Deformation of cantilever foundation pit engineering in sand ground: centrifuge model test

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Abstract. A centrifuge model test was conducted to investigate the excavation-induced deformation characteristics of the foundation pit engineering in sand ground. Laser displacement sensors (LDSs) and the particle image velocimetry (PIV) technology were jointly used to obtain the horizontal deflection ($\delta_H$) of the retaining wall and ground surface settlement ($\delta_V$), and the relationship between $\delta_H$ and $\delta_V$. Test results show that the profile of $\delta_V$ is a spandrel type with the maximum values ($\delta_{Vm}$) close to the wall, which is consistent with Peck’s result. While, the profile of the retaining wall deflection is a straight line with the maximum values ($\delta_{Hm}$) at the top. The $\delta_{Vm}$ is equal to 1.05~1.75 $\delta_{Hm}$ for the cantilever foundation pit engineering in sand ground. Although the deformation obtained by PIV method is smaller than that obtained by LDSs because of the inevitable boundary effect of the model box, PIV is an effective method to get the deformation characteristic in the deep zone.

1. Introduction

Controlling ground surface settlement around the excavation zone and the deflection of supporting structures is an essential task in the design of an excavation project. Excessive deformation of the foundation pit frequently damages the adjacent properties in urban areas. The magnitude of the deformation is related to many factors, such as soil properties, structural properties, and excavation geometry [0]. Currently, a number of researches have been reported to give the relationship between those factors and the deformation of foundation pit. Research methods mainly include statistical analysis, theoretical analysis, laboratory model tests and finite element numerical simulation [0-0]. Many deformation prediction curves and empirical formulas have been put forward to estimate the values and influence ranges of the horizontal deflection and ground surface settlement [0, 0, 0]. However, these researches focus on the deformation of foundation pit in soft clay ground, and there is only a limited amount of researches available regarding the projects in sand ground. Besides, research methods also have certain limitations. For example, statistical analysis method has engineering conditions and geographical dependence; theoretical methods have many simplifications; laboratory small-scale model tests cannot create the stress state in prototype due to the self-weight stress dissimilarity; numerical simulation has a large dependence on the selection of constitutive model and soil parameters.

Geotechnical centrifuge model test is the most advanced and effective method in geotechnical engineering research. Its principle is based on creating the same self-weight stress in the model as in a prototype by accelerating a model in a centrifuge $N$ times of the Earth’s gravitational acceleration ($1g$). On this basis, the mechanical deformation characteristics and interaction of soil and structures are
studied. Therefore, a centrifuge model test was conducted to investigate the excavation-induced deformation characteristics of the foundation pit engineering in sand ground. Laser displacement sensors (LDSs) and the particle image velocimetry (PIV) technology were used to obtain the horizontal deflection of the supporting structure and the ground surface settlement. Besides, in order to make test results more prominent, a cantilever wall was adopted as the supporting structure and the deep excavation was conducted. Research results can be used to predict the deformation characteristics of similar foundation pit projects, which is useful in protecting adjacent buildings.

2. Centrifuge model test setup and procedure
The test was carried out at 40g on geotechnical centrifuge ZJU-400 in Zhejiang University.

2.1. Excavation method
Currently, three methods are always used in centrifuge model tests on foundation pit engineering. (1) Model excavation is carried out at 1g and then the centrifuge model is subjected to an increasing centrifugal acceleration field [6]. (2) Draining heavy liquid in-flight to simulate the soil excavation [7] or (3) excavation in-flight with an advanced robot excavator [8]. However, these methods have some disadvantages, such as the inability to accurately simulate the excavation process or the difficulty of implementation. Therefore, the excavation device in reference [9] was applied in this research, which was more accurately to simulate the unloading process in-flight.

2.2. Foundation pit model preparation
Fujian standard sand (FS) was used to prepare the foundation pit model. The physical and mechanical parameters of FS are shown in Table 1. The sand pluviation method was used to build the model. The falling height was determined to be 1010 mm to get a relative density of 85% according to the calibration result of the pluviation device, which is shown in Figure 1.

| Items          | Dr (relative density) | \( \gamma_d \) (kN/m\(^3\)) | c (kPa) | \( d_{50} \) (mm) | e | \( e_{\text{min}} \) | \( e_{\text{max}} \) | \( \phi(\°) \) |
|---------------|----------------------|-----------------------------|--------|-------------------|---|----------------|----------------|--------|
| Value         | 85%                  | 15.9                        | 0      | 0.17              | 0.663 | 0.612          | 0.957          | 32     |

![Figure 1. Calibration of the sand pluviation device.](image1)

![Figure 2. Model setup (unit: mm).](image2)

The model test was designed based on a foundation pit engineering with the pile-anchor supporting structure in north China. As shown in Figure 2, the height of the foundation model (the prototype) was 650mm (26m), the length was 850mm (34m), and the width was 400mm (16m). The height of the model retaining wall was 550mm (22m). The depth of the pit was 250mm (10m), which was filled with three earth-filled bags with the thickness of 60mm (2.4m), 80mm (3.2m) and 110mm (4.4m). The model retaining wall was made of an aluminum alloy plate with a thickness of 9.5 mm and a modulus
of elasticity of 68.9 GPa according to the principle of equivalent flexural stiffness \(E_p \times I_p = N^4 \times E_m \times I_m\), where \(E_p\) and \(E_m\) are the elastic modulus of the prototype concrete and aluminum alloy, respectively; \(I_p\) and \(I_m\) are the moment of inertia of the concrete pile and aluminum alloy plate, respectively; \(N = 40\) here.

Four LDSs (L1, L2, L3, and L4) were used to get the settlement of the ground behind the retaining wall, as shown in Figure 2. Besides, a high-speed camera arranged in front of the observation window was used to get model photos for PIV analysis.

3. Test results
All the laboratory-measured deformation were converted to counterpart results in the field as well as time and dimensions according to similarity scales.

3.1. Measured surface settlement by sensors
The induced surface settlement along with the excavation process (actually, time) obtained by LDSs are shown in Figure 3. It can be seen that the ground surface settlement (\(\delta V\)) gradually increased during the excavation process. L1, which is closest to the retaining wall, has the maximum value of the measured settlement. By contrast, L4 has the minimum value and the least change in the process. Furthermore, based on the analysis, induced \(\delta V\) at different positions from the retaining wall after each excavation stage can be obtained. As shown in Figure 4, the maximum measured ground surface settlements (\(\delta V_m\)) at the position of L1 are -5 mm, -22.5 mm and -48.8 mm in stage 1, stage 2 and stage 3, respectively. It should be noted that stage 0, stage 1, stage 2 and stage 3 refer to the moment before the excavation and the first, second, third excavation stage, respectively.

![Figure 3](image1)

3.2. Foundation deformation by PIV
In many model tests, PIV technology was often used to obtain the ground deformation effectively. Therefore, this technology was taken to get the ground deformation caused by foundation pit excavation in this research. Considering the accuracy and focus of the test, only a model area of 12 m \(\times\) 13 m was used for PIV analysis. Figure 5 comparatively presents the soil displacement vectors behind the retaining wall during the excavation process. Results are magnified 10 times to ensure a better visualization of the displacement field. It can be seen that the induced foundation deformation is not obvious in stage 1, but significant in stage 2 and stage 3.

The induced \(\delta V\), as shown in Figure 6, is obtained according to the deformation parameters of the horizontal grids in the model surface. It can be seen that the profile of \(\delta V\) is a spandrel type, which is similar to Peck’s result [0]. \(\delta V\) at 4.8 m distance (L1) from the retaining wall are -2 mm, -7.5 mm and -15 mm in stage 1, in stage 2 and in stage 3 respectively. Obviously, these values are much smaller than the measured ones (-5 mm, -22.5 mm and -48.8 mm, respectively). Because the inevitable boundary effect of the model box reduces the soil deformation in the model side. And the measured \(\delta V\) by LDSs are actually in the middle of the ground surface.

![Figure 4](image2)

![Figure 5](image3)
Similarly, the horizontal deflection ($\delta_H$) of the retaining wall or the soil near the wall can be obtained by extracting the deformation parameters of the vertical grids. As shown in Figure 7, the induced horizontal deflection profile of the retaining wall can be linear fitted. Obviously, $\delta_H$ is also affected by the boundary effect.

3.3. Comparison of $\delta_V$ between test results and theoretical predictions

As can be seen above, the deformation of the foundation pit is significant in the third excavation stage, so this section focuses on $\delta_V$ in stage 3. There are two general types of settlement profile caused by excavations: spandrel type and concave type. Many researchers have proposed empirical methods for predicting both types of settlement profile [2, 4, 5]. Figure 8 shows $\delta_V$ in stage 3 by different prediction methods. It can be seen that the values by LDSs are between that by Peck’s method and Bowles’s method [4, 10]. Therefore, we can assume that the maximum ground surface settlement ($\delta_{Vm-3}$) is 110mm near the retaining wall, which is about 1.1% of the final excavation depth.
3.4. Relationship between $\delta_V$ and $\delta_H$

Horizontal deflection ($\delta_H$) of the retaining wall is closely related to ground surface settlement ($\delta_V$). Once the relationship is determined, $\delta_V$ can be predicted by $\delta_H$. Many studies have been carried out in this field [0, 0]. Therefore, this section also discusses the relationship in the case of the cantilever foundation pit engineering in sand ground. As mentioned above, the deformation obtained by PIV method is smaller than that obtained by LDSs because of the inevitable boundary effect of the model box. However, in the context of studying the relationship between $\delta_V$ and $\delta_H$, this boundary effect can be eliminated by the dimensionless method.

Figure 9 shows the relationship between the maximum dimensionless horizontal deflection ($\delta_{Hm}/H_e$) of the retaining wall and the maximum dimensionless ground surface settlement ($\delta_{Vm}/H_e$). $H_e$ herein is defined as the excavation depth. As shown in Figure 9, $\delta_{Vm}$ is equal to 1.05~1.75 $\delta_{Hm}$ for the cantilever foundation pit in sand ground. However, $\delta_{Vm}$ is equal to 0.5~0.7 $\delta_{Hm}$ for most excavation cases in Taipei [0], and 0.71~1.0 $\delta_{Hm}$ for those excavation projects in Shanghai [0]. Therefore, it can be seen that the deformation caused by excavation in sand ground is more obvious. The support or anchor structure plays an important role in controlling the deformation of the foundation pit.

![Figure 9. Relationship between $\delta_H$ and $\delta_V$ by PIV.](image)

3.5. Ground surface settlement profile

The magnitude and distribution of the settlement are related to many factors such as construction quality, ground condition, excavation depth, and support system. A theoretical method to predict those result will be complex and inaccurate. Therefore, most of the prediction approaches were obtained based on field measurement. Figure 10 presents the final ground surface settlement profile in this research and some of the empirical methods currently used in engineering practice. It can be seen that the ground surface settlement profile in this study is between the profiles proposed by Bowel and Hsieh & Ou [5, 10]. Besides, it is just in zone I for sand and soft to hard clay, which is proposed by Peck [4].

![Figure 10. Surface settlement profile.](image)

4. Conclusions

A centrifuge model test was conducted to investigate the excavation-induced deformation characteristics of the foundation pit engineering in sand ground. LDSs and PIV technology were used to obtain the retaining wall deflection and the ground surface settlement. The findings are summarized as follows:

(1) The induced foundation deformation gradually increased during the excavation process. More specifically, the deformation is not obvious in stage 1, but significant in stage 2 and stage 3. The profile of the induced ground surface settlement ($\delta_V$) in this study is a spandrel type, in which the maximum ground surface settlement ($\delta_{Vm}$) occurs very close to the wall. It is consistent with Peck’s result. While, the profile of the retaining wall deflection is a straight line with the maximum values at the top.
(2) The deformation of the foundation pit in sand ground is more obvious than those in soft clay ground. The maximum ground surface settlement in stage 3 ($\delta_{vm,3}$) is about 1.1 % of the final excavation depth. And $\delta_{vm}$ is equal to 1.05~1.75 times of the maximum wall deflection ($\delta_{hm}$) for the cantilever foundation pit engineering in sand ground.

(3) The deformation obtained by PIV method is smaller than that obtained by LDSs because of the inevitable boundary effect of the model box. However, PIV is an effective method to get the deformation characteristic in the deep zone.

(4) Further tests in the context of the other soils will be carried out to study the excavation-induced deformation characteristics in the future.

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References
[1] Ou C, Hsieh P, and Chioh D, 1993. Characteristics of ground surface settlement during excavation. Can. Geotech. J., 30(5):758-67.
[2] Liu G and Wang W, 2009. Excavation engineering manual. 2nd ed. Beijing: China Architecture and Building Press.
[3] Roboski J and Finno R, 2016. Distributions of ground movements parallel to deep excavations in clay. Can. Geotech. J., 43(1): 43-58.
[4] Peck R, 1969. Deep excavation and tunneling in soft ground. Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering, State-of-the-Art-Volume, Mexico City, pp. 225-290.
[5] Hsieh P and Ou C, 1998. Shape of ground surface settlement profiles caused by excavation. Can. Geotech. J., 35(6):1004-17.
[6] Lyndon A and Schofield A, 1972. Centrifuge model test of short term failure in London clay. Geotechnique, 20 (4), 440 - 2.
[7] Ong D, Leung C, and Chow Y, 2006. Pile behavior due to excavation-induced soil movement in clay. 1: Stable wall. J. Geotech. Geoenviron., 132 (1): 36-44.
[8] Goh A, Teh C, and Wong K, 1997. Analysis of piles subjected to embankment-induced lateral soil movements. J. Geotech. Geoenviron., 123 (9), 792-801.
[9] Li L and Fu Q, 2017. Lateral behavior of composite foundation due to adjacent excavation: centrifuge model test. China Civil Engineering Journal, 50(6): 85-94.
[10] Bowles J, 1988. Foundation analysis and design. 4th ed. McGraw-Hill Book Company, New York.