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A model test study of three-dimensional deformation behavior of retaining structures of rowed piles

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Abstract. To improve the accuracy of methods for analyzing retaining structures, a model test study was conducted to simulate the process of excavation in sand. The displacements and moments of the rowed piles in corresponding excavation stages were measured and analyzed. The method for analyzing three dimensional behaviour of retaining structures based on additional earth pressure theory showed accuracy better that form the methods based on traditional three-dimensional elastic reaction method based on total earth pressure theories. The applicability and validity of the additional earth pressure theory was discussed and verified.

1. Introduction

Flexible retaining structures such as sheet-pile wall, diaphragm wall and rowed pile wall are commonly used in foundation pit engineering over the world. The main methods for analysing flexible retaining structure are static equilibrium method (SEM), elastic reaction method (ERM) and finite element method (FEM) [1], among which the ERM is more convenient and hence widely used. But, as both the initial and early improved ERMs are suitable for two-dimensional cases, i.e. in plane condition [1, 2], they are incapable of considering the spatial effect of retaining structures. Though, in the latest improvement of the ERM [3], the horizontal forces and displacements at the junctions of retaining piles and the top beam over the piles was considered, the improved versions of ERM is virtually a quasi-three-dimensional elastic reaction method as the effects of moment and torsion in retaining structures are still ignored and the accuracy of the results by this method is still unsatisfiable in cases where the influence of deformation of retaining structures is strictly controlled. Therefore, the methods for analyzing the behaviour of retaining structures with good accuracy would require a reasonable reflection of the spatial effects of retaining structures, and are badly needed in practice.

Though there have been many model tests in two dimensions and field measurements of the retaining structures in last several decades, the three dimensional behaviour of retaining structures for entire foundation pits is still unclear, especially lacking of model tests in three-dimension conditions. In developing a method above mentioned, a series of model tests and a large number of nonlinear finite element simulations of three dimensional retaining structures for excavation have been conducted in Tianjin University since 2010, among which a model test of three-dimensional deformation behaviour of a retaining structure of rowed piles in a fine sand is introduced herein, together with comparison of the test results with those from newly developed three-dimensional method for calculating retaining structures of rowed piles based on additional earth pressure theory [4].

2. Setup and description of the model test

2.1. Conditions of model tests

The three dimensional model test of the behaviour of retaining piles during excavation was conducted in the underground engineering laboratory at Tianjin University. The excavation is simulated in a soil box with effective inner dimensions are 3.0 m in length, 1.0 m in width and a total height of 1.2 m. A fine river sand was used to simulate foundation soil. The parameters of mechanical properties of the sand are shown in Table 1, in which H is the height of the retaining structure and δ_{acr} the critical horizontal displacement of the retaining structure, i.e. the rowed piles herein [5].

The material for the model retaining structure which was composed of 28 rowed hollow model piles is a kind of plexiglass, whose Young's modulus is 3 GPa and thickness is 2 mm. The cross-sectional size of the hollow model pile is 16 mm × 16 mm, and the length of a pile is 1000 mm. A solid top beam with a rectangular cross section which is of 20 mm in height and 3 mm in width was attached the heads of all the piles to unite all the members into a entire retaining structure.

Table 1. The parameters of mechanical properties of the sand.

Cohesion c /kPa	Internal friction angle φ / °	Unit weight γ /kNm^{-3}	M value in ERM m /kNm^{-4}	δ_{acr}/H
0	32.6	14.0	10000	0.4%

2.2. Arrangement of piles and measuring points

Foundation pit is rectangular in horizontal plane and the layout of retaining structure is shown in Fig. 1. Considering the symmetry of the foundation pit, half of the retaining structure of foundation pit was set and tested. The rowed piles were arranged with a centre-to-centre pile spacing of 30 mm. The piles were numbered clockwise from Pile 1 at the left bottom corner point to Pile 8 at the left top corner point, and continued to pile 21 and then to pile 28 at the right top and bottom corner points, respectively, as shown in Figure 1. Pile 8 (referred as corner pile) and Pile 14 (referred as central pile) were selected as measuring piles. Pile 14 was instrumented to measure the horizontal deflections y-direction and corresponding internal bending moments along the pile length. The measurement points of displacements and moments of the pile were arranged as shown in Figure 2.

2.3. Measures to prevent sand leakage

The dry river sand was selected in this experiment. The sand is loose and non-cohesive in the dry state. It could flow into the foundation pit from the spacing between the rowed piles during excavation process. Therefore, a sheet of a geotextile with smaller stiffness was adhered to the outside of the retaining structure to prevent the sand between piles from leaking out during the excavation. Then the development and rebalancing of the shear stress in the range of shear strength between rowed piles increased the earth pressure at the row of piles, i.e., each row pile suffered from the earth pressure in the range of calculated width set by pile spacing.

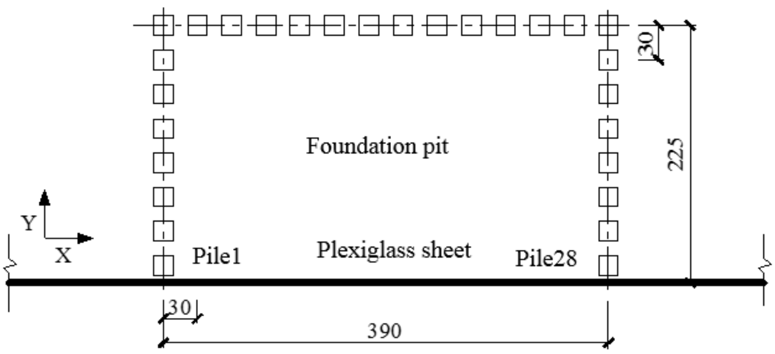

Figure 1. Plane size and pile layout of foundation pits (unit: mm)

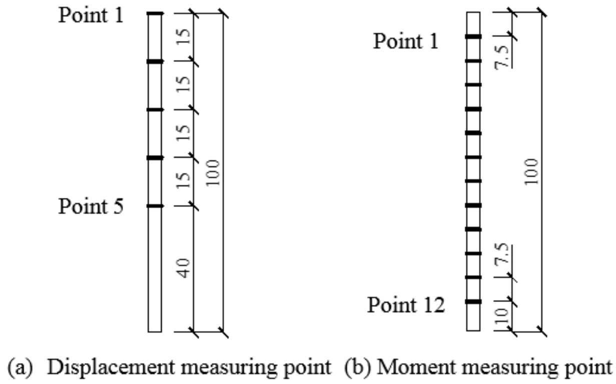

Figure 2. Arrangement of measurement points for displacements and moments

2.4. Main process of excavation

The sand was filled in by layers in the experiment. The height of each layer was 100 mm, and the surface of each layer of soil was smoothed after the end of filling. When filling the soil to the elevation of the pile bottom, put the model structure into the soil box. When filling the soil to the displacement measuring points of Pile 8 and Pile 14, the electronic micrometer were setup at the outside of the box to measure the displacement of the measuring points of the pile, as shown in Figure 3. Bending moments of the piles were determined by the measured data of strain gauge attached to the pile surface.

Figure 3. Arrangement of electronic dial indicators

Figure 4. Excavation of the third layer

After completing the filling of soil and the installation of electronic micrometer, the soil surface was smoothed, and entire model was placed for a period of time that is enough to form initial static condition. After the soil was stable, the excavation process was simulated by removing soil with in the inner range that confined by the retaining piles. The total excavation depth of the model foundation pit was 45 cm, and excavation was finished in three stages in each test times, so the excavation depth in each stage was 15 cm. After each layer of sand was excavated, the displacements and bending strain values of each measuring points were recorded. The foundation pit excavated to the third layer or last stage is shown in Figure 4. The simulation of the excavation process was repeated under the same condition in 3 times and the results of the test were taken as the averages values from the measured data.

3. Methods of data analysis

The purpose of this test is to verify the validity of a new method for analyzing the spatial behaviour of three dimensional retaining structures. The new method is called additional earth pressure method (AEPM) which is based on the theory of additional earth pressure, while the classical method for analyzing the three dimensional retaining structures can be referred as total earth pressure method (TEPM) which is based on classical earth pressure theories such as Rankine's earth pressure theory and/or Coulomb's earth pressure theory.

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The common back ground to both AEPM and TEPM is that the retaining rowed piles and the bracing top beam are simplified as straight bars, which are simulated by the corresponding spatial beam element, while ignoring their gravity. Furthermore, the soil resistance of the embedded part of retaining piles below the bottom of the foundation pit is simulated by a continuous spring distribution i.e. the ERM, and each member in the retaining structure can be simply regarded as a unit for truss structures in space, providing an effective way for the combination of elastic reaction method and finite element method. The three-dimensional method for calculating retaining structures of rowed piles based on elastic reaction method and finite element method of space bar structure is finally obtained [4].

In the AEPM, additional earth pressure is defined as the difference between static earth pressure and actual earth pressure acting on retaining structure [4], which is a function of displacement of soil in considering the soil-structure interaction and shows the trend of synchronous development with the displacement. It conforms to the basic principle soil deformation caused by additional stress in soil mechanics [5, 6]. In the TEPM, the earth pressure acting behind the wall is adopted by Rankine's earth pressure or Coulomb's earth pressure, and it is incapable of dealing with the interaction between soils and retaining structures. Due to the application of additional earth pressure that dependent to the deformation soil/piles, the AEPM are able to give internal forces and deformations of a global retaining structure with the process of excavation, and provides results with accuracy higher than that from TEPM.

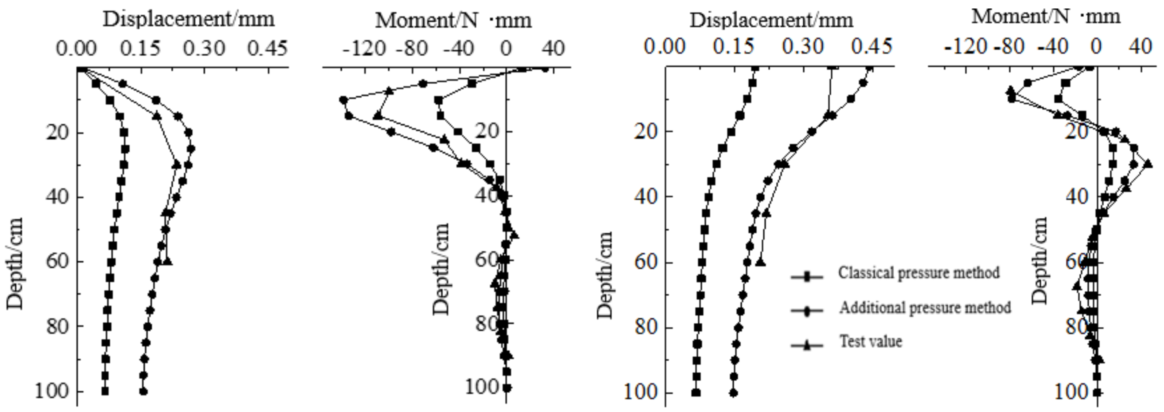
A computer program call TDAP for analyzing three-dimensional retaining structures based on both AEPM and TEPM was coded in FORTRAN language [6]. The TDAP program is adopted herein to analyze the measured data.

4. Result analysis of the model test
The displacements and moments of Pile 8 (the corner pile) and Pile 14 (the central pile) of the retaining structure under three stages of excavation of the foundation pit are given in Figures 5 to 7, respectively. The test results are also compared with the results that calculated by both classical earth pressure method and additional earth pressure method, respectively, as can be seen in Figures 5 to 7.

4.1. Excavation stage 1
Figure 5 is the horizontal displacements and moments of corner pile and central pile at the end of excavation stages 1. As can be seen from Figure 5, (1) the displacements and moments obtained by the two methods are similar, but their values are quite different, and the value of the additional earth pressure method is always larger. (2) The test value of displacements and moments above the surface of excavation are slightly less than those of the additional earth pressure method and are larger than those from the classical earth pressure method. So, the correctness of the calculation results from additional earth pressure method is preliminarily proved. (3) The maximum displacement of corner pile is smaller than that of central pile, and the maximum moment of corner pile and central pile occurs near the surface of excavation, but the maximum moment of corner pile is much larger than that of central pile, which shows the spatial effect of foundation pit.

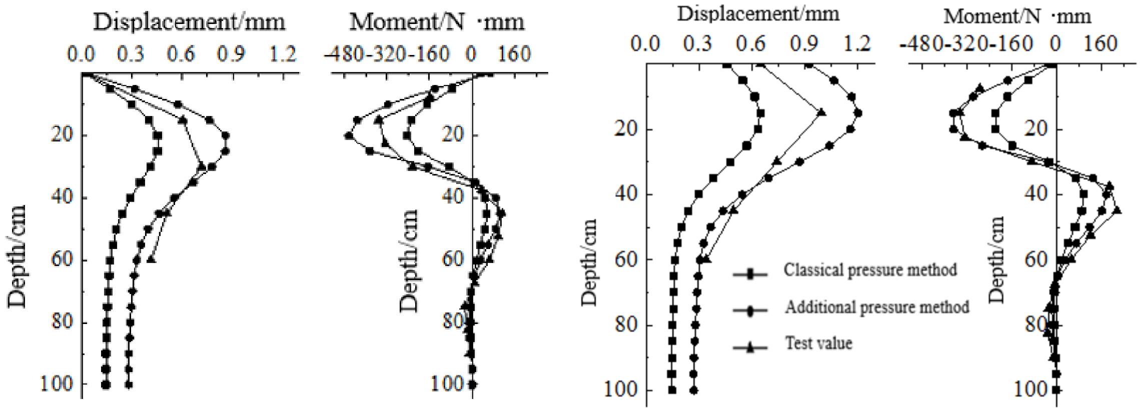
4.2. Excavation stage 2
Figure 6 is the horizontal displacements and moments of corner pile and central pile at the end of excavation stages 2. As can be seen from Figure 6, (1) the distribution trend of the displacements and moments of piles in different positions calculated by the two methods are still similar, and the numerical difference between the two methods is still large. (2) The test value of displacements and moments is also similar to those calculated by the additional earth pressure method, which further proves that results from the additional earth pressure method are correct. (3) With the increase of the depth of excavation, the influence of restraint of the top beam on the position of the maximum displacement of pile decreases gradually, so the position of the maximum displacement of piles rises. And, the position of the maximum displacement of corner pile is closer to the surface of excavation

than that of central pile. In addition, the position of the maximum moment of corner pile and central pile also occurs above the surface of excavation. The maximum moment of corner pile is larger than that of central pile.



(a) Corner pile displacement (b) Corner pile moment (c) Central pile displacement (d) Central pile moment

Figure 5. Displacements and moments of pile at different positions in excavation stage 1



(a) Corner pile displacement (b) Corner pile moment (c) Central pile displacement (d) Central pile moment

Figure 6. Displacements and moments of pile at different positions in excavation stage 2

4.3. Excavation stage 3

Figure 7 is the horizontal displacements and moments of corner pile and central pile at the end of excavation stages 3. As can be seen from Figure 7, the distribution trend of displacements and moments of the pile in different position obtained by the two methods are still similar, and the relative difference between the two methods is smaller than that of excavation stage 1 and 2. The test data of displacements and moments is similar to the value of the additional earth pressure method, and proves that the actual earth pressure obtained from the additional earth pressure theory is more accurate.

5. Conclusion

Based on the model test, this study is focus on the deformation and internal force distribution of retaining structures under different conditions of excavation, and the conclusions are as follows:

The test data exhibited the same tendency with the results from three dimensional analysis by AEPM, and indicate that the additional earth pressure method is of better accuracy than TEPM.

In the retaining structure, top beams have a certain restraint effect on the deformation of retaining piles. This restraint effect is the largest at the top of piles and decreases gradually with the increase of the depth of excavation. At the same time, the retaining piles were also imbedded by the soil below the surface of excavation, which limited the displacements of the retaining pile to a small range.

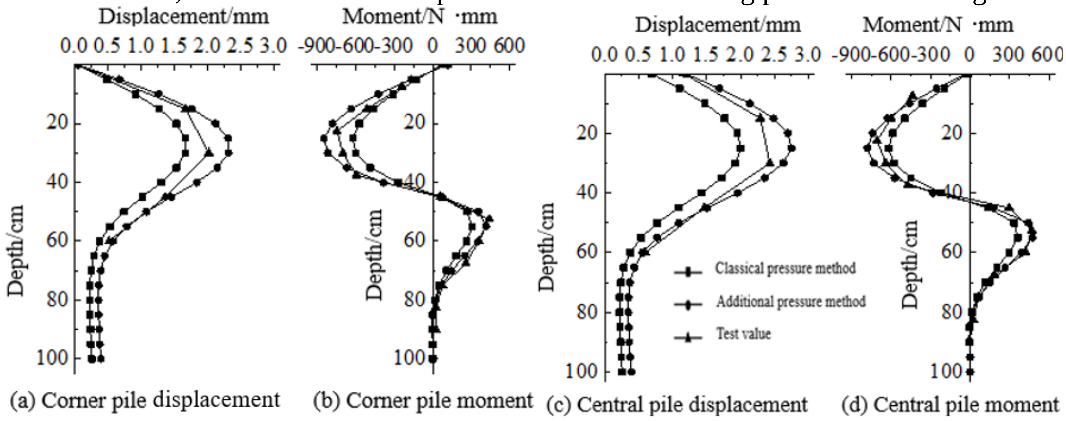


Figure 7. Displacements and moments of pile at different positions ns in excavation stage 3

In the same depth of the foundation pit, the displacement of the pile at the central position is the largest, while the moment of the corner pile is the largest, which reflects the spatial effect of the whole foundation pit. Therefore, considering the spatial effect of the foundation pit, the results of three-dimensional deformation analysis of the retaining structure are similar to the actual situation of the retaining structure.

Through the model test, the validity of the AEPM for the overall analysis of retaining structures is verified, and the applicability and advantages of the additional earth pressure theory is also well demonstrated.

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