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Deformation characteristics of large-scale deep foundation pit in Nanjing floodplain area

Caractéristiques de déformation de la fosse de fondation profonde à grande échelle dans la plaine inondable de Nanjing

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ABSTRACT: The presence of soft soils in coastal areas has led to the emergence of large-scale deep foundation pits in those regions. The complex and sensitive nature of soft soil poses challenges to control the deformation of a large-scale deep foundation pit. A comprehensive understanding of the deformation characteristics of large-scale deep foundation pit in soft soil areas plays an important role in risk assessment, foundation pit design, and construction. The influence of soft soil thickness on the deformation of the foundation pits was discussed based on the data collected from 24 large-scale deep foundation pits in the Nanjing floodplain area. The characteristics of ground settlement around the foundation pit, soil settlement near retaining walls, and horizontal displacement of retaining structure were summarized and discussed. Moreover, the prediction curve for the ground settlement based upon the excavation depth of a large-scale deep foundation pit in the floodplain area was obtained as part of this study. Furthermore, the influence zones of the foundation pit were established to safeguard the surrounding underground structures and roads.
KEYWORDS: foundation pits; deformation characteristics; soft soil; floodplain; areas

1 INTRODUCTION

With the acceleration of urbanization in the past decade, construction agencies have to make effective use of existing land resources to meet the increasing demands for infrastructure in China. Infrastructure construction in coastal regions can expand the scope of urbanization and relieve the increasing demands for infrastructures (Sengupta et al. 2018). More and more large-sized deep foundation pits have been adopted in constructing infrastructure projects located in coastal areas. However, the sensitive geological conditions of soft soil areas and complicated surrounding environments bring challenges to the design and deformation control of foundation pit (Mindel et al. 2015; Shen et al. 2014). The extensive distribution of soft soils in the floodplain regions of the Yangtze River are characterized by their low shear strength, high compressibility, high moisture content, and small osmotic coefficient, which pose challenges to engineering construction (Cai et al. 2017; Ding et al. 2019). In addition, dense urban buildings and underground pipelines as well as crossing roads further increase difficulties in controlling soil deformation around large foundation pits in soft soil strata. The frequent occurrences of accidents during the excavation of the foundation pit can be explained by buckling and failure of the supporting system of foundation pits, and environmental effects of excavation of foundation pit. Therefore, designers and constructors have to fully understand the deformation laws of foundation pit projects to control foundation pit deformation to assure the safety of the supporting system and surrounding environment of deep foundation pits (Tan et al. 2020).

Although foundation pit projects in different soft soil areas have similar sizes or shapes, the deformation laws might differ significantly due to regional differences caused by the soil strata and the surrounding environment. Since the foundation pit project has a strong regional characteristic and high risks, design and construction experiences are very important for consideration during the execution of those projects. It is very necessary to summarize the deformation characteristics of foundation pit projects in typical regions (Tan and Wang 2013; Chen et al. 2015; Zeng et al. 2019; Cui et al. 2016). Although influences of thickness of soft soil layer on the deformation of foundation pit, surface settlement characteristics, and distribution pattern surrounding the pits as well as deformation characteristics of envelop enclosures have been analyzed, these regions present unique deformation characteristics, which are related to local soft soil layers. Only a few studies have summarized deformation characteristics of soft soil foundation pits in floodplain areas in Nanjing (Di et al. 2016; Xia et al. 2006; Zhou et al. 2016). Moreover, these studies only analyzed deformation features of foundation pits.

Based on 24 soft soil foundation pit projects in floodplain areas of Yangtze River in Nanjing, this study introduced hydrogeological conditions and analyzed deformation characteristics in the study area, including influences of thickness of soft soil layer on the deformation of foundation pits, surrounding surface settlement characteristics, and distribution characteristics as well as deformation characteristics of envelop enclosures. The outcomes of the current study can provide references to the design and construction of soft soil foundation pit projects in floodplain areas of rivers.

2 ENGINEERING BACKGROUND OF FOUNDATION PIT IN FLOODPLAIN AREAS IN NANJING

There are dense municipal pipelines, crossing roads, and buildings in the study area, which warrant high requirements on construction environmental control and protection for foundation pit projects. The formation of stratigraphic sedimentary in the study area is closely related to the shifting of river channels. Soil sediments are mainly composed of floodplain-phase fine sediments and coarse riverbed sediments. The deep and thick sludge layer also contains silts. In this study, engineering data of 24 soft soil foundation pits in the study area was applied to analyze deformation characteristics.

Soil parameter indices of typical strata in the study area are provided in Table 1. Muddy soil has a relatively high porosity ratio, high moisture content, small osmotic coefficient, and a large difference with the osmotic coefficient of the underlying sandy soil layer (Cai et al. 2017). These characteristics of muddy soil determine the support type and dewatering mode of the foundation pit. Engineering details of some foundation pits in the study area are listed in Table 2. With the increase in excavation depth of foundation pits, the lateral pressure over the retaining structure increases accordingly, and the cantilever support cannot prevent foundation pit deformation any more. Cast-in-place concrete support is a common supporting structure for foundation pits in soft soil areas. It has characteristics of high rigidity, good integrity, flexible layout, ensuring construction quality, and applicability to many types of soft soil foundation pits with irregular plane shapes. In the study area, common supporting structures of foundation pit include soil nailing support, gravity-type barricade, cantilever support with cast-in-situ bored piles, cantilever support with manual hole digging piles, bored pile plus concrete support, digging pile plus steel support, combined support, SMW construction method, and underground continuous wall.

Table 1 Soil parameter indices of typical strata in floodplain areas of Nanjing

Type of soil layer	Void ratio	Water content (%)	Unit weight (kN/m^3)	Cohesion (kPa)	Friction angle (°)	Vertical permeability coefficient (cm/s)	Horizontal permeability coefficient (cm/s)
Plain fill	0.75-0.90	20-32	18.5-20	5-8	10-12	1-1×10^{-4}	1-1×10^{-4}
Muddy silty clay	1.02-1.30	37.5-47.4	16.8-18.1	8.0-14.7	15-18	1-3×10^{-6}	1-5×10^{-6}
Silty clay	0.75-0.95	30-37.4	18-18.5	27-33	18-20	1-5×10^{-5}	2-8×10^{-5}
Silty sand and fine sand	0.75-0.75	25.4-34.6	18.5-20.5	3-6.8	30-34.9	1-2×10^{-3}	2-3×10^{-3}

Table 2 Engineering details of some of the foundation pits in floodplain areas of Nanjing

List of projects	Type of support	Excavation depth of foundation pit (m)
Nanjing Lunegn project	Soil nailing wall, gravity retaining wall	7.0
Nanjing Haixia project	Soil nailing wall, gravity retaining wall	4.7
Primary School project	Soil nailing wall, cantilever support	6.5
Nanjing G45 project	SMW piles, a reinforced concrete support	10.5
Yanshan Road project	SMW piles, a reinforced concrete support	9.5
Nanhu Stadium project	Bored pile, a reinforced concrete support	8.8
Jiangdongmen Community Center project	Bored pile, a reinforced concrete support	8.5
Zijing project	Bored pile, three reinforced concrete supports	18.5
Gulou District State Assets Center project	Bored pile, three reinforced concrete supports	18.5
Jinrongchegn project	Diaphragm wall, four reinforced concrete supports	23.5

The phreatic layer in the study area exists in the near-surface fill stratum and belongs to an aquitard. Water supplementary sources at about 1m below surface mainly include atmospheric precipitation and domestic water. The water level is sensitive to seasonal changes. Specifically, there is a high water level during rainy seasons and the maximum annual variation amplitude reaches 1m. The phreatic layer influences construction of the foundation pit slightly. The sand layer is the confined water-bearing aquifer in the study area, which contains the silty-fine sand and middle-coarse sand mixed with cobbles and gravels. There are significant differences among confined water aquifers in terms of permeability and their ability to bear micropressure. The silty clay mixed with silt has weak permeability and it can be used as a water-proof roof. However, both foundation pit design and construction in floodplain areas shall consider the fact that silty-fine sands in the water-proof roof might form connected hydraulic channels with the sand layer, thus resulting in piping problems.

3 ANALYSIS OF DEFORMATION CHARACTERISTICS OF FOUNDATION PITS IN FLOODPLAIN AREAS IN NANJING

Deformation laws of foundation pits in the study area were summarized by a thorough investigation of 24 foundation pits and statistical analysis of monitoring data.

3.1 *Effects of the thickness of soft soil layer on the surface settlement around the foundation pit*

The soft soil layers in the floodplain areas can affect the surrounding surface settlement of the foundation pit to some extent. The soft soil thickness in this study was defined as the sum of the thickness of the silty clay and the silty clay mixed with the silty soil layer above the barricade. Due to differences of depth, barricade depth, and thickness of soft soil layer among different foundation pits, the thickness of soft soil layer and surrounding surface settlement of pits have to be redefined, which were considered as the normalized thickness of soft soil (h_s/H_w) and normalized surrounding surface settlement of pits (δ_{vm}/H) (Tan and Wang 2013). In these two expressions, h_s is the thickness of the soft soil layer above the barricade bottom, H_w is the depth of barricade, δ_{vm} is the maximum surrounding surface settlement of pits, and H is the excavation depth of the foundation pit. The relationship between the normalized thickness of soft soil and normalized maximum surface settlement behind the barricade is shown in Figure 1. It can be observed that the overall growth trends are consistent although data points are relatively scattered around. The maximum surface settlement is positively related to the thickness of the soft soil layer. About 86% of data fluctuates between straight lines y1 and y2 and the shadow areas are the main distribution zones of the relationship between surface settlement behind barricade and thickness of soft soil in the study area.

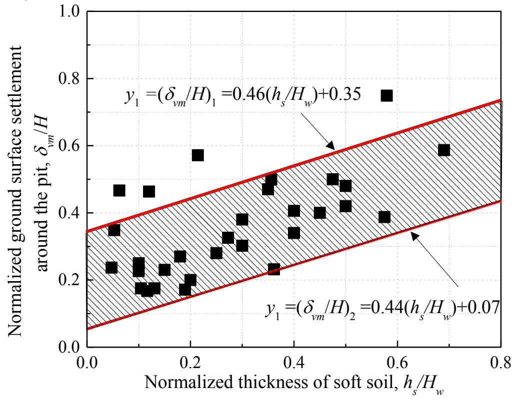

Figure 1 Relations between the thickness of soft soils and maximum settlement

3.2 *Surrounding surface settlement characteristics and distribution pattern of foundation pits*

Based on the data statistics related to soft soil foundation pits, Peck (1969) reported that the maximum surface settlement around the foundation pit (δ_{vm}) is higher than 1% of H. However, Wong et al. (2002) conducted statistical analysis on the foundation pit in Singapore and concluded that the mean δ_{vm} is 0.24%H. The relationship between the maximum surrounding surface settlement of the foundation pit (δ_{vm}) and excavation depth (H) in the study area is shown in Figure 2. With the increase in excavation depth of foundation pits, the maximum surrounding surface settlement increases gradually, up to 0.7%H. The mean δ_{vm} is found to be 0.38%H. When the excavation depth exceeds 17m, δ_{vm} drops suddenly to about 25mm. This is mainly because the foundation pit applies the combination of bottom continuous walls and four reinforced concrete supports to stabilize the foundation pit and decreases the surrounding surface settlement.

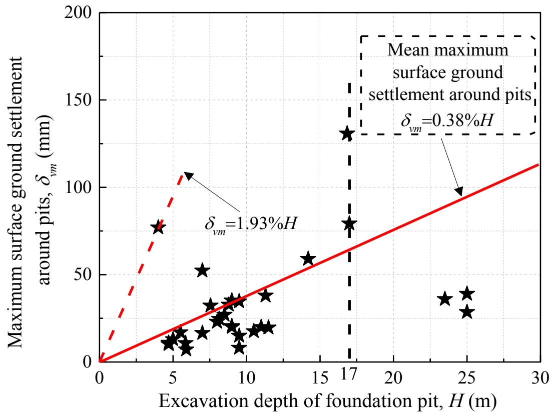

Figure 2 Relationship between maximum surrounding surface settlement (δ_{vm}) and excavation depth (H) of foundation pits

The surface settlement distribution around foundation pits is shown in Figure 3. The x-coordinate refers to the ratio between the horizontal distance to the foundation pit (x) and excavation depth (H) of the foundation pit, while the y-coordinate refers to the ratio between the surrounding surface settlement at different positions (δ_v) and excavation depth (H) of foundation pit. The Peck curve zoning is shown in Fig.7. According to soil layer conditions, the settlement curve divides data into Zone I, Zone II, and Zone III. Zone I represents the surface settlement around the foundation pit in sandy soil, hard clay, and soft clay conditions. Zone II represents the surface settlement around the foundation pit in soft clay and extremely soft clay conditions. Zone III represents the surface settlement around the foundation pit in relatively deep and thick soft clay and extremely soft clay conditions. Obviously, most of the practical monitoring data of δ_v in the study area concentrates in Zone I. Therefore, a prediction curve of surface settlement around the foundation pit in the study area was set up and expressed using an exponential function:

$$\delta_v/H=-0.105+1.221e^{-0.687x/H} \quad (1)$$

In addition, it can be seen from the distribution of surface settlement around the foundation pit in the study area that surface settlement of local foundation pits is smaller than that of the soft soil layer in Peck statistics. This reveals that the row of piles and underground continuous walls can decrease surface settlement around the foundation pit effectively compared to steel sheet piles. Soft soil foundation pits with an excavation depth lower than 15m in the study area generally adopt the combination of bored piles and inner support, underground continuous wall support and new cement stirring mixed wall (SMW) method. These supporting structures have relatively higher integral rigidity and can decrease surface settlement around the foundation pit more compared to flexible supporting structures like steel sheet piles. According to data statistics, the maximum sphere of influence of surface settlement around the foundation pit in the study area is about 3.5H.

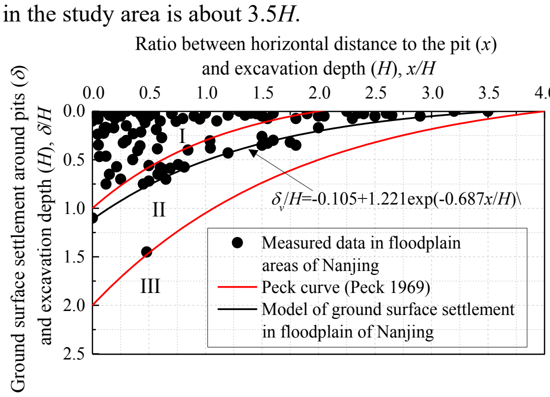

Figure 3 Surrounding surface settlement distribution of foundation pits

3.3 *Deformation characteristics of envelop enclosure*

The relationship between maximum horizontal displacement (δ_{hm}) of envelop enclosure and excavation depth of foundation pit (H) is shown in Figure 4. It can be observed that the monitoring data distributed between δ_{hm1}=0.15%H and δ_{hm2}=0.58%H. When the excavation depth is smaller than 18m, δ_{hm} is positively related to excavation depth. However, δ_{hm} is relatively small (about 35.5mm) when the excavation depth is higher than 18m. This is mainly attributed to the strong deformation constraint of the combination of underground continuous wall and four lines of reinforced concrete structures. According to statistical analysis, the mean maximum horizontal displacement of envelop enclosure of foundation pits in the study area is 0.23%H. Similar results of horizontal displacement of supporting structure were obtained in the soft clay foundation pits in Masuda, Japan, which values 0.3%H. In addition, other scholars have obtained different statistical results, such as 0.1%*H*-0.15%*H*, 0.16%H, 0.48%H, and 0.40%H.

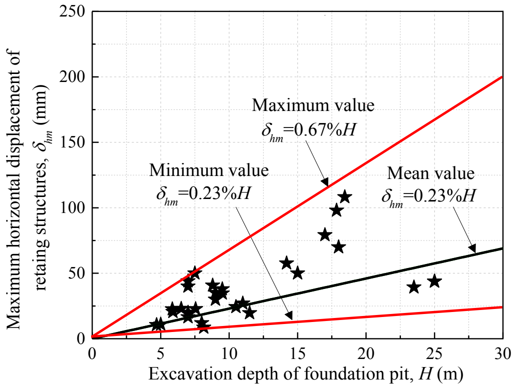

Figure 4. Relationship between maximum horizontal displacement (δ_{hm}) of envelop enclosure and excavation depth (H) of foundation pits

5 CONCLUSIONS

(1) Various supporting types for typical soft soil foundation pits and hydrogeological conditions of the study area are summarized thoroughly.

(2) The maximum surface settlement around the foundation pit, the maximum horizontal displacement of supporting structure, and maximum buried depth of walls are positively related to the thickness of soft soil layers.

(3) The average maximum surface settlement of soft soil foundation pits in the study area is 0.38%H. Besides, the distribution pattern of the surface settlement around the foundation pit in the study area is provided. The maximum sphere of influence of surface settlement is about 3.5H and the average maximum horizontal displacement of envelop enclosure is 0.23%H.

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