction factor
Concrete	$2.5e^9$	$3.0e^7$	0.3	--	--	0.4
Clay soil	$1.9e^9$	$3.0e^4$	0.35	17.4	18.29	0.4

Table 2 shows the plate space values of various concrete plate-expanded pile models. C30 was used as concrete to construct the pile (Tran et al., 2012), and clay soil, always used for foundation, was used as soil surrounding the pile. The detailed parameters are as listed in Table 3.

4.2 Result Analysis of Finite Element Calculation

4.2.1 Displacement Analysis

Calculated based on theory, the uplift bearing capacity of single pile should be around 1067KN. then draw the maximum displacement value of each model under the same load of around 1000KN into the diagram of curve as shown in Figure 7.

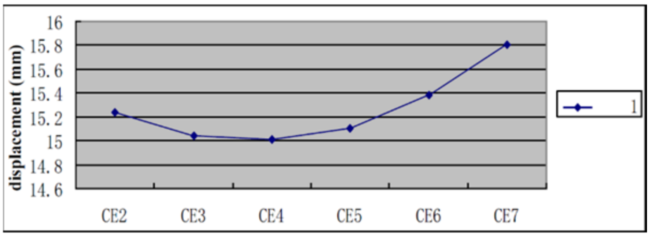


Figure 7: Maximum vertical displacement value of each model under the same load

From Figure 7 it can be seen that under the same load, displacement of model pile with place space 1000 (CE2) was larger than that of pile with place space 1500 (CE3), 2000 (CE4) and 2500 (CE5). That's because there was punching failure to the soil as a whole between plates when the plate space was too small, causing the vertical displacement value a little larger than that of pile with reasonable plate space. Such space can not give a full play to the function of double plates, so the uplift bearing capacity of the piles would decrease. On the contrary, when the plate space was 3500 (CE7), the maximum vertical displacement value of the pile would increase suddenly because at such plate space, the upper bearing plate was only 1980mm away from the surface of soil, and there would easily form punching force to the soil on top of the upper plate, which was adverse to the full play of bearing plate's functions. So such space would also lower the uplift bearing capacity of the concrete expanded-plate pile. Based on above analysis, it can be concluded that influence of plate space on the uplift bearing capacity of concrete expanded-plate pile includes 2 aspects: the value of plate space, and the space between the upper bearing plate and the surface of soil.

4.2.2 Displacement-Load Curve Analysis

By extracting from the ANSYS post-processor the maximum vertical displacement value of model CE3-CE6 after every 100KN was loaded, the variation curve of displacement with the load change can be drawn through reorganization as below in Figure 8.

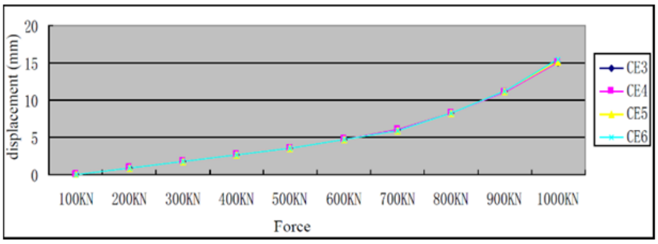


Figure 8: Displacement-load curve

From Figure 8 it can be known that the displacement of each model changed with the load variation in the same principle, and after load upgraded by 1 level each time, vertical uplift displacement value was quite near for each model, indicating that when plate space is large than the reasonable value ($\geq 3r_0$), its impact decreases gradually on uplift bearing capacity of the concrete expanded-plate pile.

5. Conclusion

Based on results of the undisturbed soil model tests and finite element analysis, the following conclusions are drawn:

(1) The conclusion obtained from the finite element analysis is consistent from that drawn from the undisturbed soil test. To make sure that the concrete expanded-plate pile has enough uplift bearing capacity, a certain distance, generally not less than 4R, must be first ensured between the upper bearing plate and surface of the soil so as to avoid punching failure to the soil layer on top of the upper plate.
(2) When N≤2.5, namely the net space between the two bearing plates is less than 2.5 times of the plate's cantilever length, the soil between the bearing plates is liable to be destroyed as a whole body, and it won't form a complete slip failure curve for the soil under the bearing plate, thus reducing the uplift bearing capacity of the piles. When the space is too large, that is, when N>5, the pile length increases much more, and with the increase of the plate space, the uplift bearing capacity increases very slowly, resulting in economical waste. Therefore, the reasonable range of the net space (S_0) for the concrete expanded-plate pile is 3 to 5 times of the cantilever length R of the plate, that is, N=3 to 5. Such setup can not only give full play to the bearing plate, but also save the project cost.

Acknowledgments

This work was financially supported by National Natural Science Foundation of China (51678275 and 51278224).

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