Deformation of metro station excavation and its influence on nearby pile foundations of bridge

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Abstract: A three-dimensional explicit finite difference simulation is carried out to investigate the deformation of a metro station excavation and its influence on the nearby embedded pile foundations in combination with an underground metro station project in Shanghai soft soil deposits, which is under-crossing an urban elevated bridge and adjacent to its pile foundations. The numerical model, taking account of the interaction among the soil, retaining structures and nearby pile foundations, is established based on the geotechnical program FLAC^{3D}, and the modified Cam-clay constitutive model is adopted to describe the deformation behavior of the soil. The computed lateral displacement curves of the retaining wall agree well with those of the in-situ measurements. This indicates that it is feasible to use the numerical model to predict the performance of the embedded piles underlying the abutment, which can not be monitored at the site. The parametric analysis and the comparison with the other relevant excavation projects show that the adopted countermeasures, which include adjustment of retaining structure scheme, inside ground reclamation and pre-installation of local concrete slab, not only restrict the deformation of the excavation itself effectively, but also protect the safety of the pile foundations as well as the upper bridge appropriately.

Key words: soft soil; excavation; pile foundation; jet grouting; cutoff curtain; deformation control

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地铁车站深基坑变形及其对邻近桥梁桩基的影响

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摘　要：采用三维显式有限差分数值模拟研究了上海软土地区某下穿城市高架桥梁并紧邻其下部桩基的地铁车站深基坑的变形及其对桥梁桩基的影响。基于 FLAC3D 建立考虑土体、基坑围护结构及桥梁桩基相互作用的三维整体计算模型，采用修正剑桥模型描述土体的变形特性，并根据实际施工工况划分不同的计算模拟步骤。基坑围护结构侧向变形计算值与现场实测值基本吻合，表明采用三维数值模型预测现场无法实施监测的承台下部桩基的变形是可行的。参数分析及现场实测数据与上海软土地区其他地铁车站深基坑实测数据的对比表明，本工程所采用的基坑支护结构方案调整、坑内地基加固及局部中板逆作等技术措施，不但有效控制基坑自身的变形，也有效保护桥梁桩基及上部结构的安全。

关键词：软土；基坑；桩基；喷射注浆；止水帷幕；变形控制

0　Introduction

The soft deposit in Shanghai is well known for its high water content, high compressibility, high plasticity, low permeability and low strength. Nevertheless, there continuously springs up with numerous deep excavation projects with construction activities of underground metro stations in Shanghai during the past decades. Most of the metro stations are seated beneath traffic arteries and usually adjacent to the existing building groups, underground municipal pipelines, and even urban elevated bridges. There would be great falling of groundwater level and massive stress relief of ground owing to dewatering and excavation during the

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construction process of underground metro stations, consequently, this may lead to significant ground movement as well as ground surface settlement[1-2]. Therefore, deformation control and environment protection are becoming the most concerned considerations during planning, design and construction of underground metro stations in soft soil areas[3].

In this paper, a three-dimensional numerical simulation is carried out to study the deformation of a metro station excavation and its influence on the nearby pile foundations of elevated bridge; meanwhile, in-situ instrumentation and comparison with other relevant excavation projects in Shanghai soft soil deposits are conducted to investigate the deformation behavior and to discuss the effectiveness of deformation control measures.

1 Project description

1.1 Project profile and retaining schemes

South Xizang Road Transfer Station of Shanghai Metro Line 8 is located beneath the crossroads at South Xizang Road and South Zhongshan Road in Huangpu District. The metro station is under-crossing the urban elevated bridge of South Zhongshan Road, and the plan layout is along the north-south direction, as illustrated in Fig. 1. The major structure of the underground metro station is composed of a 2-storey and 3-span concrete frame structure 302 m in length and 22 m in width, of which the part with axial number from 23 to 28 is the underpass beneath the urban elevated bridge (noted as Zone 6 in the following context). The excavation depth in Zone 6 is about 15.8 m with dimension of 36 m × 22 m in horizontal plan as illustrated in Fig. 2.

The elevated bridge over the excavation in Zone 6 is a simply-supported T-shaped beam structure, with longitudinal central line distance of 29.6 m between the two piers. The bridge foundation is embedded pile-supported concrete abutment, and there are 20 piles underneath each abutment with arrangement of 4 lines and 5 rows. The length of each pile shaft is 28 m and consists of two single piles connected by welding steel hoops at ends, and the depth of the joints ranges from 13 to 16 m. The minimum horizontal clearance between the retaining structure in Zone 6 and the abutment is 0.5 m and the vertical clearance over the excavation is 6.8 m.

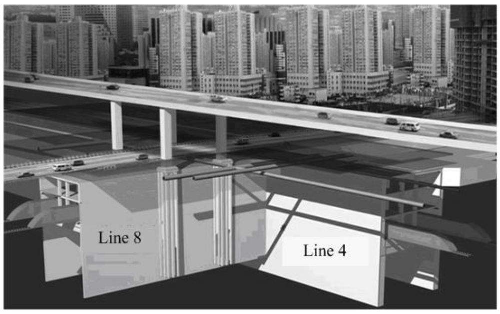


Fig. 1 Perspective of South Xizang Road Transfer Station

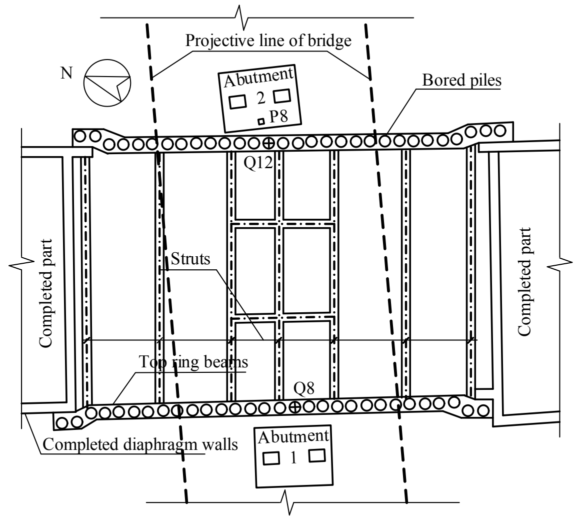


Fig. 2 Layout of station excavation in Zone 6

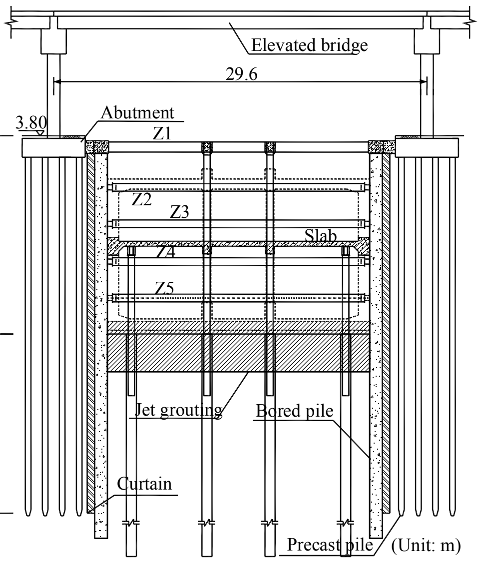


Fig. 3 Cross section of excavation in Zone 6

The conventional diaphragm wall retaining structure is inapplicable in Zone 6 owing to slurry trenching and concreting requirements, and the corresponding problems of great stress relief as well as ground disturbance effect[4]. The vertical clearance also cannot ensure smooth operation of the trenching machines. Therefore, the contiguous cast-in-place bored piles combined with jet grouting cutoff curtains are employed to retain soil and cut off groundwater seepage. The bored piles with diameter of 1 m, clearance of 0.2 m and depth of 32 m are adopted. The cross section of the first level reinforced concrete strut is 0.8 m × 0.8 m, and the diameter as well as the thickness of the other 4 steel tube struts is 0.609 and 0.016 m respectively. The cross section profile of the excavation in Zone 6 is shown in Fig. 3.

1.2 Ground conditions

The soil strata are mainly composed of a sequence of Quaternary marine deposits and alluvia. The initial ground surface elevation is about 3.8 m and the corresponding geological stratification can be described as: I miscellaneous fill, II silty clay, III silty clay, IV clay, V_1 clay, V_3 sitlty clay, VI silty clay and VII_2 fine sand. The average groundwater level is about 0.5 to 0.7 m under the ground surface. The main physical and mechanical parameters of the soil strata are given in Table 1, and the property parameters include soil layer thickness t, unit weight γ, void ratio e_0, consolidated and undrained strength parameters c_{cu} and φ_{cu}, compression and swelling parameters λ and κ for the modified Cam-clay constitutive model.

Table 1 Physical and mechanical parameters of soil strata

Strata	t /m	γ /(kN·m^{-3})	e_0	c_{cu} /kPa	φ_{cu} /(°)	λ	κ
II	3.0	18.3	0.73	20	20	0.090	0.007
III	4.5	17.5	1.32	11	18	0.133	0.01
IV	9.5	16.6	1.24	13	11	0.103	0.009
V_1	7.2	17.6	0.76	16	14	0.088	0.007
V_3	7.3	18	0.88	16	21	0.096	0.007
VI	3	19.2	0.93	44	21.5	0.058	0.005
VII_2	—	19.0	0.72	4	31.5	0.025	0.002

2 Numerical modeling

The mesh of the strata, retaining structure, piles and abutments are illustrated in Fig. 4. The overall dimension of the numerical model is 200 m × 200 m × 60 m. The ground surface is free of restriction, the outer vertical cut boundary faces are fixed in normal directions, and the base face of the model is fixed in three directions. The soil strata, reclaimed ground and abutments of the bridge are modeled with solid zones, the cast-in-place bored piles as well as the jet grouting cutoff curtains are modeled with liner structural elements the inside struts are modeled with beam structural elements the pre-installed local middle concrete slab is modeled with shell structural element and the inside pillars and supporting piles as well as the piles under the abutments are modeled with pile structural elements.

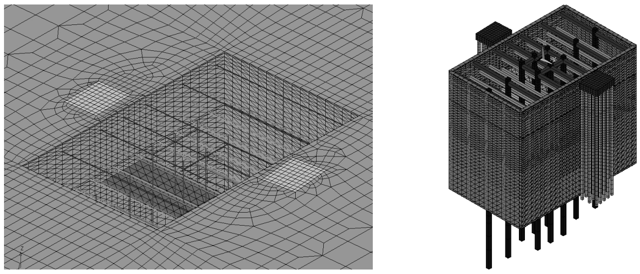


Fig. 4 Mesh of numerical model

The modified Cam-clay constitutive model is employed to describe the deformation behavior of the soil[5-6], and the falling of groundwater level is simulated appropriately by adjusting the location of phreatic surface. The property parameters under the effective stress condition are adopted in the analysis, as listed in Table 1. The Mohr-Coulomb constitutive model is adopted to describe the deformation behavior of the reclaimed soil beneath the excavation bottom, and the property parameters are defined according to the empirical data in Shanghai soft soil deposits. The calculation steps of the numerical model are presented in Table 2.

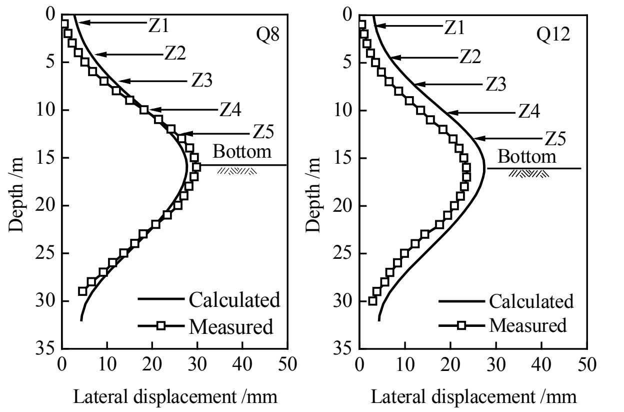
Table 2 Calculation steps of excavation in Zone 6

Step	Construction conditions
0	Compute the initial ground stress (displacement is set to zero after calculation)
1	Excavate to and install the first level struts (Z1)
2	Excavate to and install the second level struts (Z2)
3	Excavate to and install the third level struts (Z3)
4	Install the middle concrete slab, excavate to and install the fourth level struts (Z4)
5	Excavate to and install the fifth level struts (Z5)
6	Excavate to the bottom and concrete the bottom slab

3 Lateral displacement behavior

3.1 Lateral displacement of retaining structure

The predicted and measured lateral displacements of the retaining structure at instrumentation points Q8 and Q12 (Fig. 2) near the bridge abutments when the pit is excavated to the bottom (Step 6) are illustrated in Fig. 5. The maximum computed lateral displacement at point Q8 is 27.7 mm, while the maximum measured value at point Q8 is 29.3 mm. The computed lateral displacement curves agree well with the measured ones, and the maximum lateral displacement points appear close to the base face when the pit is excavated to the bottom. The lateral displacement behavior of the retaining structure is well predicted by the numerical model. Therefore, the numerical model can be adopted to investigate the deformation pattern and tendency of the embedded piles, which can not be monitored at the site because these piles are buried beneath the bridge abutments and are shielded by them.



(a) Retaining structure at point Q8 (b) Retaining structure at point Q12

Fig. 5 Comparison of lateral displacement of retaining structure

3.2 Lateral displacement of pile

The lateral displacement curves of the pile at point P8 beneath the abutment 2 at different construction stages are illustrated in Fig. 6. There is almost no lateral displacement increment of the pile top when the pit is excavated to the second level struts (Step 2), indicating that the lateral deformation of the abutment has stabilized after this construction stage. Nevertheless, the maximum value of the lateral displacement of the pile increases with the succeeding excavation and dewatering; meanwhile, the deformation profile of the pile also changes with the construction. The depth range of the inside jet grouting ground reclamation is from 1 m above to 3 m below the final excavation bottom (with depth from 14.8 to 18.8 m), the depth of the connection joints of the piles is also from 13 to 16 m. The reclaimed ground inside the excavation serves as a giant block propping system during excavating and dewatering processes owing to its large deformation stiffness and high strength characteristics, resulting in the lateral displacements of the piles around depth range of the reclaimed ground being restricted effectively. The maximum lateral displacement of the pile at point P8 is 16 mm and located at depth of 11.4 m when the pit is excavated to the bottom (Step 6), while the maximum lateral displacement of the pile top is only 2.7 mm. The overall deformation shape of the pile at P8 is like "M", of which the relative large values appear at the depth of 11.4 and 21.5 m respectively.

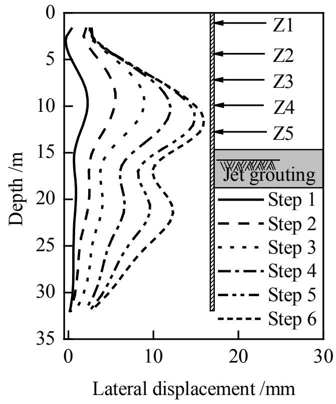
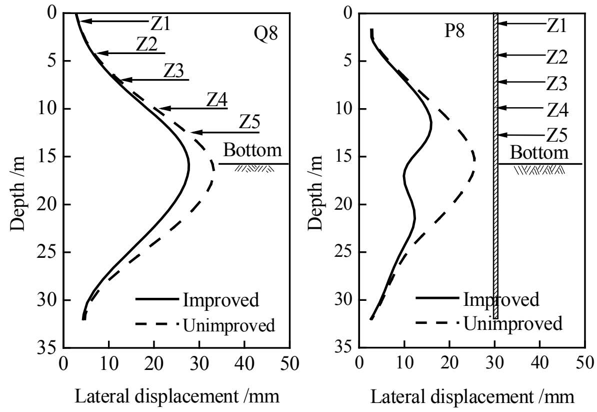


Fig. 6 Lateral displacement of pile at point P8

The influences of jet grouting ground reclamation inside the excavation on the lateral displacement of the retaining structure at point Q8 and on the pile at point P8 are shown in Fig. 7. The maximum lateral displacement of the retaining structure at point Q8 decreases from 33.2 to 27.7 mm with inside jet grouting when the pit is excavated to the bottom (Step 6), while the value of the pile at point P8 reduces from 25.6 to 16.0 mm. The influence of inside jet grouting ground reclamation on the deformation of the pile is more pronounced than that on the retaining structure, owing to the greater overall bending stiffness of the contiguous cast-in-place bored piles combined with the jet grouting cutoff curtains.



(a) Retaining structure at point Q8 (b) Pile at point P8

Fig. 7 Influence of ground reclamation on displacement of retaining structure

4 Deformation control measures and implementation effects

4.1 Deformation control measures

The conventional diaphragm wall retaining structure scheme is unsuitable for the excavation in Zone 6 due to the negative construction effect, including great stress relief, soil disturbance and construction difficulties. Therefore, the contiguous cast-in-place bored piles combined with jet grouting cutoff curtains are adopted for the excavation in Zone 6, as illustrated in Fig. 8. The concrete piles are bored with bentonite slurry to stabilize the circular trench faces; meanwhile, the piles within the distance of 4 m around the abutments are bored and concreted alternately with time interval over 48 hours to guarantee the hoop soil arching effect and to reduce the soil disturbance. The angle of jet grouting curtains near the bridge abutments is 180° back to it.

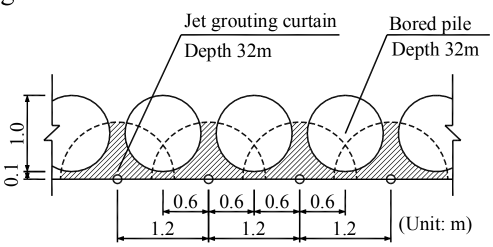


Fig. 8 Diagram of bored piles and jet grouting curtains

There are 5 level struts adopted for the excavation in Zone 6, while there are only 4 level struts for the other regular excavation sections; meanwhile, the reinforced concrete beams with cross section of 0.8 m × 0.8 m are adopted for the first level struts. The elevation of the central line for the first level strut is equal to that of the ring beam around the top of the bored piles, and the first level struts are rigidly connected to the ring beams. The longitudinal spacing between the other 4 level steel tube struts is within 3 m, and the steel walings with "H" shape are added between the steel tube struts and the bored piles to reduce stress concentration effect; meanwhile, the gaps between the steel walings and the bored piles are filled with fine aggregate concrete to enhance the global stiffness of the support system along longitudinal and transverse directions. The inside jet grouting ground reclamation with depth from 14.8 to 18.8 m and the pre-installed local middle concrete slab are also adopted to control the deformation of the retaining structure as well as the elevated bridge pile foundations.

4.2 Implementation effects

The comparison between the measured maximum lateral displacements of the retaining structure in Zone 6 and the other metro station excavation projects in Shanghai soft soil deposits[7] is shown in Fig. 9. The data of lateral displacement of the retaining structure in Zone 6 range from 0.1%H to 0.2%H, with the average value of 0.145%H, where H is the excavation depth. The measured data from the other metro station excavation projects range from 0.04%H to 0.6%H, with the average value of 0.3%H. The average maximum lateral displacement of the retaining structure in Zone 6 is only about half the value of the other metro station excavation projects, demonstrating a favorable deformation control effect.

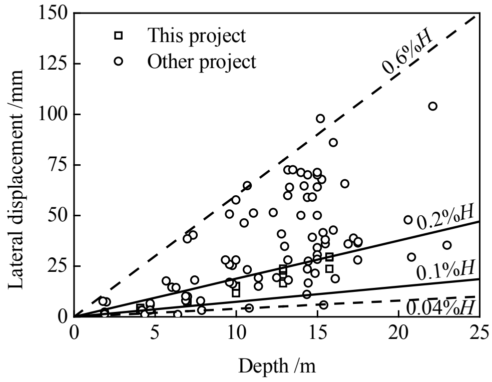


Fig. 9 Comparison of maximum lateral displacement of retaining structure

The empirical relationship between the maximum lateral displacement of retaining structure and the factor of safety against basal heave has been established by Mana and Clough (1981)[8] according to 11 excavation case histories. The empirical relationship curves presented by Mana and Clough (1981)[8], the data of this project as well as the other metro station excavation projects in Shanghai soft soil deposits are presented in Fig. 10. The point of the excavation in Zone 6 lies near to the lower limit presented by Mana and Clough (1981)[8], indicating that the lateral deformation of the retaining structure in Zone 6 are restricted effectively.

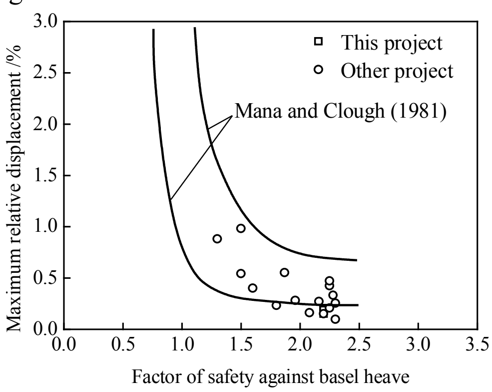


Fig. 10 Maximum relative lateral displacement of retaining structure and factor of safety against basal heave

The in-situ measured data show that the vertical displacements of the two bridge abutments are both less than 1 mm; meanwhile, the lateral displacement as well as the inclination deformation are almost negligible. The maximum falling of the outside groundwater level is less than 18 cm, indicating that the jet grouting curtains have cut off the seepage of groundwater effectively.

5 Conclusions

This paper presents the numerical simulation prediction and the in-situ monitored deformation of a metro station excavation, and the deformation influence on the nearby pile foundations of urban elevated bridge in Shanghai soft soil deposits. Based on the results of the study, the following conclusions can be drawn:

(1) The three-dimensional numerical model based on $FLAC^{3D}$ can dynamically compute the deformation behavior of the retaining structure at different construction stages and predict the lateral deformation of the embedded piles, which can not be obtained from the in-situ instrumentation.

(2) The contiguous cast-in-place bored piles with alternate construction method and with sufficient time interval, combined with jet grouting cutoff curtains with specific jet angle of 180° back to the protected piles, can guarantee hoop soil-arching effect, reduce the soil disturbance, and cut off seepage of groundwater effectively.

(3) The inside jet grouting ground reclamation can serve as a giant block propping system during dewatering and excavating periods; meanwhile, the pre-installed local middle concrete slab can act as an additional horizontal strut to restrict the lateral displacement of the nearby embedded piles and protect the joints of the piles.

(4) The average maximum lateral displacement of the retaining structure of the excavation in Zone 6 is only 0.145% to the excavation depth, which is only about half of the other metro station excavation projects in Shanghai soft soil deposits, demonstrating a favorable deformation control capability.

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