



Deformation characteristics and control for foundation pits in floodplain areas of Nanjing, China

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Abstract

A comprehensive understanding of deformation characteristics and control measures for large-scale foundation pits in soft soil regions is of increasing importance to their risk assessment, design, and construction. In this study, the influences of the thickness of soft soil on the deformation of foundation pits are discussed based on statistical data from 24 foundation pits in floodplain areas of Nanjing, China. The mean maximum ground surface settlement around the pit in floodplain areas of Nanjing was $0.38\%H$, and the maximum ground surface settlement was observed at $0.48H$. The maximum influence scope of ground surface settlement was about $3.5H$, and the average maximum horizontal displacement of supporting structures was $0.23\%H$. On this basis, a model of ground surface settlement around the pit according to excavation depth for foundation pits in floodplain areas is derived. In addition, the influence scope around the pit and relevant control measures are proposed for the protection of surrounding underground structures and roads.

Keywords Foundation pits · Deformation characteristics · Control measures · Soft soil · Floodplain areas

Introduction

With the acceleration of urbanization and demand for infrastructure in China over the past decade, construction units are being required to make use of existing land resources more effectively (Lin et al. 2021a; Qiu 2020). Infrastructure construction in coastal regions is a potential solution (Sengupta et al. 2018). Increasing numbers of large-scale foundation pits are being constructed for infrastructure in coastal areas (Luo et al. 2015; Wu et al. 2015a). However, these areas have

sensitive geological conditions due to soft soils and complex surrounding environments, which create challenges for the design and deformation control of foundation pits (Gaone et al. 2018; Mindel et al. 2015; Shen et al. 2014). Soft soils are extensively distributed in the Yangtze River floodplain regions and have the characteristics of low shear strength, high compressibility, high moisture content, and low permeability coefficient, which are problematic for engineering projects (Almeida et al. 2013; Cai et al. 2017; Ding et al. 2019). In addition, dense urban buildings, underground pipelines, and crossing roads further increase the difficulty of controlling the deformation of soil around the pit made in soft soil strata (Wu et al. 2015b). Frequent accidents occur during the excavation of foundation pits, which have two main sources: (1) buckling and failure of the foundation pit's supporting system (Tan et al. 2020) and (2) the environmental effects of pit excavation, including ground surface settlement and deformation of adjacent buildings or structures (Tan et al. 2020). During excavation, a number of accidents can occur. Moreover, it has a serious social impact and leads to economic losses (Lin et al. 2021b). In July 2005, the collapse of a deep excavation caused by improper management resulted in three deaths and four injuries (Chen et al. 2006). In September 2008, a large-scale deep excavation collapse at Xianghu station on Hangzhou Metro Line 2 resulted in 21 deaths, 24 injuries, and 49.61

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million CNY in direct economic losses (Chen et al. 2015). In June 2019, a foundation pit collapse on Dongge Road, Nanning, Guangxi damaged a nearby road (Chin et al. 2019). Therefore, designers and constructors must fully understand the deformation characteristics of foundation pit projects and implement detailed mitigation measures to assure the safety of the supporting system and the surrounding environment.

Foundation pit deformation can differ significantly due to regional differences in strata and the surrounding environment (Wang et al. 2018). Since foundation pit projects have very strong regional characteristics and high risks, design and construction experience is critical. It is essential to summarize the deformation characteristics of foundation pit projects according to the region and define corresponding control measures. The main soft soil areas relevant to foundation pit projects in China are concentrated in Shanghai (Shen et al. 2014; Tan and Wang 2013a, 2013b; Zhou et al. 2010), Hangzhou (Chen et al. 2015; Lin et al. 2020), Tianjin (Wu et al. 2019; Zeng et al. 2019), Fuzhou (Yang and Kong 2020), Guangzhou (Elbaz et al. 2018), and Shenzhen (Cui et al. 2018; Huang et al. 2020). Researchers have studied the influence of thickness of soft soil on foundation pit deformation and ground surface settlement around the pit characteristics and distributions, as well as the deformation characteristics of supporting structures (Shen et al. 2014; Tan and Wang 2013a, 2013b; Yang and Kong 2020; Yang and Liu 2017). However, different regions present unique deformation characteristics related to the local soft soil layers. Only a few studies have examined deformation characteristics in floodplain areas of Nanjing (Di et al. 2016; Xia et al. 2006; Zhou et al. 2016). Moreover, these studies have only analyzed the deformation features of single foundation pit and have not proposed detailed mitigation measures. Hence, it is essential to investigate the statistical deformation characteristics of foundation pits and propose relevant mitigation measures for soft soil strata in floodplain areas of the Yangtze River in Nanjing.

Mitigation measures may include control of settlement in the surrounding area, deformation of the supporting structure, and bottom heaves (Ahmad et al. 2019; Di et al. 2019; Ding et al. 2018; Kazantsev and Kochneva 2017; Xu et al. 2018; Zhou et al. 2010). However, such measures must be chosen according to the deformation responses of different types of pipelines and roads. Recently, foundation pit deformation control and optimization measures have attracted increasing attention. Wang et al. (2012) controlled settlement due to dewatering of buildings surrounding a foundation pit by combining barricade curtains and inverted wells. Xu et al. (2016) reported that it is much more challenging to control the deformation of a foundation pit supporting structure with a two-level support than one with a three-level support. Zhou et al. (2010) applied an underground continuous concrete wall as a waterproof curtain to relieve dewatering-induced deformation

of a foundation pit. Other measures used to relieve soil compression and ground surface settlement due to dewatering include deep cement mixing piles (Chen et al. 2013; Huang and Han 2009; Yamashita et al. 2018), diaphragm walls (Tan and Wang 2013a; Waichita et al. 2019; Yamashita et al. 2016), jet grouting piles (Njock et al. 2018; Thiyyakkandi et al. 2017; Wang et al. 2013), steel sheet piles (Kimura et al. 2007; Underwood 2020), and artificial recharge (Hussain et al. 2019; Khosravi et al. 2018; Zhang et al. 2017). Such measures focus on the deformation characteristics of foundation pits; however, no studies have thoroughly elaborated construction control, dewatering control, and pipeline and road protection measures. Good control measures will decrease safety risks while increasing the stability of foundation pits.

This study used data from 24 soft soil foundation pit projects in Yangtze River floodplain areas to analyze hydrogeological conditions and deformation characteristics. Specifically, we looked at the influences of the thickness of the soft soil on foundation pit deformation, ground surface settlement around the pit characteristics, and distribution characteristics, as well as the deformation characteristics of supporting structures. Finally, measures to control foundation pit deformation in floodplain areas of Nanjing are proposed. The results provide a guidance for the design and construction of soft soil foundation pits in river floodplain areas.

Foundation pit engineering background in floodplain areas of Nanjing

There are dense municipal pipelines, crossing roads, and buildings in floodplain areas of Nanjing, which create high requirements for construction-related environmental control and protection measures for foundation pit projects. The sedimentary stratigraphy in floodplain areas of Nanjing is closely related to the shifting of river channels, i.e., the complex stratigraphic belt formed by ancient river and lake. Soil deposition is a typical “dual sediment” structure. Soil sediments are mainly composed of floodplain-phase fine sediments and coarse riverbed sediments. A deep, thick sludge layer also contains silty sands. In this study, engineering data from 24 soft soil foundation pits in floodplain areas of Nanjing were used to analyze deformation characteristics and deformation control measures. The geographical location of soft soil foundation pits in floodplain areas of Nanjing is shown in Fig. 1.

Foundation pit support types

Soil parameter indexes of typical strata in floodplain areas of Nanjing are shown in Table 1. These data were obtained from the laboratory and field tests, such as the piezocone penetration test, triaxial test, water content test, and consolidation test. Obviously, muddy soil has a relatively high porosity ratio,

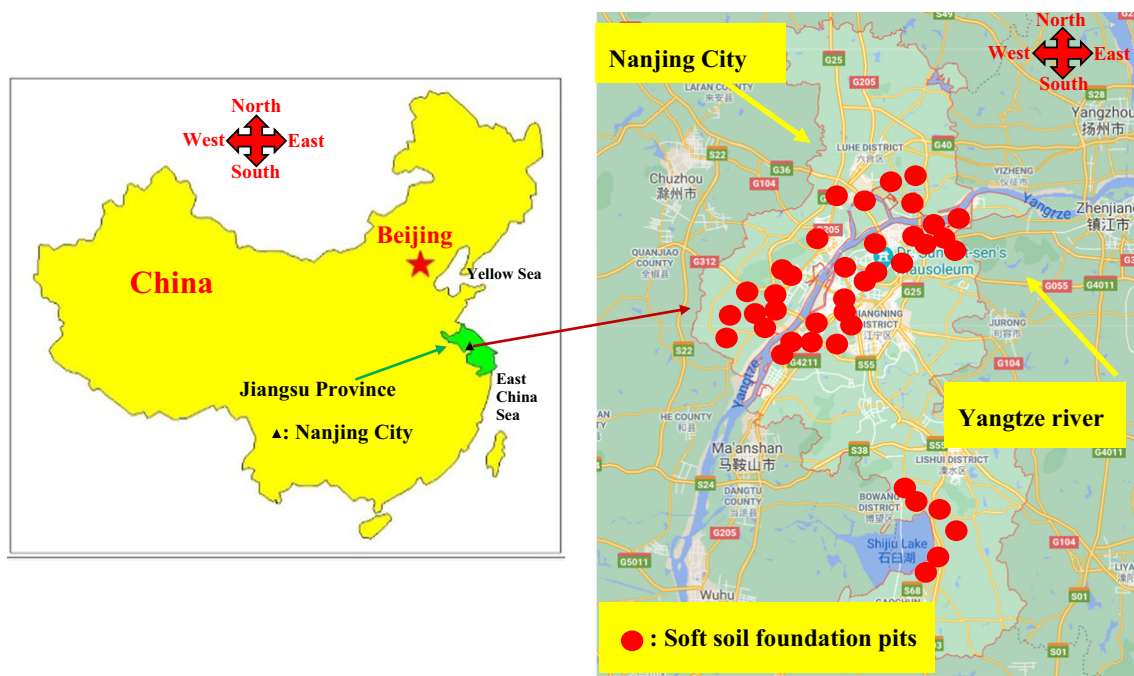


Fig. 1 Geographical location of soft soil foundation pits in floodplain areas of Nanjing

high moisture content, and small permeability coefficient (Cai et al. 2017). The permeability coefficient is greatly different from that of the underlying sandy soil layer. These characteristics of muddy soil determine the appropriate foundation pit support type and dewatering mode. Selection of the supporting structures is closely related to the surrounding environment, geological conditions, and excavation depth. The engineering details of some of the foundation pits in floodplain areas of Nanjing are listed in Table 2. With increasing excavation depth, the lateral soil pressure over the supporting structure increases, and, eventually, the cantilever supports can no longer prevent foundation pit deformation. Cast-in-place concrete supports are commonly used in soft soil foundation pits. They have the characteristics of high rigidity and integrity, flexible layout, high construction quality, and flexible applicability to many types of soft soil foundation pits with irregular plane shapes. In floodplain areas of Nanjing, common foundation pit supporting structures include soil nailing supports, gravity-type barricades, cantilever supports with cast-in-situ bored piles, cantilever supports with manual hole

digging piles, bored piles + concrete supports, digging piles + steel supports, combined supports, soil mixing wall (SMW) construction, and diaphragm walls.

Hydrogeological conditions

The main rivers include the Yangtze River and Shijiu Lake. According to hydrogeological survey, pore water is the main underground water type in floodplain areas of Nanjing. There is a great difference in permeability between the upper soft soil layer and middle and lower sandy soils in floodplain areas of Nanjing. The underground water in the sandy soil layer has a micropressure bearing capacity. Therefore, attention will be focused on dewatering problems in foundation pit projects in floodplain areas of Nanjing. Dewatering and waterproof schemes must be formulated by considering the location and scope of water areas surrounding the foundation pit, including the buried depth, thickness, and permeability of underground aquifers, seasonal variation in local underground water levels, and drainage conditions.

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

Type of soil layer	Void ratio	Water content (%)	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	$1-1 \times 10^{-4}$	$1-1 \times 10^{-4}$
Muddy silty clay	1.02–1.30	37.5–47.4	16.8–18.1	8.0–14.7	15–18	$1-3 \times 10^{-6}$	$1-5 \times 10^{-6}$
Silty clay	0.75–0.95	30–37.4	18–18.5	27–33	18–20	$1-5 \times 10^{-5}$	$2-8 \times 10^{-5}$
Silty sand and fine sand	0.75–0.75	25.4–34.6	18.5–20.5	3–6.8	30–34.9	$1-2 \times 10^{-3}$	$2-3 \times 10^{-3}$

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

Project name	Type of support	Excavation depth of foundation pit (m)
Nanjing Lunegn project 1	Soil nailing wall, gravity retaining wall	7.0
Nanjing Lunegn project 2	Soil nailing wall, gravity retaining wall	7.5
Nanjign Haixia project 1	Soil nailing wall, gravity retaining wall	4.7
Nanjign Haixia project 2	Soil nailing wall, gravity retaining wall	5.2
Nanjign Haixia project 3	Soil nailing wall, gravity retaining wall	5.5
Primary School project 1	Soil nailing wall, cantilever support	6.5
Primary School project 2	Soil nailing wall, cantilever support	7
Primary School project 3	Soil nailing wall, cantilever support	7.5
Nanjing G45 project 1	SMW piles, a reinforced concrete support	10.8
Nanjing G45 project 2	SMW piles, a reinforced concrete support	10.5
Nanjing G45 project 3	SMW piles, a reinforced concrete support	11
Yanshan Road project 1	SMW piles, a reinforced concrete support	9.5
Yanshan Road project 2	SMW piles, a reinforced concrete support	10.5
Yanshan Road project 3	SMW piles, a reinforced concrete support	10
Nanhu Stadium project 1	Bored pile, a reinforced concrete support	8.8
Nanhu Stadium project 2	Bored pile, a reinforced concrete support	9.4
Jiangdongmen Community Service Center project 1	Bored pile, a reinforced concrete support	8.5
Jiangdongmen Community Service Center project 2	Bored pile, a reinforced concrete support	9
Zijing project 1	Bored pile, three reinforced concrete supports	18.5
Zijing project 2	Bored pile, three reinforced concrete supports	17.5
Zijing project 3	Bored pile, three reinforced concrete supports	18
Gulou District State Assets Center project 1	Bored pile, three reinforced concrete supports	18.5
Gulou District State Assets Center project 2	Bored pile, three reinforced concrete supports	19.5
Jinrongchegn project	Diaphragm wall, four reinforced concrete supports	23.5

Ground water aquifer

The underground water distribution in floodplain areas of Nanjing is closely related to the Yangtze River, and the level is generally high, at about 1.5-m depth. There is an approximately 370 km² surface water area in floodplain areas of Nanjing, indicating abundant water resources. In floodplain areas of Nanjing, a phreatic layer exists in the near-surface fill stratum, which belongs to an aquitard. Water supplementary sources at about 1-m depth mainly include atmospheric

precipitation and domestic water. The underground water level is sensitive to seasonal changes. Specifically, there is a high underground water level during rainy seasons, and the maximum annual variation reaches 1 m (Chen 2019).

Confined water

A sand layer confines the water-bearing aquifer in floodplain areas of Nanjing, which contains silty-fine sand and middle-coarse sand mixed with cobbles and gravel. There are

significant differences among the confined water aquifers in terms of permeability, and the confined water aquifers bear micropressure. Silty clay mixed with silt has low permeability and can be used as a waterproof roof. However, foundation pit design and construction in floodplain areas should consider the fact that silty-fine sands in a waterproof roof might form hydraulic channels connected with the sand layer, thus causing piping problems.

Bedrock fissure water

Mudstone and siltstone are the main underground bedrocks in floodplain areas of Nanjing. There is an extensive development of closed fissures, and most are filled with gypsum, thus having poor permeability. Bedrock fissure water generally influences foundation pit excavation only slightly (Chen 2019).

Waterproof structure

Since most foundation pits in floodplain areas of Nanjing lie in urban areas, dewatering and waterproof schemes should consider not only regional geological characteristics but also the adverse impacts of dewatering on surrounding pipelines, railways, and roads. If the thickness of the sandy soil and silty soil layer is relatively high, a combination of a hanging curtain and pit dewatering is applied. If the thickness of the sandy soil and silty soil layer is small, a fully closed waterproof scheme is adopted. If the main strata are soft soil layers, a combination of supporting piles plus a barricade waterproof structure and pit dewatering is adopted. The underground water level can be lowered and quicksand and piping damage prevented by using appropriate dewatering or waterproofing schemes. Common waterproofing structures in Nanjing include waterproof curtain walls, deep stirring piles, thin-walled continuous walls, waterproof piles, and compaction grouting.

Analysis of foundation pit deformation characteristics in floodplain areas of Nanjing

The deformation characteristics of foundation pits in floodplain areas of Nanjing were summarized through investigation of 24 foundation pits and statistical analysis of monitoring data. The thickness of soft soil, horizontal displacement of the supporting structure, horizontal displacement of soft soil, and ground surface settlement of 24 foundation pits are obtained by the drilling technology, measuring scale, field displacement sensors, and buried settlement points.

Effects of thickness of the soft soil on foundation pit deformation

Ground surface settlement around the pit

Soft soil layers in floodplain areas can affect ground surface settlement around foundation pits to some extent. *Thickness of the soft soil* in this study was defined as the sum of the thickness of the layer of silty clay and silty clay mixed with silty soil above the supporting structure bottom. Due to differences in the depth and thickness of the soft soil, the thickness of the soft soil and ground surface settlement around the pit must be redefined as the normalized thickness of soft soil (h_s/H_w) and the normalized ground surface settlement around the pit (δ_{vm}/H) (Tan and Wang 2013a). In these two expressions, h_s is the thickness of the soft soil layer above the supporting structure bottom, H_w is the supporting structure depth, δ_{vm} is the maximum ground surface settlement around the pit, and H is the foundation pit excavation depth. The relationship between the normalized thickness of the soft soil and normalized maximum ground surface settlement around the pit is shown in Fig. 2. Obviously, the overall growth trends are consistent, although the data points are relatively scattered. The maximum ground surface settlement is positively related to the thickness of the soft soil layer. $(\delta_{vm}/H)_2 = 0.44(h_s/H_w) + 0.07$ was determined according to the two outermost data points below all data points, and these two data points are close to most of the data points, which can show the development trend of most data. Similarly, $(\delta_{vm}/H)_1 = 0.46(h_s/H_w) + 0.35$ was determined according to the two outermost data points above all data points. About 86% of the data fluctuates between lines $(\delta_{vm}/H)_1 = 0.46(h_s/H_w) + 0.35$ and $(\delta_{vm}/H)_2 = 0.44(h_s/H_w) + 0.07$ in Fig. 2, and the shadow area represents the main distribution zone of the relationship between

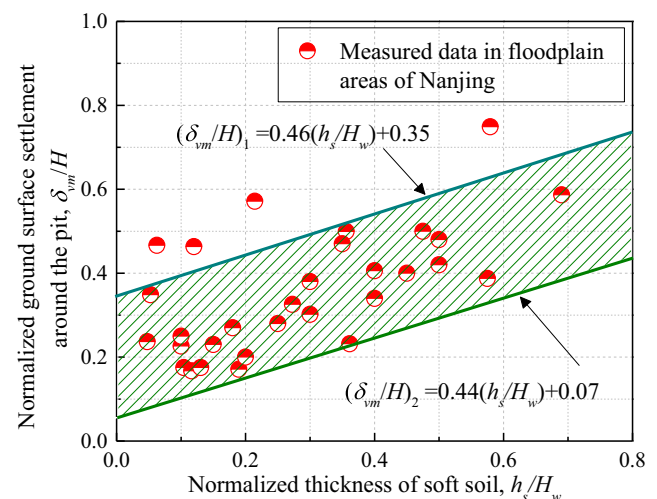


Fig. 2 Relationship between the normalized thickness of the soft soil and the normalized ground surface settlement around the pit

ground surface settlement around the pit and thickness of the soft soil in floodplain areas of Nanjing.

Horizontal displacement of supporting structures

The relationship between h_s/H_w and the normalized maximum horizontal displacement of the supporting structure (δ_{hm}/H) is shown in Fig. 3, where δ_{hm} is the maximum horizontal displacement of the supporting structure. $h_s/H_w = 0.4$ was determined by the distribution of data point. Obviously, data points over 0.4 are very discrete. A positive relationship is observed between h_s/H_w and δ_{hm}/H , but about 90% of the data is concentrated in the region where h_s/H_w is less than 0.4. Some dispersed data points show that the thickness of the soft soil is relatively small when the maximum horizontal displacement of the supporting structure is relatively high, indicating that the thickness of the soft soil is not the only influence on the maximum horizontal displacement. The determination criteria of $hm/H_w = 0.85$ and $hs/H_w = 0.6$ are similar to $hs/H_w = 0.4$ in Fig. 3. The relationship between h_s/H_w and the location of the normalized maximum horizontal displacement of the supporting structure (h_m/H) is shown in Fig. 4. Clearly, 80% of the h_m/H values are less than 0.85. The h_m/H value increases with increases in h_s/H_w , showing significant fluctuation of the growth rate. Moreover, all monitoring data generally fluctuate in the region where $h_s/H_w < 0.6$.

Ground surface settlement around the pit characteristics and distribution pattern

Factors, i.e., the foundation pit dewatering, excavation of adjacent foundation pit, insufficient depth of anchor into soil, and time effect, can affect the ground surface settlement around the pit. Based on data related to soft soil foundation pits, Peck (1969) reported that the maximum ground surface

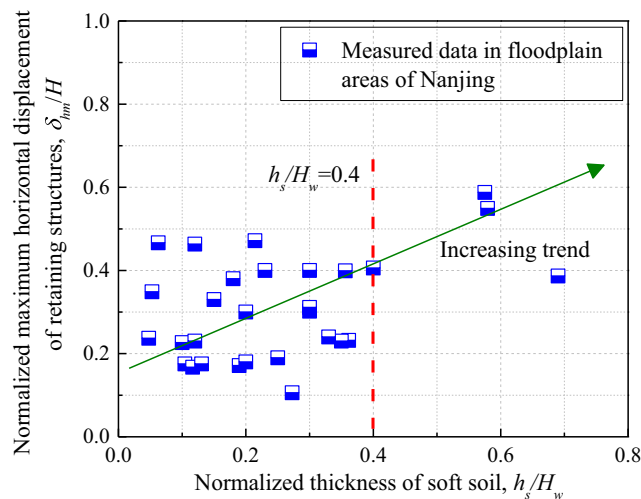


Fig. 3 Relationship between the normalized thickness of soft soil and the normalized maximum horizontal displacement of supporting structures

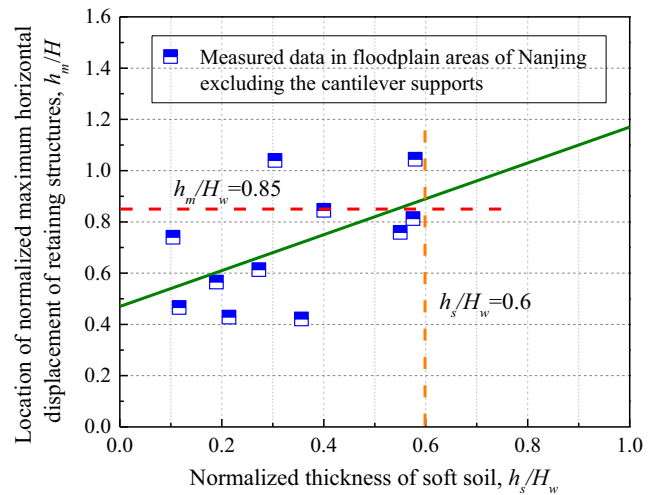


Fig. 4 Relationship between the normalized thickness of soft soil and the location of the normalized maximum horizontal displacement of the supporting structure

settlement around the pit (δ_{vm}) is greater than $1\%H$. However, Wong et al. (1997) analyzed a foundation pit in Singapore and concluded that the mean $\delta_{vm} = 0.24\%H$. The relationship between the maximum ground surface settlement around the pit (δ_{vm}) and excavation depth (H) in floodplain areas of Nanjing is shown in Fig. 5. The $\delta_{vm} = 0.38\%H$ was determined according to the maximum correlation coefficient. With increasing excavation depth, the maximum ground surface settlement around the pit increases gradually up to $\delta_{vm} = 1.93\%H$ and the mean $\delta_{vm} = 0.38\%H$. When the excavation depth exceeds 17 m, δ_{vm} drops suddenly to about 25 mm. This is mainly because the foundation pit applies a combination of diaphragm wall and four reinforced concrete supports for stability, which decreases the ground surface settlement around the pit. The relationship between the location of the normalized maximum ground surface settlement around the pit (x_{vm}/H) and excavation depth (H) is shown in Fig. 6. It shows that the maximum

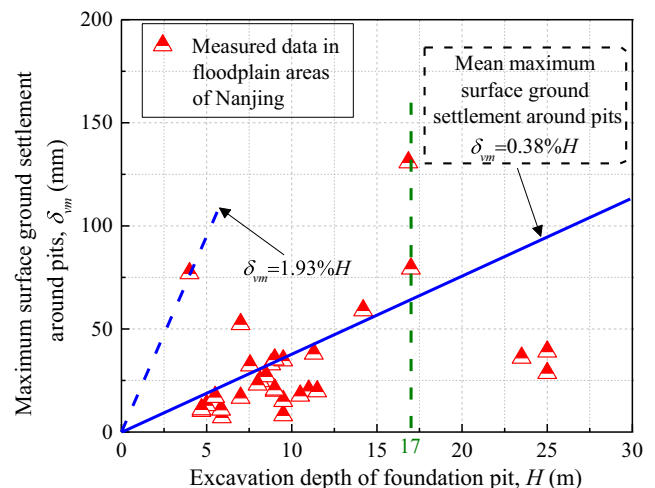


Fig. 5 Relationship between the maximum ground surface settlement around the pit (δ_{vm}) and excavation depth (H) of foundation pits

ground surface settlement around the pit is mainly located within $0.2\text{--}0.75H$. According to statistical analysis, the average x_{vm} in floodplain areas of Nanjing is $0.48H$.

The ground surface settlement distribution around the pit is shown in Fig. 7. The x -coordinate refers to the ratio between the horizontal distance to the foundation pit (x) and its excavation depth (H), while the y -coordinate refers to the ratio between the ground surface settlement around the pit at different positions (δ_v) and excavation depth (H). Peck curve zoning is shown in Fig. 7. According to the soil layer conditions, the settlement curve is divided into Zones I, II, and III. Zone I represents the ground surface settlement around the pit in sandy soil, hard clay, and soft clay conditions. Zone II represents ground surface settlement around the pit in soft clay and extremely soft clay conditions. Zone III represents ground surface settlement around the pit in relatively deep, thick soft clay and extremely soft clay conditions. Obviously, most practical monitoring data on δ_v from the floodplain areas of Nanjing is concentrated in Zone I. Therefore, a model of ground surface settlement around the pit for the floodplain areas of Nanjing was constructed, which has the exponential function:

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

In addition, it can be seen from the distribution of ground surface settlement around the pit that the settlement of local foundation pits is less than that of statistics from Peck (1969). This reveals that rows of piles and diaphragm walls can decrease settlement more effectively than steel sheet piles. Soft soil foundation pits with excavation depths < 15 m in floodplain areas of Nanjing generally adopt a combination of bored piles and inner supports, diaphragm wall supports, and the new cement mixed wall (SMW) method. These supporting

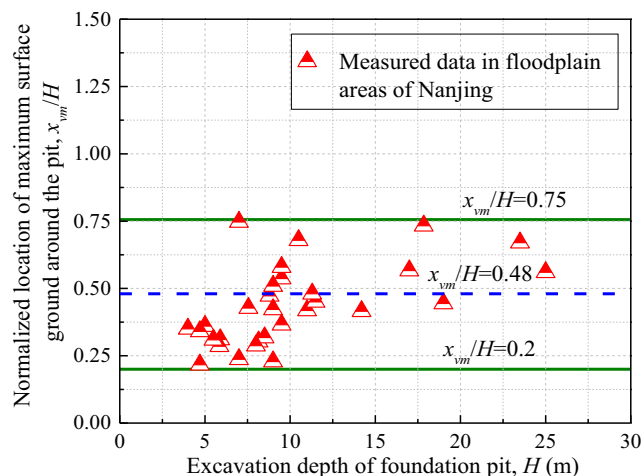


Fig. 6 Relationship between the location of the normalized maximum ground surface settlement around the pit (x_{vm}/H) and excavation depth (H) of the foundation pit

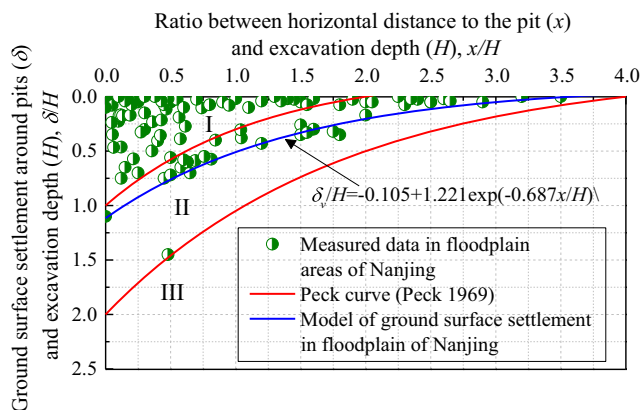


Fig. 7 Distribution of ground surface settlement around the pit

structures have relatively high integral rigidity and can decrease settlement more than flexible supporting structures like steel sheet piles. According to the data, the maximum influence scope of settlement in floodplain areas of Nanjing is about $3.5H$.

Deformation characteristics of supporting structures

The relationship between the maximum horizontal displacement (δ_{hm}) of supporting structures and foundation pit excavation depth (H) is shown in Fig. 8. Clearly, the monitoring data are generally distributed between $\delta_{hm1} = 0.08\%H$ and $\delta_{hm2} = 0.67\%H$. When the excavation depth is < 18 m, δ_{hm} is positively related to the excavation depth. However, δ_{hm} is relatively small (about 35.5 mm) at excavation depths > 18 m. This is mainly attributed to the strong deformation constraint conferred by the combination of the diaphragm wall and four lines of reinforced concrete. According to statistical analysis, the mean maximum horizontal displacement of supporting structures is $0.23\%H$. Similar results for the horizontal displacement of supporting structures were gained for soft clay foundation pits in Masuda, Japan ($0.3\%H$) (Masuda 1993). In addition, other scholars have gained different results, such as $0.1\text{--}0.15\%H$ (Wong et al. 1997), $0.16\%H$ (Long 2001), $0.48\%H$ (Moormann 2004), and $0.40\%H$ (Ou et al. 1993).

The relationship between the location of the maximum horizontal displacement (y_{hm}) of supporting structures and foundation pit excavation depth (H) is shown in Fig. 9. Most data points fall near $y_{hm} = 0.6H$, indicating that the maximum horizontal displacement of most foundation pits in floodplain areas of Nanjing occurs at middle to lower excavation depths. At depths of 5–10 m, the location is close to the ground surface, and the region where these data points lie in adopts cantilever supports. Foundation pit projects with cantilever supports are characterized by the maximum horizontal displacement occurring on the top of supporting structures. Besides, it was found through monitoring data that the horizontal displacement characteristics of supporting supports

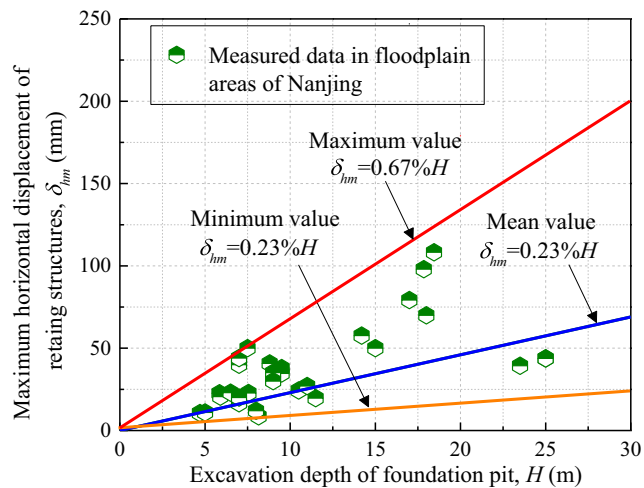


Fig. 8 Relationship between maximum horizontal displacement (δ_{hm}) of supporting structures and foundation pit excavation depth (H)

combining bored piles with a single line of reinforced concrete for foundation pits with excavation depths < 10 m in floodplain areas of Nanjing were similar to those of foundation pits with cantilever pile supports.

Deformation control for foundation pit projects in floodplain areas of Nanjing

Deformation of foundation pits involves many factors, including the shape of the foundation pit, excavation depth, and the existence of underground water (Moormann 2004; Tan and Wang 2013b). It is impossible to have uniform deformation standards due to the different geological conditions in different regions. According to the construction experiences of foundation pit projects in floodplain areas of Nanjing over the years, basic deformation standards have been defined,

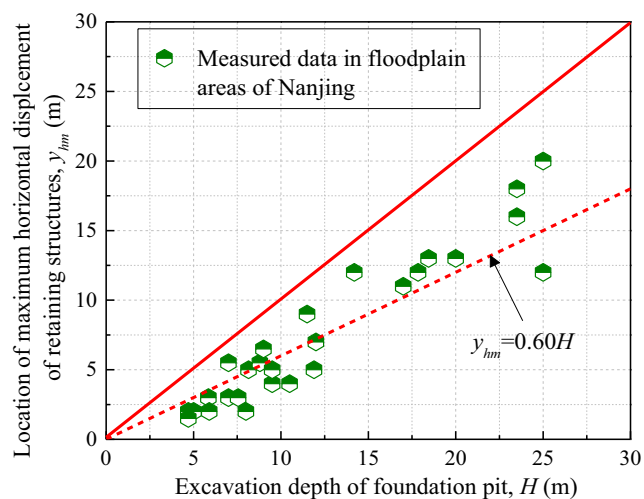


Fig. 9 Relationship between the location of the maximum horizontal displacement of the supporting structure and foundation pit excavation depth

which include (1) cumulative horizontal displacement in different stages of no more than 15–45 mm, (2) horizontal displacement rate < 0.5 mm/day, and (3) cumulative settlement of buildings < 10 mm and settlement rate < 0.3 mm/day.

Foundation pit construction control measures

There are two main causes of ground surface settlement around the pit. (1) Excavation-induced unloading causes deformation of the supporting structure, while plastic heave at the bottom of the foundation pit and dewatering cause consolidation settlement of the surrounding soil (Zhang et al. 2013). (2) Construction factors, such as the poor-quality mud protection, strata soil loss caused by pumping from wells, dynamic loads during construction (Wu et al. 2019). Therefore, the influences of construction on foundation pit deformation can be significantly relieved by adopting positive control measures.

Detailed data on the hydrogeological and surrounding environmental conditions must be obtained before construction. Meanwhile, the influences of the construction on underground pipelines, roads, railways, and buildings should be estimated. To reduce the influences of foundation pit construction on deformation and the surrounding environment, the following countermeasures are recommended:

- (1) The floodplain areas of Nanjing should be zoned according to the degrees of influence of the foundation pit excavation. The horizontal scope of influence is generally $1-4H$. According to the construction experiences of soft soil foundation pits in Shanghai, Li (2006) defined scopes of strong (plastic zone), weak (elastic zone), and zero influence. Different construction countermeasures were adopted to assure the safety of foundation pits. Similarly, we divided the scope of influence into Zones A ($0-1.0H$), B ($1.0-2.5H$), and C ($>2.5H$) according to statistical data from the floodplain areas of Nanjing. Zone A is most influenced by foundation pit construction, where underground buildings and pipelines deform greatly. It is suggested that monitoring and control over underground pipelines and roads are strengthened in Zone B, and settlement should be closely monitored. For Zones A and B, we suggest predicting the deformation of underground pipelines and roads before construction, adopting protection measures, and strengthening monitoring. The underground pipelines and roads in Zone C are influenced the least, and, generally, no special measures are needed.
- (2) Optimization of the construction process. Before the construction of project, the organization and implementation plan of overall division and section construction shall be prepared. Organize experts to discuss the excavation of retaining structure, soil excavation, construction

technology and process deployment of main structure by pit, zone, and section. The construction scheme of the supporting structure should be determined according to the sequence of soil excavation. Full consideration should be paid to the corner effect of foundation pit during the excavation process. To avoid over-excavation, manual excavation should be considered when the excavation of foundation pit is close to the calculated excavation depth. During zone-based excavation of soil layers, one must consider the progress of support installation. Moreover, we suggest excavating foundation pits in strict accordance with the construction scheme and with timely setting of supports. According to the established plan, the slope repair and protection measures of soil platform shall be implemented, the drainage measures at the top and toe of slope shall be improved, and the long-term ponding at the top and toe of slope shall be strictly prohibited.

- (3) Reverse construction. Many projects in floodplain areas of Nanjing have adopted reverse construction methods. According to practical monitoring data, using reverse construction methods, the horizontal deformation of diaphragm walls and the ground surface settlement around the pit are significantly less than when using other techniques.
- (4) Strengthening the supporting structure. The horizontal displacement of diaphragm walls, bottom plastic heave, and ground surface settlement around the pit can be relieved by increasing the buried depth or rigidity of the supporting structures. It is beneficial for the supporting structure to enter the rock strata. Moreover, inserting the bottom of the supporting structure into sandy soil layers should be avoided.
- (5) Strengthening dynamic monitoring. We suggest timely dynamic monitoring of the deformation, deformation rates, and axial forces occurring at different parts of a foundation pit project to determine the states of various parameters during construction, predict the next construction state, further optimize the construction scheme, and maintain engineering safety.

Control measures for foundation pit dewatering

The average distance from the underground water level to the surface in floodplain areas of Nanjing is 0.5–0.7 m. There is a thick, saturated, silty clay layer over the upper soil layers with a moisture content of about 37–47%. Moreover, soil layers are mainly mixed with silt layers. Therefore, control over underground water during foundation construction is vital (Shaour et al. 2008).

Foundation pit projects in floodplain areas of Nanjing mainly apply the well-point dewatering method. Well-point

dewatering method can reduce water content in soil, promote soil consolidation, improve foundation strength, reduce lateral displacement and settlement of soil slope, stabilize slope, reduce uplift of base soil, reduce earthwork excavation, shorten construction period, improve engineering quality, and ensure construction safety. In order to reduce the impact on the surrounding buildings, the well-point dewatering method can not carry out long-term continuous pumping work, and intermittent pumping work is needed. This method can lower underground water levels surrounding the foundation pit, increase the effective stress of soil layers, trigger consolidation, and thereby produce ground surface settlement around the pit. Greatly differential settlement may cause cracking and settlement of adjacent buildings, roads, railways, and public municipal pipelines to different extents (Khosravi et al. 2018). To decrease the influences of dewatering on foundation pit deformation, the following technological measures can be adopted:

- (1) Field data on geological factors, including the stratigraphic distribution, fossil river courses, and underground water distribution, must be determined accurately before implementing the well-point dewatering method. Moreover, the distributions of different types of adjacent pipelines, and, especially, railways and underground tunnels, and the basic and structural forms of buildings, need to be determined.
- (2) If a deep foundation pit project reinforces the soil, the soil layer strength is increased, and the moisture content and permeability of the soil may change accordingly. The number of practical well points should be adjusted according to the practical situation.
- (3) When there are protection buildings surrounding a foundation pit, the dewatering system should be set as far away from them as possible. It should also include a recharge system to maintain the underground water level below protection buildings and avoid their settlement. Notably, the recharge system must be designed in detail, including the setting of water-level observation wells, distances between recharge wells and dewatering wells, and the diameters and depths of recharge wells. The recharge facilities can also include recharge sand well or recharge sand grooves.
- (4) The dewatering depth and pumping amount should be controlled to prevent quicksand and piping. During well-point dewatering and pit dewatering, close attention should be paid to construction progress to ensure that the dewatering curved surface is 0.5–1.0 m below the excavation surface.
- (5) Well points in the pit should be closed in a timely manner. Besides, attention should be paid to closing of depressuring well points inserted into the confined aquifer. This is because poor closing of wells can easily cause abrasive blasting and water security accidents.

- (6) Strengthening of monitoring. The groundwater level, pumping amount, deformation of adjacent roads and pipelines, and ground surface settlement within the influence scope of the foundation pit should be monitored carefully during the dewatering period and for a period after construction.

Pipeline protection measures

Horizontal displacement of supporting structures caused by excavation of foundation pits can influence adjacent pipelines significantly (Yang and Kong 2020). Different pipelines have different responses to control measures, and horizontal forces should be considered in pipeline deformation. Grouting reinforcement at the bottom of pipelines can control settlement effectively but does not control horizontal deformation significantly. In foundation pits, reinforcing soils in passive zones can control the horizontal deformation of pipelines to some extent.

If the cumulative settlement of pipelines is too large or the settlement rate changes suddenly, more monitoring points should be set and grouting measures should be adopted in a timely manner to control continuous deformation of pipelines. If pipelines are lifted up, grouting pressure should be adjusted in a timely manner to ensure the normal use of pipelines and the safety of foundation pits.

Whether compaction grouting should be applied to pipelines near foundation pits is decided according to monitoring data. Suspension reinforcement should be applied to pipelines that run through foundation pits and cannot be moved. If tap water pipelines run through the upper part of a foundation pit, they must be removed. The settlement threshold of underground pipelines should be assessed in a timely manner by considering the settlement value, settlement rate, and differential settlement.

Besides, pipeline protection schemes are formulated according to the bearing capacity of underground buried pipelines with different rigidities to deformation (Liu et al. 2020). For reinforced concrete pipelines that are sensitive to deformation, it is necessary to determine their direction, position, and interface types before excavation and pre-determine the protection scheme in addition to the supporting reinforcement. Plastic or rubber pipelines with low rigidity require corresponding protection measures if there will be high rotation during construction.

Conclusions

In this study, the geological engineering conditions and supporting types of foundation pits in floodplain areas of Nanjing were analyzed. A statistical analysis of detailed

geological exploration data and monitoring data from 24 foundation pits in floodplain areas of Nanjing was carried out. The deformation characteristics and control measures of foundation pits in floodplain areas of Nanjing were investigated. Some conclusions can be drawn:

- (1) The supporting types of typical soft soil foundation pits and the hydrogeological conditions in floodplain areas of Nanjing were summarized thoroughly. Common support types and waterproof and dewatering structures were analyzed and discussed.
- (2) In floodplain areas of Nanjing, the maximum ground surface settlement around the pit of foundation pits, maximum horizontal displacement of supporting structures, and maximum buried depth of walls are positively related to the thickness of the soft soil.
- (3) The mean maximum ground surface settlement around the pit in floodplain areas of Nanjing was $0.38\%H$, and the maximum ground surface settlement was observed at $0.48H$. The distribution pattern of ground surface settlement around the pit in floodplain areas of Nanjing was determined. The maximum influence scope of ground surface settlement was about $3.5H$, and the average maximum horizontal displacement of supporting structures was $0.23\%H$.
- (4) To decrease construction influences on the deformation of foundation pits and the surrounding environment, the influence scope of pit excavation should be zoned and appropriate control measures applied to the different zones. Moreover, the environmental influences of foundation pit dewatering were discussed and control measures proposed. Finally, protection measures for controlling the deformation of underground pipelines and surrounding roads were proposed.

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Data availability All data, models, and code generated or used during the study appear in the submitted article.

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