Inverse Method: Deep Foundation Pit Construction

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ABSTRACT: With the development of urban construction, deep foundation pit projects have been extensively studied. This paper firstly briefly explains the inverse method and then introduces the construction plan and site monitoring plan in a deep foundation pit project in Zhengzhou, Henan Province. The deformation of the surrounding soil of the deep foundation pit was monitored. It was found that the maximum deep horizontal displacement of the foundation pit was 18.39 mm on the north side, 22.98 mm on the south side, 22.67 mm on the east side, and 18.14 mm on the west side; the displacement on the southeast side was larger than that on the northwest side under the influence of the traffic road, and the displacement kept growing with the progress of the construction; the settlement of the surrounding ground surface was between 0 mm and 10 mm; when the soil of the second floor underground started to be excavated, the ground surface settlement accelerated, and the maximum settlement value was - 8.93 mm, which was smaller than the prewarning value. The results verify that the inverse construction method has a small influence on the deformation of the surrounding soil and can be widely applied in actual projects.

KEYWORDS: Inverse method, Deep foundation pit, Soil deformation, Field monitoring, Construction plan.

1. INTRODUCTION

Urban development has further intensified the conflict between people and land; thus, underground space has been further developed (Chen et al., 2020), such as underground parking lots, underground warehouses, and underground subways (Bian et al., 2021). Deep foundation pit engineering has also been developed (Hu, 2017), leading to continuously innovative construction technology (Nelson, 2015). In urban construction, as the project is mostly close to buildings, roads, etc., the complexity is extremely high, and slight negligence will not only affect the project itself but may even endanger other buildings and facilities nearby, causing huge economic losses and even casualties. Therefore, it is necessary to monitor the surrounding soil deformation (Wang, 2021). Deep foundation pit projects have received extensive attention from researchers (Zhao et al., 2015). Collins Williams (2015) monitored the axial force of the reinforced concrete inner support during the construction of deep foundation pits and modeled it using ABAQUS. He found that the sensitivity of the vibrating wire sensor, temperature, and shrinkage of the concrete caused errors between the measured and design values, and the measured values were much larger than the design values. You et al., (2018) studied the drainage scheme of deep foundation pits near the Yangtze River and designed two schemes. They found that the first scheme could meet the dewatering requirements but caused settlement beyond the limit, while the second scheme could control the deformation of the embankment. Zhang et al. (2015) conducted on-site monitoring of the deformation of the surrounding historic preservation buildings after deep foundation pit excavation. They found that the settlement value of the buildings increased with the increase of excavation depth, while soil mixing wall reinforcement and the concrete casting of the bottom slab were beneficial to control building deformation. Lu et al. (2015) monitored the deformation of the support and land in different construction stages of the deep foundation pit. They found that the maximum horizontal displacement appeared at the top of the pit, which provided some references for the scientific construction of similar projects. This paper studied the deformation of the soil around the deep foundation pit under the inverse method and analyzed the buried monitoring points through on-site monitoring to understand the soil deformation at different locations. This work aims to contribute to the further application of the inverse method in the deep foundation pit project.

2. OVERVIEW OF INVERSE EXCAVATION CONSTRUCTION PROJECT

2.1 Inverse Method

The inverse method is a process that uses a top-down sequence for construction (Tang and Zhao, 2016), which supports the foundation pit with the help of the basement floor structure. During construction, the underground diaphragm wall is completed first, and then the beam-slab structure of the first floor is constructed, followed by downward layer-by-layer excavation under the ground and the construction of floor slabs.

Compared with other processes, it shortens the construction period, reduces the cost, and greatly reduces the amount of excavation and transportation of earth, will not cause hazards due to blasting vibration or support unloading, and avoids weathering and collapse caused by long-time exposure (Weng et al., 2016). In addition, its form of underground closed operation also effectively reduces dust and controls the construction noise and the influence on ground traffic.

2.2 Project Overview

A deep foundation pit project in Zhengzhou, Henan Province, used the total inverse construction method. The project covered 7800 m^2 and had a total area of 47000 m^2. The foundation pit was 76 m long from north to south and 86 m long from east to west and had an excavation area of 6580 m^2 and a depth of 12.78 m. The surrounding environment of the foundation pit is shown in Figure 1.

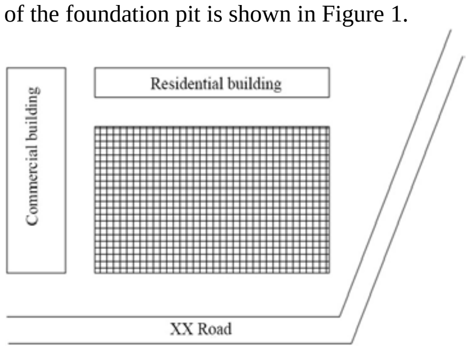

Figure 1 The surrounding environment of the deep foundation pit project

The construction site was nearly flat. The buried depth of the bedrock was about 25 m, and the upper part of the bedrock was mainly clayey soil. The specific soils at different layers are shown in Table 1.

Table 1 Distribution of soil layers

Sequence number of stratum	**Lithologic character**	**Color**	**Layer thickness/m**	**Specific weight/(kN/m^3)**	**Cohesive force/kpa**	**Internal friction angle/°**
1	Miscellaneous fill	/	1.32	18	0	12
2	Silty soil	Mixed	1.97	18	23	14
3	Silty clay	Auburnish yellow ~ yellowish gray	2.98	19	46	16
4	Silt	Greyish white	5.46	18	11	15
5	Silty-fine sand	Auburnish yellow ~ brownish yellow	6.71	17	16	15
6	Silty clay	Gray black ~ black	4.12	19	46	16
7	Strongly weathered muddy sandstone	Brownish red	4.83	23	200	27
8	Medium-weathered muddy sandstone	Brownish red	2.71	25	400	25

In the project, the enclosure structure was an underground diaphragm wall, the structural floor slab was laterally supported, and the intermediate pile foundation was a bored pile. The project was divided into six phases, and one of the phases is shown in Figure 2.

The six phases are as follows.

Phase 1: excavation of soil above the top slab
Phase 2: structural construction of top slab
Phase 3: soil excavation of the first-floor underground
Phase 4: structural construction of the first-floor underground
Phase 5: soil excavation of the second-floor underground
Phase 6: construction of bottom slab structure and remaining parts

Figure 2 The project construction process

2.3 On-site Monitoring Program

Due to the complexity of the environment and the limitations of the model, the results of the theoretical calculation often differ from the actual situation, which makes it difficult to judge the problems that may be encountered during construction and cannot accurately reflect the changes in the project; therefore, the on-site monitoring of the project is particularly important (Wang et al., 2019). It is necessary to determine a good monitoring plan, arrange the measurement points and determine the alert value according to the construction plan before the construction. This paper mainly studied the soil deformation around the foundation pit. The arranged measurement points included the deep horizontal displacement measurement points at the foundation pit and the surrounding surface settlement measurement points, as shown in Figure 3.

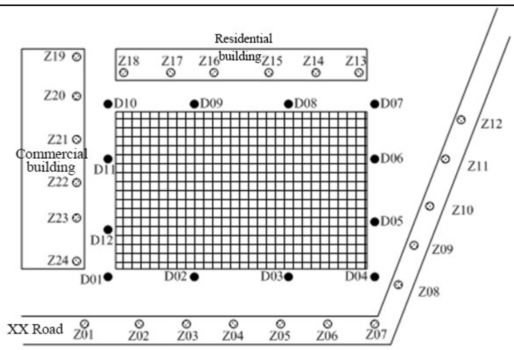

Figure 3 The layout of on-site monitoring points

As shown in Figure 3, D01-D12 are the deep horizontal displacement measurement points, and Z01-Z24 are the surrounding surface settlement measurement points. The specific monitoring scheme is as follows.

(1) Deep horizontal displacement monitoring: before excavation, inclinometer tubes were buried inside the enclosure structure. They were placed vertically, with the bottoms sealed and the mouths closed with bricks for protection. Monitoring started three or four days later. An early warning was given when the daily change reached 3 mm, or the cumulative change reached 60 mm.
(2) Surrounding surface settlement monitoring: rigid measurement points were implanted around the foundation pit, fixed with concrete, protected by bricklaying, and covered with protective caps to avoid damage. An early warning was given when the daily change reached 3mm, or the cumulative change reached 50 mm.

3. SOIL DEFORMATION ANALYSIS

3.1 Deep Horizontal Displacement Analysis

During the construction of the enclosure, the maximum horizontal displacement of every inclinometer tube is shown in Table 2.

Table 2 Maximum horizontal displacement of deep soil body

Number of inclinometer tube	**Maximum horizontal displacement/mm**	**Distance from the surface/m**
D01	22.07	3.3
D02	22.98	4.5
D03	18.64	3.7
D04	17.36	3.1
D05	18.14	3.5
D06	17.64	4.2
D07	15.67	4.1
D08	16.78	4.0
D09	17.84	4.5
D10	18.39	3.7
D11	22.45	4.9
D12	22.67	4.9

It was seen from Table 2 that the maximum horizontal displacement of the north side of the pit was 15.67-18.39 mm, the south side was 17.36-22.98 mm, which was larger than the north side, the east side was 22.67 mm, and the west side was 18.14 mm. Specifically, the southeast side of the pit was close to the traffic road, and the traffic flow of this road was large, so that the traffic load may have been influenced; the north side was a residential building, and the west side was a commercial building, which brought relatively small pressure to the soil. In addition, the north-south side of the pit was long, and the east-west side was short. Therefore, the maximum horizontal displacement of the north-south side was also greater than the east-west side. Then, in terms of the distance from the surface, in the internal corner area, such as D01 and D04, the corresponding depth was around 3-4 m from the surface, while in the middle area, such as D08 and D09, the corresponding depth was around 4-5 m.

The cumulative displacement variation of the inclinometer tubes with the construction progress is shown in Figures 4 and 5.

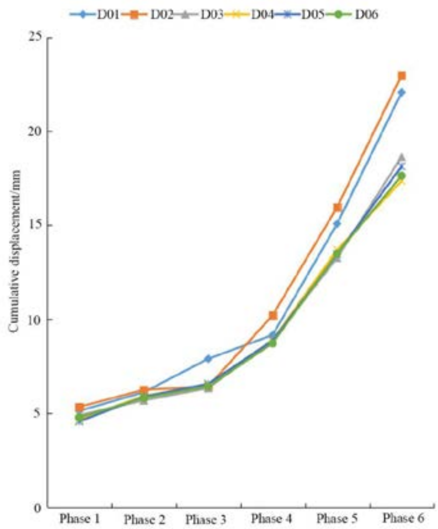

Figure 4 Cumulative displacement of D01-D06

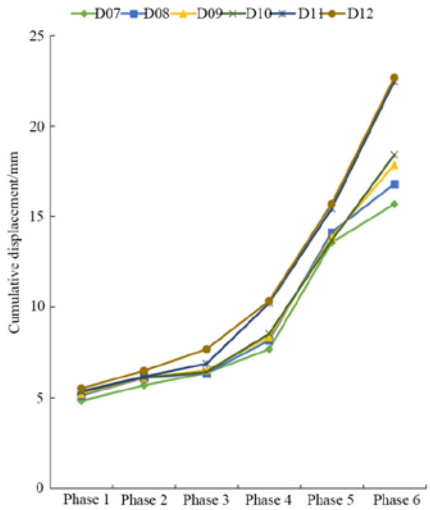

Figure 5 Cumulative displacement of D07-D12

It was seen from Figures 4 and 5 that with the progress of the construction, the displacement of the inclinometer tubes also increased, but none of them exceeded the control range, and the early warning value was 60 mm; the maximum cumulative displacement of the inclinometer tubes was smaller than 25 mm. Specifically, in phases 1, 2, and 3, the deep horizontal displacement was small, and the cumulative displacement was smaller than 10 mm; in phases 4, 5, and 6, the development of displacement was rapid, and the exposure time of deep soil increased with the increase of the excavation depth, which accelerated the soil deformation.

3.2 Surrounding Surface Settlement Analysis

The excavation of a foundation pit will cause the settlement of the surrounding ground surface, thus causing the settlement of buildings. According to the monitoring results, the values of surface settlement around the foundation pit were small, between 1 mm and 10 mm, which were smaller than the early warning values. The largest surface settlement appeared in Z04 and Z08, one was located in the midpoint of the foundation pit, and one was located in the internal corner of the foundation pit, and the settlement changes of these two points were specifically analyzed, as shown in Figure 6.

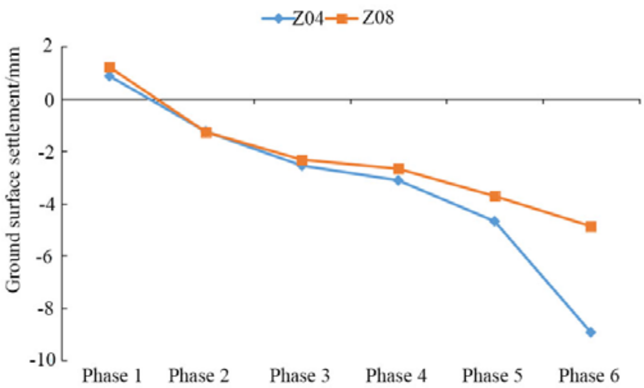

Figure 6 Analysis of surface settlement changes in Z04 and Z08

It was seen from Figure 6 that as the excavation depth of the foundation pit increased, the settlement value of the surrounding ground surface also increased; due to the extrusion of the fender posts and the surrounding soil body, ground heave appeared. The settlement value of Z04 was greater than that of Z08, the maximum settlement value of Z04 was -8.93 mm, and the maximum settlement value of Z08 was -4.87 mm. In addition, in the early stage of the project, the change of the surrounding ground surface settlement was relatively slow; however, after phase 5, the settlement value of the ground surface showed a rapid increase. The rapid increase was because the lateral pressure of the surrounding soil on the supporting structure increased as the exposure time of the foundation pit grew, which caused the rheological effect of the soil.

4. DISCUSSION

The construction of many projects in cities is located in areas with dense buildings, which often brings about effects such as soil deformation and ground settlement. It is necessary to monitor these changes in order to ensure the safety of construction. This paper studied the construction of deep foundation pits and carried out on-site monitoring of a deep foundation pit project using the inverse method.

It was found from the change of deep horizontal displacement that the maximum horizontal displacement of the south and east sides of this deep foundation pit project was higher during the construction of the enclosure structure, reaching 22.98 mm and 22.67 mm, respectively. According to the actual situation of the site, there was a traffic road with high traffic flow on the southeast side of the project, resulting in more pressure on the soil on the east and south sides and more significant displacement. Then, when the construction entered phase 4, the development of displacement was faster; from phase 1 to phase 3, the displacement developed from about 5 mm to about 7 mm, and from phase 4 to phase 6, the displacement developed from about 10 mm to about 20 mm, which may be because the deepened excavation of soil led to the long time exposure of deep soil, thus accelerating the soil deformation.

The results of the surrounding surface settlement analysis demonstrated that the overall settlement value of the foundation pit was small, and the maximum settlement value appeared in Z04 and Z08. It was seen from Figure 6 that the change of surface settlement was more obvious in the later stage of the project, and in phase 6, the maximum settlement value of Z04 reached -8.93 mm, and the maximum settlement value of Z08 reached -4.87 mm. However, in general, the deep horizontal displacement and surrounding surface settlement were less than the early warning values, which indicated that the use of the inverse excavation method in deep foundation pit projects had good safety.

5. CONCLUSIONS

This paper studied a deep foundation pit project in Zhengzhou, Henan Province, China, which adopted the inverse method, and analyzed the impact of the inverse excavation construction on the deformation of the surrounding soil by arranging on-site measurement points. The results are as follows.

(1) The deep horizontal displacements of the foundation pit were all below 25 mm, which was smaller than the early warning values.
(2) The maximum horizontal displacement occurred at the southeast side of the pit, which was influenced by the traffic road.
(3) The maximum value of deep horizontal displacement was 22.98 mm.
(4) The value of the surrounding surface settlement was between 1 mm and 10 mm, which was smaller than the early warning value.
(5) When the excavation of the second floor underground started, the change of surface settlement became fast.

The results showed that the impact of inverse excavation on the surrounding soil deformation was small, which verified the advantages of the inverse method in deep foundation pit projects. This work contributes to the further promotion and application of the inverse method.

6. ACKNOWLEDGEMENT

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