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Study on the disturbance and recompression settlement of soft soil induced by foundation pit excavation

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Abstract: The deep excavation of foundation pit in soft soil layer will cause serious disturbance to the soil at the bottom of the pit. Affected by excavation disturbance, the mechanical properties and stress state of the soil at the bottom of the pit will change. Hence, it is important to accurately evaluate the degree of soil disturbance caused by excavation and the influence of disturbance on soil mechanical properties. Based on the summary of the existing evaluation methods of soil disturbance, taking the foundation pit excavation of Taihu tunnel as an example, the distribution of disturbance degree and the depth of strong disturbed zone of soil under the center of the pit bottom under different excavation depths were studied by using the finite element simulation method. Then, taking the undrained shear strength as an evaluation index, a method for evaluating excavation disturbance of clayey soil based on the cone tip resistance in the piezocone penetration test (CPTU) was established. The soil disturbance calculated through cone tip resistance was agreeable with that determined by numerical calculation. Finally, combined with the soil disturbance determined by the finite element method, the settlement of disturbed soil at the bottom of the pit under different base additional stresses was calculated considering the settlement of soil disturbance. The results showed that the soil disturbance would cause a significant increase in the base settlement. When the base additional stress increased from 100 kPa to 150 kPa, the ratio of base settlement with soil disturbance to that without soil disturbance would increase from 1.43 to 2.24.

Keywords: soft soil; excavation; disturbance; piezocone penetration test(CPTU); settlement

1 Introduction

‘Structure’ is an important characteristic of soft soil in coastal areas of China. Construction on the structural soft soil layer will cause serious disturbance to the surrounding soil and destroy the structure of the soil, which will change the stress state and mechanical properties of the soil[1]. Previous studies have shown that after being disturbed, the soil's yield stress[2], undrained shear strength[3], compression index[4], consolidation coefficient[5], small strain shear modulus[6] decrease, while the soil's failure strain[7], coefficient of compressibility[8], damping ratio[9] increase. Therefore, using the mechanical parameters of undisturbed soil to analyze the strength, deformation and stability of disturbed soil will cause engineering safety problems. With the increasing scale of engineering construction in soft soil areas in China, it is of great practical significance to establish the estimation method of construction disturbance and explore the variation of mechanical properties of disturbed soil and its corresponding engineering effect.

Since the mechanical parameters of disturbed soil are changed, many researchers employed different mechanical indexes to establish the estimation method of soil disturbance and the relationship between the variation of mechanical parameters and disturbance degree[10]. However, the above indexes were obtained through laboratory tests. Due to the disturbance in the process of sampling, transportation, storage and sample preparation, the evaluation of construction disturbance using indoor laboratory tests is limited and it is necessary to assess the construction disturbance by means of on-site monitoring or in-situ testing. Xu et al.[11] and Li et al.[12] carried out the static cone penetration tests on the soil above the shield tunnel before and after the construction. The results showed that due to the disturbance of shield construction and the reconsolidation of disturbed soil after construction, the cone resistance for soil above the shield tunnel decreased first and then increased slightly. Chen et al.[13] measured the cone-tip resistance of the soil inside and outside the pit after the collapse of a foundation pit, and the results showed that the cone-tip resistance of the soil at the bottom surface of the pit was attenuated by 80%. According to the results of on-site monitoring or in-situ testing, some researchers have established construction disturbance estimation methods, as shown in Table 1.

The increase of settlement deformation of disturbed soil is one of the adverse effects of construction disturbance. The previous test results showed that the compression curve of disturbed soil tended to be gradual with the increase of disturbance, resulting in the decrease of yield stress and compression index. Through CRS tests, Lim et al.[9] found that the yield stress of undisturbed soil was twice that of disturbed soil. Based on the tests, Santagata et al.[19] revealed

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that the compression index of disturbed soil was only 72% of the original in-situ value. Wang et al.[20] analyzed the construction disturbance of soft soil foundation in Wenzhou, and they demonstrated that the disturbance degree of foundation soil was up to 30% and the final settlement increased by 25% compared to the undisturbed condition. Saye[21] analyzed the foundation settlement of expressway and presented that the foundation settlement of expressway increased with the increase of disturbance degree of foundation soil. In view of the settlement calculation of disturbed soil, Chen et al.[13] studied the effect of the collapse of a foundation pit on the soil disturbance, and established a disturbance evaluation method and settlement calculation method of the soil at the bottom of the pit. Wang et al.[22] simplified the compression curve of disturbed soil into three broken lines, and established the relationship between soil deformation parameters and disturbance degree as well as the calculation method of settlement deformation of disturbed soil. Liu et al. [23] believed that after soil stress exceeded yield stress, the development of soil deformation can be divided into damage stage and further compaction stage, and five-section broken line can be used to simulate the compression curve of undisturbed soil and disturbed soil. Based on these findings, they also established a calculation method of soil compression deformation considering the disturbance effect. By using shear strain as an index, Meng et al.[16] developed a reduction method of soil deformation parameters considering soil disturbance and a calculation method for post-construction settlement of ground surface disturbed by shield construction.

Table 1 Existing methods to estimate soil disturbance induced by construction

Number of indicators	Evaluation index	Evaluation formula	Literature source
1	Effective stress σ'	$\mathrm{SD}=1-\sigma'_{\mathrm{d}}/\sigma'_0$	Literature [11]
	Shear stress τ	$\mathrm{SD}=\tau_{\mathrm{d}}/\tau_{\mathrm{f}}$	Literature [12]
	Undrained shear strength S_{u}	$\mathrm{SD}=S_{\mathrm{u}}^{\mathrm{d}}/S_{\mathrm{u}}^{0}$	Literature [14]
	Pore water pressure u	$\mathrm{SD}=u_{\mathrm{d}}/u_0$	Literature [15]
	Construction disturbance-induced shear stress γ	$\mathrm{SD}=\gamma_{\mathrm{d}}/\gamma_0$	Literature [16]
3	Spherical stress p Deviatoric stress q Void ratio e	$\mathrm{SD}=\dfrac{\sqrt{\Delta p^2+\Delta q^2+\Delta e^2}}{\sqrt{p_{\mathrm{f}}^2+q_{\mathrm{f}}^2+e_{\mathrm{f}}^2}}$	Literature [17]
4	Spherical stress p Deviatoric stress q Void ratio e Water content ω	$\mathrm{SD}=\dfrac{1}{4}\left(\dfrac{\Delta p}{\Delta p_{\mathrm{f}}}+\dfrac{\Delta q}{\Delta q_{\mathrm{f}}}+\dfrac{\Delta e}{\Delta e_{\mathrm{f}}}+\dfrac{\Delta\omega}{\Delta\omega_{\mathrm{f}}}\right)$	Literature [18]

Notes: SD is the disturbance degree of soil; the subscript 0 indicates the undisturbed state; d denotes the disturbance state; and f represents the state of failure.

The above studies show that construction disturbance has adverse effects on the prevention and control of soil deformation in engineering. Therefore, it is very crucial to develop an estimation method for construction disturbance to accurately evaluate the settlement deformation of disturbed soil. However, most of the existing construction disturbance evaluation methods are based on on-site monitoring, which generally have the problems of poor timeliness, difficult monitoring and low monitoring accuracy. In this paper, the foundation pit engineering of Taihu tunnel was selected as an example. The distribution of disturbance degree of the soil in the center of pit bottom under different excavation depths, and the method of determining the depth of strong disturbance area were studied by using the numerical simulation method. Next, according to the results of piezocone penetration tests (CPTU) before and after foundation pit excavation and using the undrained shear strength of soil as the evaluation index, the method for evaluating construction disturbance of cohesive soil was developed based on the cone tip resistance of CPTU. Finally, the settlement deformation of the soil at the bottom of the foundation pit after excavation disturbance was calculated and analyzed. The results can provide a reference for the design and construction of Taihu tunnel and other similar foundation pit engineering projects.

2 Disturbance analysis of Taihu tunnel foundation pit excavation

2.1 Project overview and geological conditions

Taihu tunnel is located in Wuxi city, Jiangsu province, with a total length of about 10 790 m, of which the section underneath the lake accounts for more than 90%. In this section, the cofferdam cut and cover method is adopted for alternative bay construction of the tunnel. The construction sequence is as follows: installation of cofferdam–pumping–excavation of foundation pit–construction of main tunnel structure–backfilling–removal of cofferdam–backwater. The construction of cofferdam and excavation of foundation pit in the section crossing the lake is displayed in Fig. 1. The foundation pit of Taihu tunnel is a typical strip shape, and the excavation depth is between 12.0 and 15.3 m. Different support methods are adopted for the foundation pits of different sections of the tunnel according to the corresponding geological conditions. In this work, two typical sections are selected for research, as shown in Fig. 2. All the foundation pits are supported by the combination of slope and retaining structure. The excavation depths of the foundation pit at section 1 and section 2 are 15.15 m and 15 m, respectively. ϕ1 000 mm@1 200 mm bored piles are adopted as the retaining structure in section 1 and ϕ850 mm@600 mm tri-axis mixing piles are adopted to stop water; in section 2 soil mixing wall (SMW) is used as the retaining structure and ϕ850 mm@600 mm tri-axis mixing piles inserted by HW700×300×13×24 structural steel are adopted in the SMW method. Section 1 is provided with three internal supports where the first is 800 mm×1 000 mm concrete support; both the second and the third are 609 mm diameter steel pipe support, with 16 mm wall thickness and 8 m internal support spacing. Section 2 is equipped with two internal supports where the first is concrete support and the second is steel support, and support materials and spacing are the same as section 1. The groundwater at the foundation pit site is on the surface, so before excavation, pipe well dewatering was used to lower the groundwater level to 1 m below the excavation face. The excavation sequence of foundation pit is shown in Table 2.

The underlying soil layer of foundation pit site is mainly composed of Holocene cohesive soil layer and upper Pleistocene cohesive soil and silt, with silt in some parts. The distribution of soil layer is shown in Fig. 2, and the basic parameters of soil layer are shown in Table 3. In the soil layers of the site, 1-2 mucky clay layer has poor engineering properties. The excavation range of section 1 slope is 1-2 mucky clay layer. Therefore, before the slope excavation, the soil above the excavation surface was solidified with cement.

2.2 Finite element numerical simulation

The excavation of foundation pit is a complex load–unloading problem. In this paper, the Hardening Soil Model (HS) in Plaxis2D finite element software was used to simulate the excavation of foundation pit. This model (HS) can reflect the change of soil modulus with the change of stress state and distinguish the loading and unloading modulus, which is very suitable for the simulation of foundation pit excavation. Soil parameters were obtained by stress path triaxial tests and consolidation tests on undisturbed soil samples, as listed in Table 3.

(a) Cofferdam installation (b) Foundation pit excavation

Fig. 1 Construction photos of Taihu tunnel site

Table 2 Excavation sequence of foundation pit

Construction steps	Construction contents
1	Surface leveling, pit dewatering, slope excavation to the first support elevation, pouring the first support
2	Dewatering in the pit, excavating the soil to the elevation of the second support, and installing the second support
3	Dewatering in the pit, excavating the soil to the elevation of the third support, and installing the third support
4	Dewatering in the pit, excavating the soil to the pit bottom elevation, and pouring the bottom plate

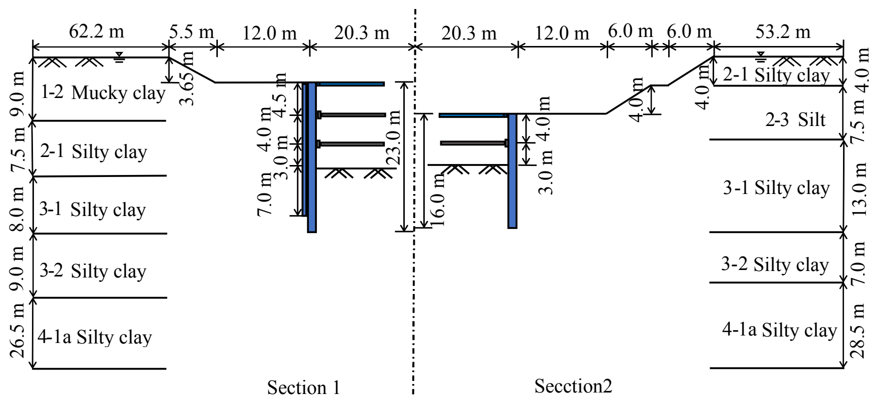


Fig. 2 Schematic diagram of foundation pit section of Taihu tunnel

Table 3 Physical and mechanical parameters of each soil layer

Soil layer	e_0	γ_0 /(kN • m^{-3})	$E_{\text{ode}}^{\text{ref}}$ /MPa	E_{50}^{ref} /MPa	$E_{\text{ur}}^{\text{ref}}$ /MPa	c' /kPa	φ' /(°)	m
1-2 Mucky clay	1.39	16.9	2.39	3.59	24.84	8.6	25.3	1.0
2-1 Silty clay	0.66	20.1	7.08	7.08	56.64	22.0	24.5	0.9
2-3 Silt	0.77	19.4	12.50	15.00	62.50	11.8	27.1	0.8
3-1 Silty clay	0.66	20.1	7.19	7.19	52.95	21.6	22.2	0.9
3-2 Silty clay	1.07	18.4	3.59	5.39	38.72	10.0	21.5	0.9
4-1a Silty clay	0.77	18.9	6.40	6.40	52.00	16.7	21.6	0.9

Notes: e_0 is the void ratio of soil under in-situ stress; γ_0 is the natural unit weight; $E_{\text{ode}}^{\text{ref}}$ is the reference tangent stiffness of consolidation test; E_{50}^{ref} the reference secant stiffness of triaxial compression test; $E_{\text{ur}}^{\text{ref}}$ is the reference secant stiffness for unloading and reloading; c' is the effective cohesion; φ' is the effective internal friction angle; m is the stress correlation coefficient; and the reference pressure is 100 kPa.

The other parameters are failure ratio R_{f} of 0.9 and Poisson's ratio of unloading and loading v_{ur} of 0.2. Since the plane shape of the foundation pit of Taihu tunnel is long strip and the selected sections are far away from the corner of foundation pit, so two-dimensional numerical simulation can get accurate results. The soil was simulated by a 15-node two-dimensional plane strain element, and 1/2 of the size of the foundation pit was taken for modeling in consideration of the symmetry of the foundation pit. The bottom of the model was the complete constrained boundary, the two sides were the symmetric boundary and the normal displacement constraint boundary, respectively, and the top was free. The size of the model was the same as that shown in Fig. 2. The width of the model was 100 m, which was about 4 times the excavation width. The depth of the model was 60 m, about 4 times the excavation depth, which can eliminate the influence of boundary effect on the deformation of the foundation pit. In the finite element model, the bolt element was used to simulate the support, and the plate element was used to simulate both row pile support and SMW sheet pile wall. The bending stiffness and thickness of the plate element were determined by the equivalent principle of bending resistance. In the supporting structure, the elastic modulus of concrete was 30 GPa and the corresponding Poisson's ratio was 0.2, while the elastic modulus of structural steel was 206 GPa and the corresponding Poisson's ratio was 0.25. The steps of finite element calculation refer to Table 2.

2.3 Analysis of excavation disturbance

According to the number of indexes, the estimation methods for construction disturbance listed in Table 1 can be divided into single-index estimation method and multi-index estimation method. Although using multiple indexes to evaluate construction disturbance can comprehensively reflect the change of stress state and mechanical properties of soil before and after disturbance, different indexes have different sensitivities to construction disturbance, so it is necessary to reasonably determine the weight of different evaluation indexes and the relationship between them. However, the existing multi-index evaluation methods of construction disturbance are all based on the assumed weight of each index, and the relationship between indicators is also often assumed as an addition or product relationship. Therefore, the multi-index evaluation method is lack of reasonable physical meaning, and its application in practical engineering is limited. The single index estimation method is widely used in construction disturbance evaluation because of its clear physical meaning and easy index determination. The change of effective stress is not only one of the most basic influencing factors of soil disturbance, but also closely related to the mechanical properties of soil. Hence, effective stress is the most suitable index to assess soil disturbance[24]. The change of effective stress before and after construction can be obtained by on-site monitoring[12] or finite element simulation[12]. By referring to the definition presented by Xu et al. [11, 25], the disturbance of foundation pit excavation expressed by effective stress is as follows:

$$\mathrm{SD} = 1 - \sigma'_{\mathrm{d}} / \sigma'_0 = u_{\mathrm{w}} / \sigma'_0 \tag{1}$$

where SD represents the disturbance of soil; σ'_{d} and σ'_0 are respectively the effective stress of soil before and after disturbance; and u_{w} represents the excess pore water pressure generated by disturbance.

Figure 3 shows the distribution of soil disturbance degree at different excavation depths in the foundation pit center of section 1 and section 2 along the depth. Each curve in Fig. 3 represents the distribution of the disturbance degree of soil below the corresponding excavation level along the depth, and the ordinate is the distance from the original ground surface. The excess pore pressure of multi-layer soil at the interface of soil layer would change abruptly. Within the excavation depth and one time depth below the bottom of the pit, the soil layers of section 1 and section 2 are 2-1 silty clay and 3-1 silty clay, respectively. The mechanical properties of the two soil layers are very similar and the abrupt change of excess pore pressure at the interface is small. Therefore, the smooth curves were used to replace the abrupt change of excess pore pressure at the interface. It can be seen from Fig. 3 that the disturbance degree of all the soils at the bottom of the pit decreases along depth, and the rate of reduction decrease with the increase of depth. That is, after foundation pit excavation, in a certain depth below the pit bottom, the soil disturbance degree was large, but the disturbance degree decreased quickly, while the soil disturbance degree was small, but the disturbance degree decreased slowly. In addition, the deeper the excavation depth is, the smaller the variation of soil disturbance in the same depth range below the pit bottom is. This phenomenon indicates that the deeper the excavation is, the greater the influence depth of excavation disturbance is. In Fig. 3, at the same excavation depth, the soil disturbance at the bottom surface of section 1 and section 2 is basically the same. The disturbance degree of the soil at the bottom surface of section 1 is about 0.48, and that at the bottom surface of section 2 is about 0.5. After the collapse of a foundation pit with a 16 m excavation depth, Chen et al.[13] studied the disturbance degree of the soil at the bottom of the pit, and found that the disturbance degree of the soil at the bottom surface reached 0.8. For a foundation pit with 15 m excavation depth, the disturbance degree of the soil at the bottom surface of the foundation pit was calculated to be about 0.5 in this paper, suggesting that the additional soil disturbance caused by foundation pit collapse is very serious in Chen et al.'s research[13].

The existed research has shown that if $\mathrm{SD} < 0.3$, the soil disturbance can be considered to be small[26]. The intersection of the dash line and the disturbance degree curve in Fig. 3 can be used to determine the strong disturbance area under different excavation depths. Pan et al. [27] put forward the critical unloading ratio to evaluate the influence depth of excavation unloading. The formula for calculating the influence depth of excavation unloading h_{cr} is as follows:

$$h_{\mathrm{cr}} = H\left(1 - R_{\mathrm{cr}}\right) / R_{\mathrm{cr}} \tag{2}$$

where H is the excavation depth and R_{cr} is the critical unloading ratio. The influence depth of excavation unloading h_{cr} is the boundary criterion of disturbance degree of the soil below the pit bottom after excavation. The strength of the soil at the depth below the foundation pit smaller than h_{cr} reduces greatly, belonging to the strong disturbance area; while the strength of the soil at the depth below the foundation pit greater than h_{cr} is basically close to the undisturbed strength, belonging to the weak disturbance area. Previous studies have shown that the critical unloading ratio R_{cr} of different types of soil ranges from 0.66 to 0.90 [28–30]. Figure 4 compares the strong disturbance area determined by critical unloading ratio R_{cr} to that determined by soil disturbance SD. As can be seen from Fig. 4, the depth of the strong disturbance area determined by the SD that is calculated by finite element method is between the upper limit and the lower limit of the influence depth of excavation unloading h_{cr}, that is, $\mathrm{SD} < 0.3$ can be used as the standard to determine the depth of the strong disturbance area. The critical unloading ratio corresponding to the strong disturbed area determined by SD that was calculated by finite element method is about 0.75. Through one-dimensional compression tests on the 3-1 silty clay layer, the critical unloading ratio of 3-1 silty clay layer was determined to be 0.81, which was close to the results of finite element calculation. Since the unloading ratio calculated by the finite element method is the average value of the critical unloading ratio of the soil layers within the influence range of the foundation pit excavation, so it is different from the critical unloading ratio of the 3-1 silty clay layer to some extent.

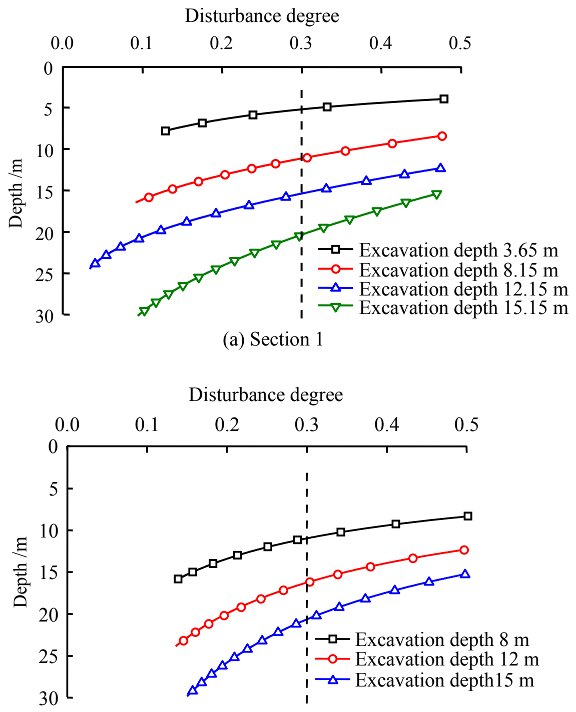


Fig. 3 Distributions of the disturbance degree of soil below the excavation level with depth

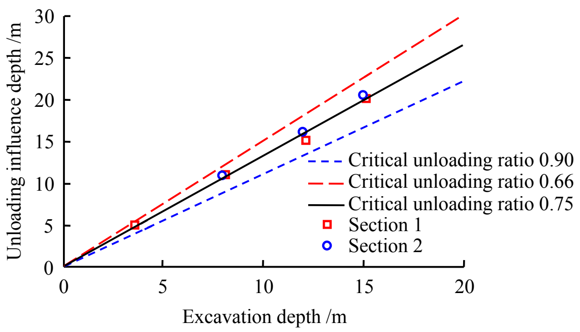


Fig. 4 Relationship between strong disturbance zone depth and excavation depth

2.4 Construction disturbance estimation method of cohesive soil based on CPTU

Although the disturbance of foundation pit excavation can be predicted by numerical simulation, the prediction accuracy depends on the rationality of the selected constitutive model and the accuracy of the constitutive model parameters. For foundation pit engineering, the variation of soil stress state is very complicated in the process of foundation pit excavation, which requires advanced soil constitutive model to simulate. The required parameters of these models are mainly obtained through laboratory tests. However, as mentioned above, the representativeness of soil samples and the disturbance during soil sampling have a great influence on the accuracy of parameters obtained from laboratory tests. Therefore, it is necessary to develop a practical construction disturbance estimation method based on in-situ testing.

CPTU is an in-situ testing method widely used in engineering practice. This method can be used for continuous measurement of in-situ soil, which can not only accurately achieve the in-situ stress state and mechanical properties of soil, but also reflect the variation of formation within the depth of the test. Penetration resistance is one of the main parameters obtained by CPTU, which is affected by mechanical properties, stress state and stress history of soil. Therefore, the change of penetration resistance before and after disturbance can reflect the disturbance degree of soil[11–12]. Chen et al.[13] measured the cone tip resistance q_c of the soil inside and outside the pit after the collapse of a foundation pit, and adopted the cone tip resistance as an index to develop a method to estimate the disturbance degree of the soil at the bottom of the pit:

$$\mathrm{SD} = (q_c^0 - q_c^d) / q_c^0 \tag{3}$$

where q_c^0 is the cone tip resistance of undisturbed soil; q_c^d is the cone tip resistance of disturbed soil. It can be found from Eq. (3) that the disturbance degree of soil is represented by the relative variation of cone-tip resistance. Although the change of cone tip resistance can reflect the disturbance degree of soil, the establishment of Eq. (3) is not from the perspective of soil parameters, which leads to the unclear physical significance of Eq. (3).

Nagaraj et al.[31] demonstrated that there was a linear relationship between the undrained shear strength S_u and the yield stress of soil before and after disturbance. Therefore, the undrained shear strength S_u could reflect the change of both the strength characteristics and the compression characteristics of soil. Compared with the direct use of cone tip resistance as disturbance evaluation index, using the undrained shear strength S_u of soil as the evaluation index to develop the construction disturbance evaluation method has more definite physical significance. The soil disturbance degree, which takes the undrained shear strength as the index S_u, can be calculated by the following formula:

$$\mathrm{SD} = \left(S_u^0 - S_u^d\right) / S_u^0 \tag{4}$$

where S_u^0 is the undrained shear strength of undisturbed soil and S_u^d is the undrained shear strength of disturbed soil. The undrained shear strength of soil can be directly derived from the modified cone tip resistance q_t as shown in Eq. (5).

$$q_t = N_{kt} S_u + \sigma_{v0} \tag{5}$$

$$q_t = q_c + u_2 (1 - a) \tag{6}$$

where N_{kt} is the cone tip coefficient; σ_{v0} is the overburden stress of soil at the test depth; q_t is the cone tip resistance after modifying the pore pressure; q_c is the measured cone tip resistance; u_2 is the pore pressure measured at the cone shoulder position; and a is the effective area ratio. Therefore, the construction disturbance defined by the modified cone tip resistance q_t is given as

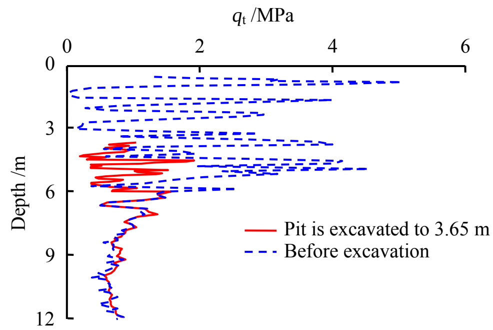
$$SD=\left[\left(q_t^0-\sigma_{v0}\right)-\left(q_t^d-\sigma_{v0}^d\right)\right]/\left(q_t^0-\sigma_{v0}\right) \quad (7)$$

where q_t^0 and q_t^d are respectively the cone tip resistance modified by pore pressure before and after disturbance; and σ_{v0} and σ_{v0}^d are the overburden stress of soil before and after disturbance, respectively. Equation (7) adopts the undrained shear strength as the index, which is applicable to the calculation of the disturbance degree of clay formation. Since it is difficult to determine the drainage conditions of CPTU in silt layer, the calculation of disturbance degree of silt layer is still in accordance with Eq.(3). The calculation of disturbance degree based on Eq. (7) can be considered as the modification of Eq. (3), but its physical significance is more explicit.

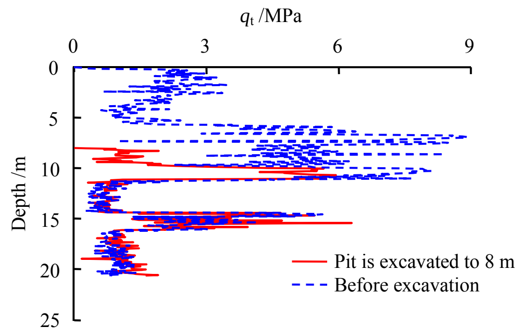
Combined with Eqs. (3) and (7), the excavation disturbance was calculated and analyzed based on the results of CPTU on the Taihu tunnel foundation pit before and after excavation. The modern multifunctional CPTU system independently developed by Southeast University was adopted for in-situ testing, as shown in Fig. 5. The system is equipped with the latest multifunctional digital probe with testing modules for measuring cone tip resistance, side friction resistance, pore pressure and seismic waves. The specifications of the probe are as follows: the area of cone bottom is 10 cm^2, the apex angle of cone tip is 60 °, the area of side wall friction sleeve is 150 cm^2, the pore pressure permeable element is located at the cone shoulder, and the effective area ratio of the probe is 0.8. CPTU were carried out on the section 1 and section 2 of the foundation pit described in section 2.1 of this paper before and after excavation. The general situation of CPTU is illustrated in Fig. 5 and both tests were conducted before and after slope excavation. The slope excavation depths of section 1 and section 2 were 3.65 m and 8 m, respectively. The testing results of cone tip resistance of soil at the bottom of the pit q_t at section 1 and section 2 before and after excavation are present in Fig. 6. It can be seen from the figure that after the excavation of foundation pit, the cone tip resistance of the soil within a certain depth below the excavation surface decreases compared with the original in-situ value. In other words, the effect of excavation disturbance is obvious in this section. The cone tip resistance curves of section 1 basically coincide at the depth beyond 5.8 m below the pit bottom, while the cone tip resistance curves of section 2 basically coincide when the depth is over 11.8 m below the pit. Ideally, the cone resistance can fully reflect the change of soil stress state. However, restricted by the testing accuracy of the equipment, the cone tip resistance attenuation area is consistent with the strong disturbance area defined in section 2.3, that is, it is more reasonable to use the CPTU to divide strong disturbance area. The stress state and mechanical properties of soil in this area changed greatly, while the stress state and mechanical properties of soil below this area had little change.

Figure 7 displays the distribution of disturbance degree of the soil at the bottom of the pit along the depth after the slope excavation of section 1 and section 2. The scatter in Fig.7 is the disturbance degree calculated by using Eqs. (7) and (3) based on CPTU, and the solid line represents the disturbance degree calculated by the finite element method in section 2.3. It is found that the magnitude and variation trend of disturbance degree defined by the two methods are consistent. The disturbance degree of the soil at the bottom of the pit decreases gradually along the depth. The disturbance degree of the soil on the surface of the pit bottom calculated by Eqs. (7) and (3) is about 0.6.

Fig. 5 Photos of CPTU on site

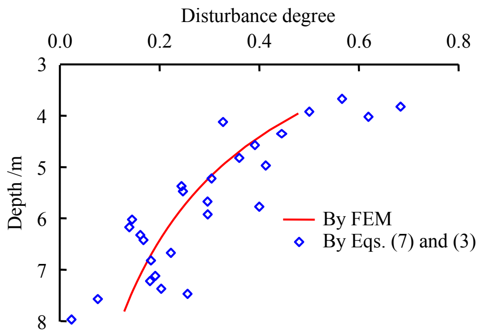


(a) Secion 1

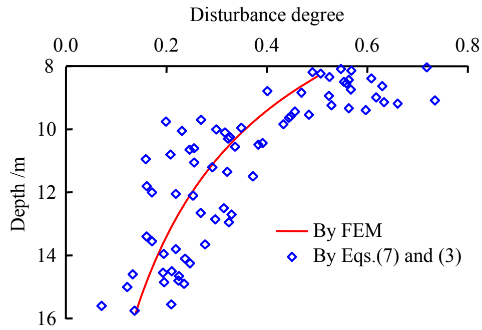


(b) Section 2

Fig. 6 Comparison of cone tip resistance before and after pit excavation



(a) Section 1



(b) Section 2

Fig. 7 Comparison of soil disturbance degree distribution below the excavation level with depth

The measured value of cone tip resistance can reflect the spatial variability of the soil within the test depth. Therefore, the distribution of soil disturbance degree calculated by Eqs. (7) and (3) presents a certain discreteness. The CPTU is carried out on the in-situ soil, and the measured values can truly reflect the changes of stress state and mechanical properties of the soil before and after disturbance. In addition, CPTU is convenient and fast and can adapt to various foundation pit site conditions. Therefore, compared with the finite element method and on-site monitoring, the CPTU is more superior to evaluate the disturbance degree of the soil of the pit bottom before and after excavation.

3 Calculation of soil settlement deformation considering excavation disturbance

Underground structures such as foundation pits and immersed tube tunnels are all compensation foundations, that is, after the construction of the underground structure, the base pressure is less than or equal to the overburden stress of the soil prior to construction, and the settlement deformation of foundation soil layer is rebound and recompression deformation, which is usually small. However, the field measurement has shown that a large amount of settlement deformation has arisen after the construction of underground structures such as foundation pits and immersed tube tunnels[32, 33]. Some studies have shown that the compression deformation characteristics of disturbed soil would change significantly, and the construction disturbance is one of the main reasons for the large settlement deformation of the above foundation[13,34]. The settlement deformation characteristics of the disturbed soil are illustrated in Fig. 8. Figure 8 shows the compression curve model of disturbed soil, undisturbed soil and remolded soil established by Chen et al.[13]. The model has been applied to the analysis of the settlement and deformation of foundation pit disturbed soil. In this model, the broken line *ABC* is the compression curve of undisturbed soil, the straight line *AC* is the compression curve of remolded soil, the broken line *A B′ C* is the compression curve of disturbed soil, and all the three curves intersect at $0.42\,e_0$. The yield stress of normally consolidated clay σ_y is equal to its overburden stress. After being disturbed, the yield stress of disturbed soil decreases to $\sigma_{y,d}$. When the soil is unloaded and then loaded to σ_y, the compression of disturbed soil Δe^d is much larger than the recompression of undisturbed soil Δe. Therefore, a large settlement deformation of soil occurs.

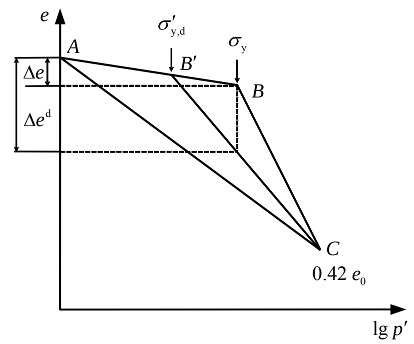


Fig. 8 Schematic diagram of disturbed soil compression curve

Based on Fig. 8, the compression curves of undisturbed soil and disturbed soil are simplified into two broken lines, and it is assumed that the disturbance does not affect the rebound index of soil[13]. The layerwise summation method is adopted to establish the settlement calculation formulas considering soil disturbance, as shown in Eqs. (8)–(10):

$$S_d=\sum_{i=1}^{n}\varepsilon_i H_i=\sum_{i=1}^{n}H_i\Delta e_i/\left(1+e_{0i}\right) \tag{8}$$

$$\Delta e_i=C_s\lg\left(\sigma'_{y,d}/\sigma'_1\right)+C_c^d\left\{\lg\left[(\sigma'_1+\Delta\sigma)/\sigma'_{y,d}\right]\right\},\quad \sigma'_1+\Delta\sigma'>\sigma'_{y,d} \tag{9}$$

$$\Delta e_i=C_s\lg\left[\left(\sigma'_1+\Delta\sigma\right)/\sigma'_1\right],\sigma'_1+\Delta\sigma'<\sigma'_{y,d} \tag{10}$$

where S_d is the settlement of disturbed soil; n is the number of layers of foundation; ε_i is the compression strain of the i^{th} soil layer; H_i is the thickness of the i^{th} soil layer; Δe_i is the change of void ratio of the i^{th} soil layer; e_{0i} is the initial void ratio of the i^{th} soil layer; C_s is the rebound index; $\sigma'_{y,d}$ is the yield stress of the disturbed soil; σ'_1 is the effective self-weight stress after excavation; C_c^d is the compression index of the disturbed soil; and $\Delta\sigma'$ is the effective additional stress. The relationships between yield stress, compression index and disturbance degree of disturbed soil can be described by Eqs. (11) and (12)[16]:

$$\sigma'_{y,d}=\left(1-\mathrm{SD}\right)\sigma'_y \tag{11}$$

$$C_c^d=\left(1-\mathrm{SD}\right)\left(C_c-C_{cr}\right)+C_r \tag{12}$$

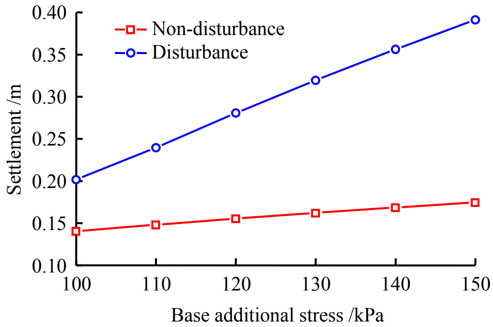


Fig. 9 Relationship between foundation settlement and base additional stress considering soil disturbance

Figure 9 shows the relationship between the settlement deformation at the center of the pit bottom and the additional stress at the base with or without the disturbance effect after section 1 of Taihu tunnel was excavated to the pit bottom. The settlement deformation was calculated according to the layerwise summation method shown in Eqs. (8)–(10), and the disturbance degree of the soil at the bottom of the pit was calculated by the finite element method in section 2.2. The calculated depth was 15.35 m below the bottom of the pit, slightly more than one time the excavation depth. The disturbance degree here was 0.12, suggesting that the excavation disturbance had a weak influence. The foundation soil was divided into 8 layers, with the exception of the first layer of 1.35 m, the other layers of 2 m. The effective stress of soil at the foundation pit bottom was calculated in term of strip load, and the effective self-weight stress after excavation was calculated from the bottom of the foundation pit. The yield stress $\sigma'_{\mathrm{y,d}}$ and compression index $C_{\mathrm{c}}^{\mathrm{d}}$ of disturbed soil were calculated by Eqs. (11) and (12). It can be observed from Fig. 9 that the settlement deformation of foundation soil without considering soil disturbance is much smaller than that with considering soil disturbance, and the difference between them increases with increasing the base additional stress. When the base additional stress was 100 kPa, the foundation soil settlement considering soil disturbance was 20.16 cm, and that without soil disturbance was 14.05 cm, and the ratio of the two was 1.43. When the base additional stress increased to 150 kPa, the foundation soil settlement considering soil disturbance was 39.13 cm, and that without soil disturbance was 17.46 cm, and the ratio of the two was 2.24. The above calculation shows that the total settlement of the disturbed soil at the bottom of the pit is large under the action of overburden load. In practical engineering, when the settlement deformation of disturbed soil exceeds the design requirements, foundation reinforcement measures can be adopted to reduce the settlement deformation of disturbed soil at the bottom of the pit[13], so as to meet the design requirements.

4 Conclusion

The excavation of Taihu tunnel foundation pit was investigated as an case in this paper. The effective stress was selected as the index, and the finite element method was adopted to analyze the distribution law of the pit bottom soil disturbance along the depth and the depth of the strong disturbance zone at different excavation depths. Furthermore, through the in-situ CPTU test, the cone tip resistance of the soil at the bottom of the pit before and after excavation were compared, and the undrained shear strength was used as the index to establish the evaluation method of excavation disturbance of cohesive soil based on cone tip resistance. Finally, the settlement deformation of soil under different base additional stresses was analyzed by using the settlement deformation calculation method considering soil disturbance. Some conclusions are drawn as follows:

(1) The effective stress was used as the disturbance evaluation index. After the excavation of Taihu tunnel foundation pit, the soil disturbance degree gradually decreased along the depth, and the reduction rate decreased with the increase of depth. The deeper the excavation depth is, the more slowly the soil disturbance degree at the pit bottom decreases, and the greater the depth affected by excavation disturbance is.

(2) The case in this paper verified that the disturbance degree equal to 0.3 can be used as the basis for the division of strong disturbance area and weak disturbance area. The area with disturbance degree greater than 0.3 was the strong disturbance area, where the soil strength decreased greatly; the area with disturbance degree smaller than 0.3 was the weak disturbance area, where the soil strength was basically unchanged.

(3) After the excavation of the foundation pit, the cone tip resistance of the soil decreased, and the variation of the cone tip resistance can reflect the soil disturbance caused by the foundation excavation. Based on this, the undrained shear strength was used as the index to develop the disturbance evaluation method for cohesive soil based on the cone tip resistance of CPTU.

(4) Affected by excavation disturbance, the real settlement deformation of the disturbed soil at the bottom of the pit was much larger than that of the undisturbed soil, and the difference between the two increased with the increase of additional stress on the base. When the base additional stress increased from 100 kPa to 150 kPa, the ratio of foundation soil settlement considering soil disturbance to that without considering soil disturbance increased from 1.43 to 2.24.

References

[1] LIU En-long, SHEN Zhu-jiang, FAN Wen. Advance in researches on structured clay[J]. Rock and Soil Mechanics, 2005, 26(Suppl.): 1–8.
[2] HONG Z S, HAN J. Evaluation of sample quality of sensitive clay using intrinsic compression concept[J]. Journal of Geotechnical and Geoenvironmental Engineering, 2007, 133(1): 83–90.
[3] BERRE T. Effect of sample disturbance on triaxial and oedometer behaviour of a stiff and heavily over-consolidated clay[J]. Canadian Geotechnical Journal, 2014, 51(8): 896–910.

[4] KHEMISSA M. Effects of disturbance on the behaviour of a normally consolidated soft clay[J]. European Journal of Enviromental and Civil Engineering, 2010, 14(3): 361–378.

[5] SHEN Zhu-jiang. Engineering properties of soft soils and design of soft ground[J]. Chinese Journal of Geotechnical Engineering, 1998, 20(1): 100–111.

[6] TAN T S, LEE F H, CHONG P T, et al. Effect of sampling disturbance on properties of Singapore clay[J]. Journal of Geotechnical and Geoenvironmental Engineering, 2002, 128(11): 898–906.

[7] SANTAGATA MARIKA, GERMAINE J T. Effect of OCR on sampling disturbance of cohesive soils and evaluation of laboratory reconsolidation procedures[J]. Canadian Geotechnical Journal, 2005, 42(2): 459–474.

[8] LUNNE T, BERRE T, ANDERSEN K H, et al. Effects of sample disturbance and consolidation procedures on measured shear strength of soft marine Norwegian clays[J]. Canadian Geotechnical Journal, 2006, 43(7): 726–750.

[9] LIM G T, PINEDA J, BOUKPETI N, et al. Effects of sampling disturbance in geotechnical design[J]. Canadian Geotechnical Journal, 2019, 56(2): 275–289.

[10] DEJONG J T, KRAGE C P, ALBIN B M, et al. Work-based framework for sample quality evaluation of low plasticity soils[J]. Journal of Geotechnical and Geoenvironmental Engineering, 2018, 144(10): 04018074.

[11] XU Y, SUN D, SUN J, et al. Soil disturbance of Shanghai silty clay during EPB tunnelling[J]. Tunnelling and Underground Space Technology, 2003, 18(5): 537–545.

[12] LI Chun-lin, MIAO Lin-chang. Determination of the range of shield tunneling-induced soil disturbance[J]. Rock and Soil Mechanics, 2016, 37(3): 759–766.

[13] CHEN Yun-min, HU Qi, CHEN Ren-peng. Soil disturbance by the collapse of retaining wall for a pit excavation and the induced additional settlement: a case study of Hangzhou Metro Xianghu Station[J]. China Civil Engineering Journal, 2014, 47(7): 110–117.

[14] WANG Jun, GAO Yu-feng. Effect of construction disturbance and loading rate on settlement of soft sensitive clays[J]. Geotechnical Investigation and Surveying, 2015, 43(3): 23–30.

[15] CHEN Bao, XU Sheng-wen, PENG Fang-le, et al. Experimental study of indices for evaluating small disturbance in underground-cross construction[J]. Chinese Journal of Rock Mechanics and Engineering, 2011, 30(Suppl.1): 2682–2689.

[16] MENG Fan-yan, CHEN Ren-peng, KANG Xin. Effects of tunneling-induced soil disturbance on the post-construction settlement in structured soft soils[J]. Tunnelling and Underground Space Technology, 2018, 80: 53–63.

[17] ZHANG Meng-xi. Study on engineering properties of soil masses disturbed due to construction[D]. Shanghai: Tongji University, 2003.

[18] WANG Jing-chun. Behaviors of deep excavation considering disturbance effects due to construction[D]. Hangzhou: Zhenjiang University, 2008.

[19] SANTAGATA M C, GERMAINE J T. Sampling disturbance effects in normally consolidated clays[J]. Journal of Geotechnique and Geoenvironmental Engineering, 2002, 128(12): 997–1006.

[20] WANG Li-zhong, LI Ling-ling, DING Li. Experimental study on the structure property on soft clay[J]. China Civil Engineering Journal, 2002, 35(1): 88–92, 106.

[21] SAYE S R. Assessment of soil disturbance by the installation of displacement sand drains and prefabricated vertical drains[C]//Proceedings of Soil Behavior and Soft Ground Construction. Cambridge, Massachusetts: [s. n.], 2003: 325–362.

[22] WANG Jun, GAO Yu-feng. Settlement characteristics analysis of disturbed structured soft clay ground[J]. Rock and Soil Mechanics, 2006, 27(8): 1384–1388.

[23] LIU Hai-tao, GUO Yuan-cheng. Analysis on additional settlement of structured soft clay due to disturbance[J]. Chinese Journal of Underground Space and Engineering, 2015, 11(1): 17–22.

[24] WEI Ru-long. The strength and deformation of soft clay[M]. Beijing: China Communications Press, 1987.

[25] XU Yong-fu, CHEN Jian-shan, FU De-ming. Effect of shield tunneling on mechanical properties of soils[J]. Chinese Journal of Rock Mechanics and Engineering, 2003, 22(7): 1174–1179.

[26] XU Jian-ping, ZHOU Jian, BAI Bing. The effects of sample disturbance on soil and the establishment of its evaluation index[J]. Journal of Foshan University (Natural Science Edition), 2000, 18(3): 20–24.

[27] PAN Lin-you, CHENG Yu-mei, HU Zhong-xiong. Experimental study on the shear strength of clay under the unloading state[J]. Rock and Soil Mechanics, 2001, 22(4): 490–493.

[28] DENG Zhi-jun, JIA Jian. On unloading resilience depth in deep station foundation pit[J]. Urban Mass Transit, 2008, 11(3): 52–55.

[29] ZHANG Shu-chao, ZHANG Jian-xin, ZHANG Yang, et al. Experimental study on rebound of clay due to foundation excavatiom[J]. Chinese Journal of Geotechnical Engineering, 2008, 30(Suppl.l): 426–429.

[30] CHEN Kun, YAN Shu-wang, SUN Li-qiang, et al. Analysis of deformation of deep foundation pit under excavation unloading condition[J]. Rock and Soil Mechanics, 2016, 37(4): 1075–1082.

[31] NAGARAJ T S, MIURA N, CHUNG S G, et al. Analysis and assessment of sampling disturbance of soft sensitive clays[J]. Géotechnique, 2003, 53(7): 679–683.

[32] WEI Gang, QIU Hui-jie, WEI Xin-jiang. Analysis of construction and post-construction settlement data caused by immersed tunnel[J]. Chinese Journal of Rock Mechanics and Engineering, 2013, 32(Suppl.2): 3413–3420.

[33] NI P, SONG L, MEI G, et al. Predicting excavation-induced settlement for embedded footing: case study[J]. International Journal of Geomechanics, 2018, 18(4): 05018001.1-05018001.11.

[34] SHAO Jun-jiang. Study on Prediction and Control for Settlements of Immersed Tunnels[D]. Shanghai: Tongji University, 2003.