Deformation Characteristics of Deep Excavation for an Interchange Station Based on the Model of Hardening Soil

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Abstract: The interchange station of Foshan Metro Line 1 and Line 3 was regarded as the research object, and a three-dimensional finite element model was conducted by the software of Midas GTS to simulate the excavation of the metro station based on the constitutive model of hardening soil. The FEM results show that the diaphragm wall presents two deformation forms those are the kicking at the bottom of the wall and rigid translation into the pit. Comparing the numerical calculation and monitoring results of horizontal displacement of representative monitoring points of diaphragm wall under different excavation conditions, it is proved that the numerical results which based on the model of hardening soil is practicable in Pearl River Delta.

1. Introduction

The design and construction of deep foundation pit of subway transfer station has become one of the most important problems in subway construction. The constitutive model of Mohr-Coulomb is mostly used in the design of deep excavation now. However, its yield function exists discontinuous problem at the corner point because of the sharp angle of yield surface which will result in increasing calculation error and decreasing iteration speed [1]. But the model of hardening soil can comprehensively consider the shear dilatancy and neutral loading of clay, distinguishing the characteristics of loading or unloading, and it has good applicability for simulating the mechanical behavior of foundation pit excavation in sensitive environment [2-4]. At present, the model of hardening soil (or “HS model” for short) is used widely in Yangtze River Delta [5,6], but is relatively few in Pearl River Delta. In this paper, the typical soft soil stratum in the Pearl River Delta was regarded as the research object and based on the hardening soil model, the deformation of the underground diaphragm wall of the pit for the subway station are studied, and some reasonable suggestions are provided for excavating construction of foundation pit.

2. Description of HS model

The model of hardening soil (HS model) is proposed by Schanz et al. on the basis of Vermeer double hardening model, which adopts the failure criterion of Mohr-Coulomb. In the elastic stage, the double stiffness is adopted to consider the influence of loading and unloading of soil respectively, and the relationship between vertical strain $\varepsilon_1$ and the deviatoric stress $q$ can be simplified as a hyperbolic curve as following:

$$\varepsilon_1 = \frac{q}{2E_{50}} \frac{\sigma_1 - \sigma_3}{q_u - (\sigma_1 - \sigma_3)} = \frac{1}{2E_{50}} \frac{q}{1 - q/q_u}$$  (1)

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In which

\[ E_{50} = E_{50}^{ref} \left( \frac{\sigma_3 + c \cot \varphi}{\sigma_3^{ref} + c \cot \varphi} \right)^m \]  \hfill (2)

Where, the asymptotic value of the deviator stress is related with the peak deviatoric stress by the equation: \( q_a = q_f / R_f \) ( \( q_f \) is the peak deviatoric stress, \( R_f \) is the failure ratio); \( E_{50} \) is the secant modulus; \( \sigma_3^{ref} \) is the reference stress; \( E_{50}^{ref} \) is the reference secant modulus corresponding to the reference stress \( \sigma_3^{ref} \); \( c \) is the cohesion; \( \varphi \) is the internal friction angle; \( m \) is a power index reflecting the stress dependence of the stiffness.

The model of HS in plastic stage includes two yield surfaces, namely, the shear yield surface and the compression yield surface. The shear yield surface is defined as:

\[ f = \frac{q_a}{E_{50}} \left( \frac{q}{q_a - q} - \frac{2q}{E_{ur}} - \gamma_p \right) = 0 \]  \hfill (3)

\[ \gamma_p = \varepsilon_1^p - \varepsilon_2^p - \varepsilon_3^p \approx 2\varepsilon_1^p \]  \hfill (4)

Where

\[ E_{ur} = E_{ur}^{ref} \left( \frac{\sigma_3 + c \cot \varphi}{\sigma_3^{ref} + c \cot \varphi} \right)^m \]  \hfill (5)

In which, \( E_{ur} \) is the unloading-reloading secant modulus; \( E_{ur}^{ref} \) is the unloading-reloading reference secant modulus corresponding to the reference stress \( \sigma_3^{ref} \); \( \varepsilon_1^p \), \( \varepsilon_2^p \), \( \varepsilon_3^p \) is the plastic strain in three principal stress directions; \( \gamma_p \) is the plastic shear strain. The compression yield surface is defined as:

\[ f^c = \frac{\tilde{q}^2}{M^2} + p^2 - p_c^2 \]  \hfill (6)

Where

\[ \tilde{q} = \sigma_1 + (\delta - 1)\sigma_2 - \delta \sigma_3 \]  \hfill (7)

\[ \frac{\delta}{3 + \sin \varphi} \]  \hfill (8)

In which, \( p \) is the average principal stress; \( p_c \) is the pre-consolidation pressure; \( \tilde{q} \) is a measurement of deviation stress; \( M \) is the model auxiliary parameters related to lateral pressure coefficient.

3. Design parameters of foundation pit

The transfer station of Guicheng is a three-story island underground structure. The length of the foundation pit of Guicheng transfer station is 211.4 meters, the width of the standard section is 20.9 meters and the excavation depth of the foundation pit is 24.22 to 26.72 meters. The diaphragm wall with 1000mm thickness is used as enclosure structure, and the embedded depth of diaphragm wall is 6 meters. Considering the complexity of the surrounding environment, the deep foundation pit of the station is constructed by the open excavation method, the transfer node is constructed by the underground excavation method, and the cover excavation method is used to the overlay system. The northwest side of the foundation pit is only 2.48m away from the basement of Capita Square. From top to bottom, there are four pairs of opposite bracing and corner braces, located at-1.7m, -7.3m, -14.1m, -19.8m and-24.2m respectively starting from the ground elevation. The first and third opposite braces are the concrete support, while the second and fourth braces are the structural steel support with prestressing force, and those diameter are 609mm.
4. The model of three-dimensional finite element

4.1. The model of calculation

In this paper, the mechanical characteristics of the deep foundation pit of the station are analyzed by using the large-scale finite element analysis software of Midas GTS. The soil is simulated by 8-node hexahedron element and 6-node pentahedral element, and the diaphragm wall is simulated by 4-node plate element. The horizontal steel brace is simulated by the truss element and the concrete brace is simulated by the beam element. The size of the model is \(60m \times 230m \times 310m\). The total number of model units is 175,000. The vertical displacement at the bottom and the lateral normal displacement of the model are regarded as fixed constraints, and the ground surface is regarded as a free surface. The three-dimensional finite element model of the foundation pit is shown in Fig.1.

![Analysis model of Foundation pit](a)  
![Supporting structure model of Foundation pit](b)  

Fig. 1 Analysis model of three-dimensional finite element

4.2. Parameters of calculation

The foundation pit site of the station belongs to the marine-land alternating Alluvial-diluvial strata, the main strata is the Quaternary Holocene \(Q_4\). From top to bottom, it’s composed by artificial fill \(Q_4^{ml}\), marine-continental interfaces sedimentary layer \(Q_4^{mc}\), alluvial-diluvial sand layer \(Q_4^{al+pl}\) and residual soil layer. The lower bedrock is mainly composed of argillaceous siltstone of the Cretaceous Damingshan Formation \(K_2^{yl}\). According to the report of geotechnical engineering investigation, and the consolidation drainage triaxial tests with different stress path have been carried out to determine the parameters of HS model for all of soil layers. The relationship among stiffness modulus is shown as followings: \(E_{\text{ref}}^{\text{ref}} = E_{50}^{\text{ref}} = E_{41}^{\text{ref}} = 2.07\ \text{MPa}\). The Supporting structure is considered as the linear elastic model because of its high stiffness, and the C35 concrete is adopted for the diaphragm wall and the concrete brace. Considering the influence of construction factors, the value of elastic modulus of concrete is 21.5 Gpa and its poisson's ratio is 0.2. The elastic modulus of steel pipe brace and steel purlin is 210 Gpa and its poisson's ratio is 0.3. The specific calculation parameters are shown in Tab.1.

| Soil layer       | \(\gamma\) (KN/m³) | \(c'\) (Kpa) | \(\phi\) (º) | \(V\) | \(E_s\) (Mpa) | \(E_{\text{ref}}^{\text{ref}}\) (KPa) | \(E_{50}^{\text{ref}}\) (KPa) | \(E_{\text{ur}}^{\text{ref}}\) (KPa) |
|------------------|---------------------|--------------|--------------|------|--------------|--------------------------------------|-------------------------------|-------------------------------|
| Artificial fill  | 18.5                | 12.3         | 18           | 0.36 | 6.00         | 6                                    | 6                             | 18                            |
| Silt soil        | 15.8                | 4            | 1.6          | 0.43 | 2.07         | 2.07                                 | 2.24                          | 6.72                          |
| Mucky soil       | 17.5                | 10.2         | 4.7          | 0.42 | 2.80         | 2.8                                  | 3.02                          | 9.06                          |
| Silty clay       | 19.5                | 10.8         | 14.6         | 0.35 | 4.88         | 4.88                                 | 5.27                          | 15.81                         |
| Silty sand       | 18                  | 0            | 32           | 0.25 | 12.00        | 12                                   | 12                            | 36                            |
5. Analysis of calculation results

5.1. Displacement analysis of diaphragm wall
In order to analyze the deformation properties of the diaphragm wall in deep foundation pit of station, and to estimate the adaptability of HS model for the typical soft soil stratum in the Pearl River Delta. The typical monitoring points such as ZQT4 and ZQT24 are selected as the research objects, the specific location is shown in Fig. 2.

Tab.2  Calculating Conditions

| Stage | construction state                                      |
|-------|--------------------------------------------------------|
| 1     | Excavation to -1.7m, constructing the first support    |
| 2     | Excavation to -7.3m, constructing the second support    |
| 3     | Excavation to -14.1m, constructing the third support    |
| 4     | Excavation to -19.8m, constructing the fourth support   |
| 5     | Excavation to the bottom of the pit(-24.2m)            |
In order to verify the results of FEM based on the model of hardening soil, some of characteristic points around the foundation pit such as the point of TQY4 and TQY24 are selected to compare the monitoring and numerical simulation value of horizontal displacement of deep diaphragm wall under the third excavation condition, the comparing results is shown in Fig. 4. It can be seen that the monitoring value of deep displacement of diaphragm wall coincides well with the calculated value except the monitoring value of horizontal displacement at the bottom is smaller than its value of numerical simulation. It is indicated that the hardening soil model is suitable for simulating the mechanical properties of typical soft soil layers in the Pearl River Delta region.

6. Conclusions
The model of hardening soil is suitable for simulating the mechanical properties of the typical soft soil layers in the Pearl River Delta region. The model parameters of hardening soil can be obtained comprehensively by the triaxial consolidation drainage and loading-unloading tests of undisturbed soil and combined with conventional consolidation tests.
Because the embedded depth of diaphragm wall is relatively insufficient and the pre-applied axial force of the fourth steel support is too small, the diaphragm wall produces the rigid displacement and kicking phenomenon. In order to ensure the safety of foundation pit construction, it’s suggested that mixing piles should be adopted to reinforce the soft soil layer at the bottom of the pit and the pre-axial force of steel support should be increased.

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