Study on the Effect of Multiple Excavation Depth Pit Excavation on the Deformation of Enclosure Structure and Surrounding Buildings under Asymmetric Loading

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Abstract. To manage ground displacement during unevenly loaded, deep excavation, the impact of asymmetric load on surrounding areas during multi-depth foundation pit excavation is analyzed. An example is drawn from a deep open-cut foundation pit for an underpass tunnel in Wenzhou city. FLAC3D is used to simulate the deformation of foundation pit excavation on the envelope structure and surrounding buildings. The research results indicate that when multi-depth foundation pit is excavated Under asymmetric load, the excavation depth close to the building side will significantly increase the deformation of the supporting pile and the settlement of the building, and the maximum deformation position of the supporting pile will move downward. Moreover, as the edge distance of the excavation site expands, the horizontal displacement of the support piles nearest to the building side diminishes, while those farther away experience an increase in their horizontal displacement. The structure's subsidence diminishes as the excavation border widens; this reduction decelerates concurrently.

Keywords: Excavation; Asymmetric load; Multiple excavation depths; Deformation of enclosure structure; Building deformation

1 Introduction

Currently, foundation pit excavation is growing daily. During subsurface cavity digging, pit wall stability demands minimized soil displacement. Excavating uneven foundation pits measurably jeopardizes their structural integrity and adjacent constructions [1-2]. Consequently, examining the excavation technique for asymmetric foundation pits is essential.

In recent years, researchers have conducted extensive investigations into the stability of asymmetric foundation pits and adjacent building settlements. In terms of theoretical analysis, based on the equivalent beam method,based on the non-limit state earth pressure theory considering displacement, Fan Xiaozhen et al [3] altered the sup-

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porting structure's lateral stress. Simultaneously, soil properties and digging contexts' effect on the least required support structure depth is assessed. Deeper cuts significantly stress the whole structure, while shallower earthwork is more excavation-sensitive.Ruan Sheng et al.[4] aimed at a single-storey buttressed foundation pit under asymmetric load, based on the ultimate earth pressure method, the difference of fixed point adjustment coefficient between the support pile and the support pile under hinged and consolidated conditions is analyzed. Many scholars have studied the problem of asymmetric foundation pit excavation by numerical simulation. Cai Yuanqiang[5] simulated the entire process of foundation pit excavation across varying depth combinations.The simulation revealed that increasing the insertion depth from 6.0m to 10.5m caused the left support pile's maximum horizontal displacement to rise by 86.74%.Right support pile's peak lateral shift lessened by 65.75%, prompting a suggested design enhancement for uneven base excavations. Lin Gang et al. [6] employed the HS constitutive model of soil to compute and analyze· the horizontal displacement of the supporting pile.Gao Yiwen et al.[7] , based on a foundation pit project in Xiamen, conducted a study that integrated numerical analysis and field measurements to investigate the stress and deformation behaviors of the supporting structure under symmetric loading conditions. Guo Lin et al. [8] conducted undrained static shear and large number of cyclic loading tests on Wenzhou structural soft clay and studied the influence of structure on soil strength and its strain characteristics under long-term cyclic loading. To sum up, the above studies mostly focus on specific working conditions and parameter conditions, and lack of research on the asymmetric load foundation pit supporting structure under broader geological conditions and complex surrounding environment. However, Wenzhou soft clay is more susceptible to disturbance and deformation under load is more significant. Therefore, in this case, the above research is not applicable to Wenzhou soft clay. The deformation analysis of foundation pit supporting structure and surrounding buildings under asymmetric load and asymmetric excavation depth is still insufficient, and there are many unsolved problems.

This paper takes Wenzhou open-cut tunnel foundation pit as an example to establish a double-depth excavation model. By taking a close look at the model, the study digs into how the foundation pit warps, how much the building shifts, and the way soil stress changes when things aren't loaded evenly. It offers some real food for thought that could be a game-changer for designing and building similar projects down the road.

2 Project Overview

This project is an open-cut tunnel project in Wenzhou. The total length of the tunnel is about 1070 m. The specific location of the project is shown in Figure 1.

Fig. 1. General situation of foundation pit excavation

3 Numerical Simulation of Excavation Process of Foundation Pit

The tunnel, which is dug to a greater depth, and the basement foundation pit, excavated more shallowly, are being carried out simultaneously, resulting in an asymmetric foundation pit characterized by varying depths of excavation. Moreover, adjacent homes are positioned solely to the right of the excavation, creating an unbalanced load. This paper presents a numerical simulation study aimed at investigating the deformation of an asymmetrical excavation support structure under asymmetric loading, as well as the impact of excavation on the deformation of buildings surrounding the foundation pit.

3.1 Finite Element Analysis Model

The spatial impact of this foundation pit is minimal. During the model setup, given the foundation pit's substantial size and the load's concentration in the section, this was taken into account. Therefore, the longitudinal length is not considered and only the two-dimensional section is selected for analysis. The main analysis focuses on the impact of supporting structures and surrounding loads on the foundation pit in the section near the structure. Therefore, this paper simplifies it into a two-dimensional plane problem for research, and its physical model is shown in Figure 2. Table 1 presents the cross-sectional dimensions and material parameters of the retaining piles and internal supports.

FLAC3D was employed for a 2D numerical simulation of the foundation pit's typical section, illustrated in Figure 2. The deformation response of the soil around the foundation pit generally has obvious small deformation characteristics [9,10]. Therefore, in this simulation, it is assumed that each layer of soil is a homogeneous elastic-plastic material and the constitutive model adopts the Mohr-Coulomb model. The elastic constitutive model is adopted for retaining piles, internal supports and columns. The building is equivalent to a uniformly distributed ground load L[11]. The uniformly distributed load is applied on the left side of the enclosure structure and is considered to be 15 kPa per layer, with an average of 2.5 layers used for calculation.

The net distance between the load L and the foundation pit retaining structure is S. Because of varying excavation depths on either side of the foundation pit, the tunnel's primary section is designated as excavation area 1, with a depth of H1. Level 2, the substructure, defines cut zone 2, depth H2. In this project, the tunnel section's excavation depth is planned at 10.4 m, while the basement's is set at 8.0 m.

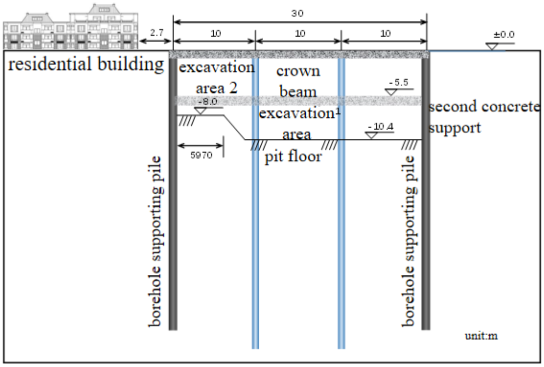


Fig. 2. Physical model of foundation pit excavation

Table 1. Material parameters of foundation pit retaining

material	Section size	densit (kN/m)	Modulus of elasticity (MPa)	poisson
top beam	700×900	25	30	0.2
Two concrete supports	800×900	25	30	0.2
drill hole Pile in situ	ϕ900	25	30	0.2

To enhance computational efficiency and address boundary effects, the model is streamlined and scaled to 5.8 times the foundation pit's dimensions. The model's base is fully fixed, while the left and right edges allow horizontal movement. Figure 3 displays rock and soil masses represented as continuous elements within the framework.

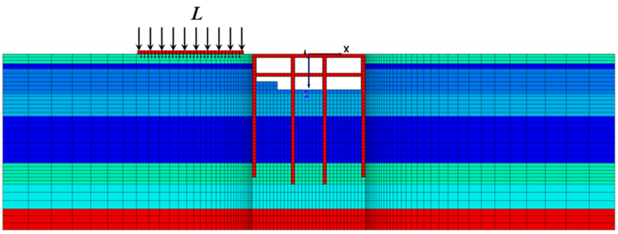


Fig. 3. Numerical model

3.2 Construction Steps and Working Conditions

Based on the actual construction conditions, the numerical simulation is conducted in the following steps:

Step 1, consider the influence of surrounding building loads on the historical ground stress balance. In this stage, the building load L is applied.

Step 2, excavate to -1.0 m and construct the crown beam.

Step 3, excavate to -6.4 m.

Step 4, the second concrete support was constructed, excavated to -8.0 m.

Step 5,digging to the pit's base.

In this numerical simulation, the following conditions are calculated:

Condition 1, $H_1=H_2=8.0$ m.

Condition 2, $H_1=10.4$ m, $H_2=8.0$ m.

Condition 3, $H_1=8.0$ m, $H_2=10.4$ m.

Condition 4, $H_1=8.0$ m, $H_2=12.0$ m.

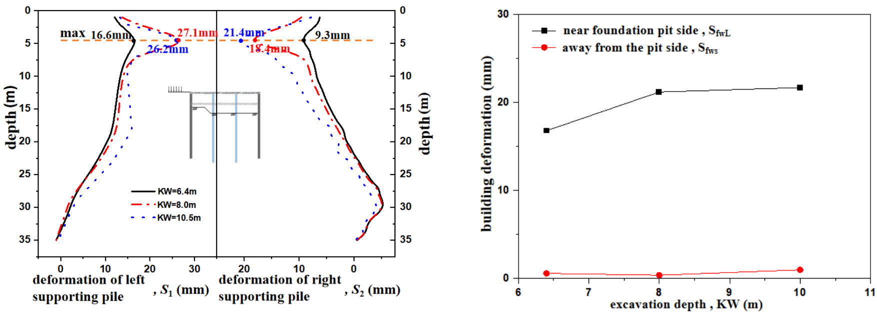
In this paper, numerical simulation analysis is performed for working condition 2, where the distance *S* from the foundation pit is 2.7 m, 5.0 m, 7.5 m, and 10 m.

4 Calculation Results and Analysis

4.1 Analysis of Typical Results During Excavation

Figure 4a illustrates foundation pit wall displacement under anticipated project stress. S1 and S2 in the figure indicate the horizontal movements of the left and right support piles, respectively, whereas KW signifies the depth of excavation. Figure 4a illustrates that pile displacement, measured horizontally during excavation, peaks mid-depth before diminishing. At digging depths KW of 6.4 m and 8.0 m, the foundation pit is actually excavated symmetrically and the deformation of the support piles is approximately symmetrical.As the building's weight biased the foundation pit's west perimeter, westward retaining pile displacement exceeded eastward. As the excavation depth increases further, excavation on the left side ceases, and the deformation curve of the support pile becomes consistent with the deformation curve from the previous excavation level. The right side of the supporting pile was excavated further to 10.4 m, and the deformation of the supporting pile on the right side increased. Delving deeper into the behavior of the supporting pile, Figure 4a illustrates how the maximum deformation is affected. As the excavation gets deeper, we see a corresponding gradual increase in the maximum horizontal displacement on the right-side supporting pile. At a depth of 6.4 m, the maximum horizontal displacement of the right support pile is 9.3 mm.At a depth of 8m, the maximum horizontal displacement of the right support pile is 18.4m. Lateral movement of the left support increases consistently up to an 8.0 m excavation depth. Figure 4a shows a maximum lateral displacement of 16.6 mm in the left support pile at a depth of 6.4 m. Once the excavation hits the 8-meter mark, the left support pile experiences a peak lateral shift of 27.1 mm. Interestingly, when the digging reaches 10.5 meters, this shift actually decreases to a relatively insignificant 26.2 mm. Basically, after digging down 8 meters around the left support piles, it's all hands on deck for excavating the right side of the pit. The leftmost pile's peak lateral displacement showed minimal change. Deeper digging, though, notably worsened the heap's integrity. As excavation deepens in right zone 1, the right supporting pile’s horizontal movement increases, whereas the left pile’s displacement decreases.

Foundation pit excavation alters subsurface soil stresses. Induced subsidence in nearby structures reflects shifts in the stress field. During excavation, the building's settlement deformation is somewhat linked to its horizontal location. Figure 4b displays the trend in corner settlement of buildings relative to excavation depth, comparing proximity to and distance from the foundation pit side. Figure 4b illustrates that greater excavation depths correlated with heightened building foundation displacement on either side.Interestingly, the degree of building settlement (S_{fwS}) varies depending on its proximity to the foundation pit. Structures located farther from the pit experience minimal settlement, while those closer to the edge show a noticeably greater degree of subsidence. This discrepancy highlights the impact of the pit's presence on adjacent buildings. When the excavation reaches a depth of 8.0m and excavation continues on the right side of the foundation pit, the settlement and deformation of the building become more gradual. Based on the available data, it can be concluded that during the foundation pit excavation, the maximum angle of building deformation is 1/1442, which is less than 1/500. This indicates that the impact of foundation pit excavation on the building remains within a safe range.



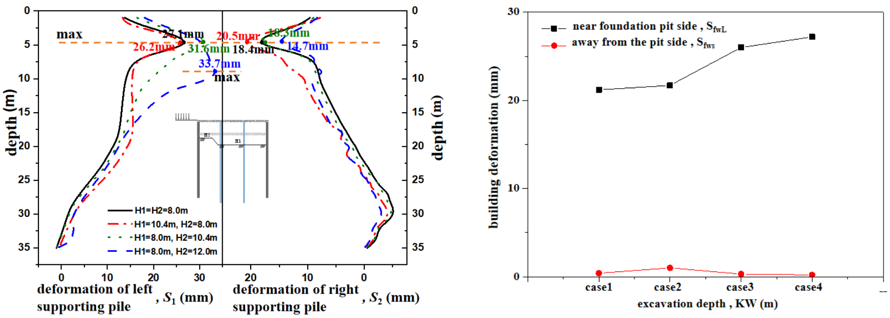
a. Horizontal displacement b. Settlement and deformation

Fig. 4. Horizontal displacement of supporting piles and settlement deformation of buildings around foundation pit during excavation of condition 2

4.2 Analysis of the Impact of Multiple Excavation Depths

Based on the analysis above, it's clear that varying excavation depths in a foundation pit significantly impacts the deformation of support piles and nearby structures, with the depth of each excavated area playing a major role. This study assesses how varying excavation depth configurations affect deformation in support piles and adjacent structures.Figure 5a illustrates the horizontal displacement curves of supporting piles under various working conditions.Figure 5a illustrates that with a symmetrical excavation of the foundation pit to a depth of 8.0m in both excavation zones 1 and 2, the horizontal displacement of the supporting piles mirrors itself on the left and right sides.The left support pile's peak lateral movement reached 27.1 mm, while the right pile's maximum was 18.4 mm. The left supporting pile experiences greater deformation than the right due to building load. With excavation area 2's depth constant and area 1 deepened to 10.4 m, the left support pile exhibits marginally less deformation. Peak lateral deflection reached 26.2 mm at the left pile, and 20.5 mm at the right. The right supporting pile experiences a 11.2% increase in deformation. When the depth of the first excavation zone stays constant while the second excavation zone's depth deepens, there is a notable rise in the horizontal deformation of the left supporting pile. As excavation zone 2 goes deeper, from 8.0 meters to 10.4 and then 12.0 meters, the left support piles showed maximum horizontal displacements of 31.6 mm and 33.7 mm, respectively. We're looking at deformation increases of 16.6% and then 24.3%, respectively, as the depth increases. Concurrently, with Excavation Zone 2 deepened to 12.0 m, the maximum lateral pile deflection shifts lower on the left retaining wall. For the right-side supporting pile, the maximum horizontal displacement to the inside of the foundation pit gradually decreases with the increase of the excavation depth in excavation zone 2. This effect stems from Zone 2's heightened excavation depth disproportionately affecting the left supporting pile nearest the structural burden. The left supporting pile's horizontal movement kicks up quite a bit, and this shift gets passed along to the right supporting pile via the support structure. This, in turn, keeps the right pile from deforming as much into the pit.With increased depth in excavation zone 1, pile deformation differential lessened from 32.2% to 30.4%. As excavation depth in zone 2 grows, pile deformation variance rises from 32.2% to 35.0% and then 56.4%. This indicates that an uneven distribution of load around the multi-excavation depth foundation pit significantly affects the horizontal deformation of the supporting piles, particularly when considering the excavation depth adjacent to the building. Proximity excavation necessitates enhanced safety protocols and oversight adjacent to structures.

Figure 5b displays structure displacement and peak settling values relative to varying trench depths. Figure 5b indicates that distance from the excavation impacts settlement negligibly, irrespective of depth. The settlement of the building near the foundation pit increases slowly under working conditions 1 and 2. In working condition 3, the settlement of the building adjacent to the foundation pit rises considerably. Conversely, under working condition 4, the rate of settlement increase for the nearby building shows a slight decline. This suggests that with a multi-depth foundation pit and an uneven building load, digging further away from the building doesn't have much of an impact. However, excavating closer to the building really makes a difference. According to the known data, the Angle of the building increases from 1/1442 to 1/1167 and 1/1111.



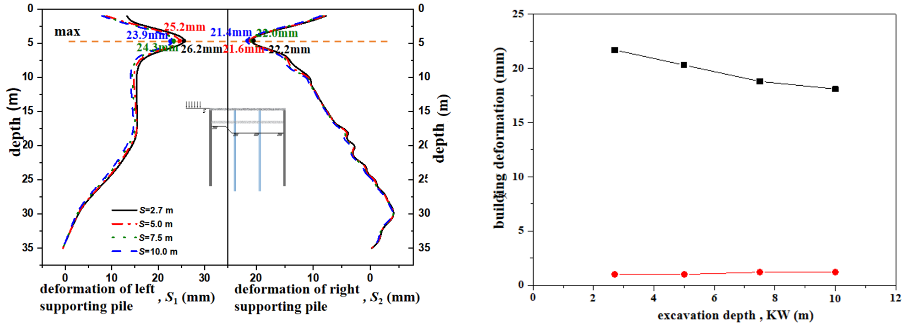
a. Horizontal displacement b. Settlement and deformation

Fig. 5. Horizontal displacement of supporting pile and settlement deformation of building under different depth of foundation pit

4.3 Analysis of the Impact of Building Pit Edge Distance

Figure 6a illustrates supporting pile lateral displacement under a 37.5kPa building load for pit-side distances of 2.7m, 5.0m, 7.5m, and 10.0m. As depicted in Figure 6a, the horizontal movement of the left support pile diminishes as the distance from the building to the foundation pit increases. When the edge distance of the construction pit is 2.7m, the left support pile experiences a maximum horizontal displacement of 26.2mm. As the excavation's boundary extends to 5.0m, 7.5m, and 10.0m, the left retaining pile's peak lateral shift reduces to 25.2mm, 24.3mm, and 23.9mm, respectively. The horizontal displacement of the right support pile into the pit increases slightly. At a distance of 2.7 meters from the construction pit edge, the left support pile experiences a maximum horizontal displacement of 21.4 millimeters. However, as the distance to the edge increases to 5.0 meters, 7.5 meters, and 10.0 meters, this maximum horizontal displacement of the left supporting pile shows a slight increase, measuring 21.6 millimeters, 22.0 millimeters, and 22.2 millimeters respectively. As we can see from the data presented in Figure 6a, the left supporting pile experiences a dip of 8.8% in its maximum horizontal displacement. On the flip side, the right supporting pile, nestled into the pit, shows a 3.7% uptick in its maximum horizontal displacement. As the structure distances itself from the excavation, added stress and displacement within the adjacent soil diminish owing to reduced load influence. Correspondingly, the left supporting pile's horizontal displacement decreases, causing the right supporting pile's horizontal displacement to increase.However, the pit edge distance minimally impacts the far-side building's supporting pile.

Figure 6b displays the building settlement deformation curve at varying distances from the pit edge. Figure 6b illustrates that augmenting a structure's distance from a retaining wall's rim results in a marginal rise in subsidence on the opposing side. The settlement of the building near the foundation pit decreases linearly with the increase of the building pit edge distance. As the distance from the construction pit's edge increases, the rate of decline gradually tapers off. Based on the available data, increasing the distance from the pit results in a gradual decrease in the building's angle, moving from a ratio of approximately 1/1449 to 1/1775.



a. Horizontal displacement b. Settlement and deformation

Fig. 6. Horizontal displacement of supporting pile and settlement deformation of building under different building pit edge distance

5 Conclusion

Using a Wenzhou tunnel foundation pit case study, FLAC3D models the impact of varied excavation depths with asymmetrical loading. This study models deformation in foundation pit supports and adjacent structures. Following the analysis, the conclusions drawn are as follows:

(1) When dealing with foundation pits that have varying excavation depths and an uneven building load on either side, the excavation depth closer to the building really throws a wrench into things. It significantly impacts how much the supporting piles bend horizontally and how much the building settles.Simultaneously, the deeper excavation adjacent to the building leads to a downward shift in the position of maximum horizontal deformation of the supporting pile on that side.

(2) The horizontal displacement of supporting piles near the building side decreases and that away from the building side increases with the increase of pit edge distance. The influence of building pit edge distance is obviously less than that of building load. The building's settlement deformation diminishes as the pit edge distance grows, though the rate of decrease progressively tapers.

The research results will provide reference for similar deep foundation pit support engineering design, excavation scheme design and construction.

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