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Stress Analysis of Semi-covered Excavation Foundation Pit in Metro Stations based on Incremental Method

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Abstract. The station foundation pit of Ningbo Metro Line 2 is taken as engineering background, the support structure form of the semi covered excavation foundation pit is introduced. The standard section of the foundation pit is considered as a plane strain problem, a force calculation and analysis model for the half cover system structure is established based on the incremental method, concentrated load of a waste truck is applied within 5.0 m cover plate range outside the middle column and an impact coefficient of 0.4 is considered, overload with value of 20kPa is applied to the rest parts of the cover plate and 5.0 m outside the diaphragm wall. The excavation of the foundation pit is divided into 5 stages, the surface overload, structural self weight, soil pressure and elastic resistance increment, and support axial force are applied respectively, and the bending moment increment of the connecting wall and cover plate system at each excavation stage are calculated. The bearing capacities of the diaphragm wall and cover plate reinforcement are respectively calculated based on the rectangular bending normal section components, and they both meet the strength requirements.

Keywords: Half cover excavation of foundation pit; incremental method; force analysis; vehicle load; bending moment.

1. Introduction

In recent years, the development and utilization of urban underground space is getting faster and faster, and underground rail transit has developed rapidly. However, the construction of subway lines is often restricted by factors such as large traffic flow, many pipelines, and dense buildings. In order to ensure the normal operation of traffic while ensuring the progress of the project and saving construction costs, the semi-covered method has been gradually applied to the subway station foundation pit project.

Many scholars have designed the semi-covered excavation foundation pit, and studied the deformation characteristics of the semi-covered excavation foundation pit by numerical simulation. HOU Zhaolu[1] puts forward half of the metro station top slab is constructed firstly, and soil is backfilled on this portion so that traffic can be resumed as soon as possible, then the second half station structure is constructed by cut-and-cover method.; Zhao Di[2] discussed the design of the concrete cover plate system (column, support, beam, panel) of the foundation pit of a semi-covered excavation station, and verified the simplified calculation in the project.; Ruan Guoyong[3] calculated the force of the main working conditions of the semi-covered excavation structure, and made a comprehensive study and detailed analysis of the semi-covered excavation design scheme. Xu Jian et al.[4] studied the influence of existing buildings on the deformation of semi-covered excavation deep foundation pit by means of numerical simulation based on the semi-covered excavation deep foundation pit of Nanjing Shanxi Road Metro Station. Xu Jian et al.[5] studied the deformation characteristics and environmental effects of semi-covered excavation deep foundation pit adjacent to existing buildings by taking the foundation form and supporting form as variables. Liu Shouhua et al.[6] comprehensively adopted the method of numerical calculation, field measurement and theoretical analysis to analyze the stress and deformation characteristics of the intermediate column in the eccentric compression foundation pit of the semi-covered excavation method.

However, so far, there are few studies on the theoretical solution of the stress analysis of the semi-covered excavation foundation pit support structure. The incremental method calculation refers to comparing the load of each construction stage with the load of the previous stage. The difference between the two is the load increment. The load increment is applied separately to the retaining structure system and the internal force and displacement of the structure are calculated. Then, it is superimposed with the internal force and displacement of the structure calculated in the same way in the previous stage. The result is the stress and deformation of the retaining structure of the foundation pit in the current construction stage[7-9]. In this paper, the foundation pit of the subway station on Ningbo Rail Transit Line 2 is taken as the engineering background. Based on the incremental method, the force calculation and analysis model of the semi-covered system structure is established. In addition to the earth pressure and the elastic resistance released by excavation, the load increment in the model also takes into account the effect of the vertical load increment on the cover plate. The bending moment increment of the diaphragm wall and the cover plate system at each excavation stage is calculated.

2. Project overview

Taking the foundation pit of the subway station on Ningbo Rail Transit Line 2 as the engineering background, the subway station is located at the intersection of two traffic arteries. It is a transfer station for Line 2 and Plan 6. The standard section of the semi-covered excavation section of the station foundation pit is 21.2 ~ 22.5 m wide, 16.82 ~ 17.29 m deep, the end well is 26.5m wide, 19.56m deep, and the total length of the foundation pit is 259.9m. There are five supports in the foundation pit, of which the first is concrete support, the cross-section size of the support is 800mm × 1000mm, and the second to fifth are steel supports with a specification of Φ609 (t = 16mm). A temporary cover plate with a thickness of 350 mm is set on the left side of the foundation pit. The vertical column of the cover plate adopts a 560 × 560 mm lattice column, which is welded by four 200 × 20 edge angle steel and the drop-out plate. The column pile adopts a Φ1000 mm bored pile, and the steel connection beam adopts double-slotted channel steel 40 b. The diaphragm wall on both sides of the foundation pit is 36.3 m deep, and the penetration ratio is 1.16. The embedded section of the diaphragm wall is located in the silty clay layer. A total of 34 concrete supports are set in the longitudinal direction of the foundation pit. The position of the intermediate column is in the same section as the support. The structural section of the standard section of the foundation pit is shown in Fig. 1.

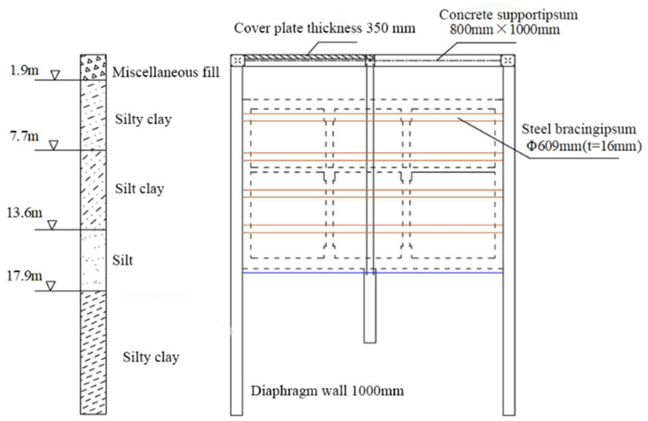


Fig. 1 Structural design of semi-covered excavation system of subway station

3. Stress calculation and analysis of semi covered excavation foundation pit structure

The enclosure structure of the semi-covered excavation system is assumed to be a rigid connection, and the excavation of the foundation pit and the main structure adopt the sequential method. Due to the narrow site, there are often muck trucks and ordinary vehicles passing through the cover plate. In addition, there are also vehicles passing through the outside of the foundation pit of the cover excavation part. In order to study the stress and deformation characteristics of diaphragm wall, internal support, cover plate and intermediate column in the construction process of semi-covered excavation method, it is necessary to reasonably consider the nonlinear problem of stress change of structural system, and adopt more accurate calculation and analysis method, so as to provide theoretical support and guidance for practical engineering construction.

During the construction of semi-covered excavation of subway station, the stress of the structural system composed of diaphragm wall, internal support, cover plate and intermediate column changes with the change of load. At present, the basic methods used to calculate the stress state of the step-by-step excavation process of the foundation pit mainly include the sum method and the incremental method. Based on the incremental method, this paper proposes a calculation and analysis model suitable for the semi-covered excavation method, and carries out the corresponding structural stress calculation and analysis.

3.1. Structure stress calculation analysis model

In foundation pit engineering, the traditional incremental method is commonly used in the study of open excavation method, and it is mainly used in the structural internal force analysis of retaining piles or retaining walls. The load increment is usually the increment of earth pressure and the increment of horizontal elastic resistance released by excavation of soil. In the semi-covered excavation method, the vertical load on the cover plate has a significant impact on the stability of the structure. Therefore, this paper considers the vertical load on the cover plate, and establishes a calculation and analysis model of the semi-covered excavation structure based on the incremental method. The model is used for the whole process of calculation and analysis. The connection between the cover plate and the diaphragm wall and the intermediate column is rigidly treated to meet the requirements of transmitting bending moment, as shown in Fig. 2.

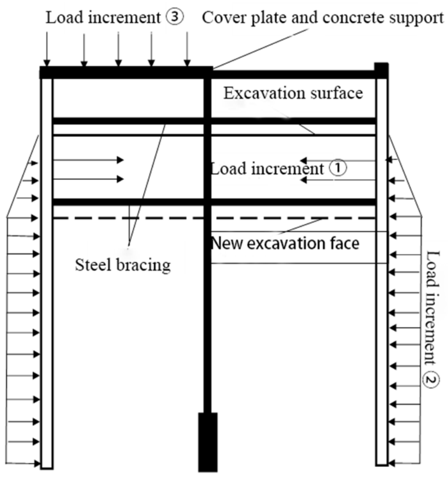


Fig. 2 Stress analysis model of semi-covered excavation system structure

3.2.Vehicle load model

3.2.1. Concentrated load model

The wheel track between the wheels on both sides of the muck truck with an average load of 30 t is 1.8 m, and the interval between the axles is 4 m and 1.4 m. The vehicle load is applied to the front axle, middle axle and rear axle of the vehicle in the proportion of 20 %, 40 % and 40 %

respectively[10,11]. The outer contour size of the 30 t load muck truck is 8m × 2.5m, and the vehicle load is distributed according to the concentrated load as shown in Fig. 3.

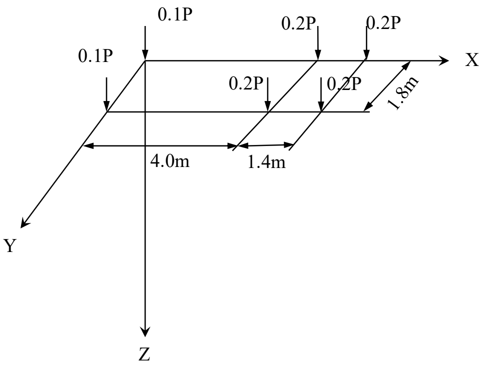


Fig. 3 Chart of load distribution of muck truck according to concentrated load

3.2.2. Load increment analysis

According to the engineering geological conditions and the corresponding geotechnical test results, the soil layer in the depth range of the foundation pit is divided into : miscellaneous fill, the static side soil pressure coefficient is 0.44, and the unit weight of the soil is 18.0 kN/m3; for the mucky clay, the earth pressure on the static side is 0.33, and the gravity of the soil is 19.5 kN/m3. For silty clay, the earth pressure coefficient of the static side is 0.38, and the soil weight is 19.0 kN/m3. For silt, the static earth pressure coefficient is 0.35, the unit weight of soil layer is 20.0 kN/m3, and the unit weight of steel support and intermediate column is 66.5 kN/m3.

In the first stage, the diaphragm wall, the intermediate column, the first concrete support and the upper cover plate were completed, and the first steel support was erected after excavation to a depth of 5.5 m. The main load increments in this stage include the self-weight of the underground continuous wall, the self-weight of the intermediate column, the self-weight of the concrete support and the self-weight of the cover plate, the elastic resistance reaction force generated by the excavation soil, the driving load acting on the cover plate and the prestress applied on the steel support 600 kN. In the second stage, the foundation pit is excavated down to a depth of 8.5 m, and the second steel support is erected. The main load increments in this stage are the soil pressure increment and the elastic resistance increment caused by the excavation of the soil in the pit, and the prestress applied to the steel support of 600 kN. In the third stage, the foundation pit is excavated to 11.5 m deep, and the third steel support is set up. The main load increments in this stage are the soil pressure increment and the elastic resistance increment caused by the excavation of the soil in the pit, and the prestress applied to the steel support of 600 kN. In the fourth stage, the foundation pit is excavated down to a depth of 14.5 m, and a fourth steel support is erected. The main load increments in this stage are the soil pressure increment caused by the excavation of the soil in the pit, the elastic resistance increment, and the 600 kN prestress applied to the steel support. In the fifth stage, the foundation pit is excavated to 17.5 m at the bottom of the pit. The load increment in this stage mainly comes from the elastic resistance increment and soil pressure increment generated by the excavated soil.

3.3.Plane simplification and internal force calculation

3.3.1. Plane simplification of semi-covered excavation system structure

The foundation pit in this paper belongs to the category of narrow foundation pit with large length-width ratio. Therefore, in the calculation of the internal force and deformation of the foundation pit structure in the semi-covered excavation construction, the standard section of the foundation pit can be considered as the plane strain problem. The cross section of the middle part of the foundation pit is selected to calculate and analyze the internal force of the structure, and the calculation width is 1.0 m. Among them, the thickness of the diaphragm wall in the semi-covered excavation system is 1.0m, the thickness of the cover plate is 0.35m, the cross-section size of the intermediate column is 0.56 m

× 0.56 m, the cross-section size of the concrete support is 0.8 m × 1.0 m, and the steel support parameter is Φ0.609 m × 0.016 m. The corresponding structural mechanical parameters are shown in table 1.

Table 1 Physical and mechanical parameters of semi covered excavation supporting structure

Member	**Specification/mm**	**Elastic modulus/GPa**	**Poisson ratio**	**Unit weight /kN·m^{-3}**
Cover plate	Thickness 350	30	0.17	25
Diaphragm wall	Thickness 1000	30	0.20	25
Intermediate column	560×560	210	0.25	30
Steel bracing	Φ609×16	206	0.25	30
Concrete support	800×1000	30	0.17	25

3.3.2. Determination of soil horizontal spring stiffness

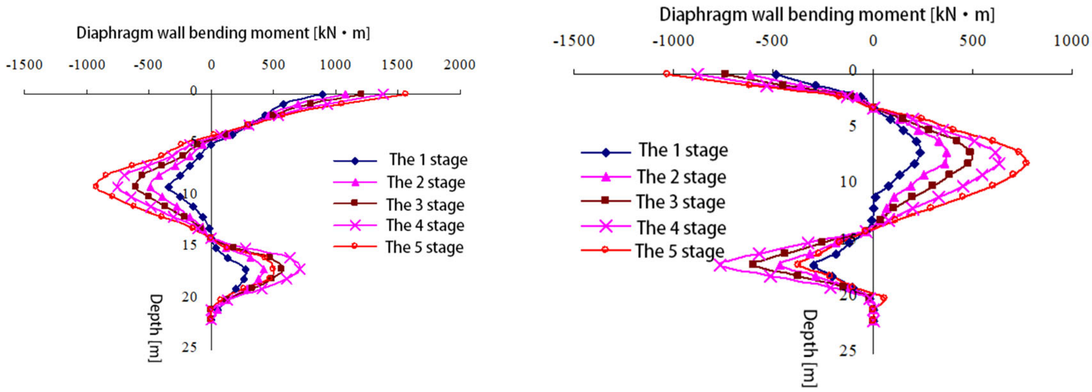
In the process of incremental calculation and analysis of the semi-covered excavation system, the reaction force increment of the elastic resistance generated by the excavation part of the soil needs to be determined by the horizontal reaction force coefficient. The physical and mechanical parameters of the soil layer are shown in Table 2.

Table 2 Soil physical and mechanical parameters

Name of soil layer	**Thickness /m**	**Unit weight /kN·m^{-3}**	**Cohesion /kPa**	**Angle of friction /°**	**Proportionality factor /M N·m^{-3}**
Miscellaneous fill	2	18	17	16.5	4.98
Mucky clay	5	19	10	17.0	9.66
Silty clay	4	19.5	11	17.0	11.53
Silty sand	4	21	0	19.0	13.71

3.3.3. The calculation results of structural internal force in each stage

The internal force calculation of the semi-covered excavation system structure is carried out after the completion of the cover plate construction, that is, after the completion of the cover plate, the diaphragm wall and the intermediate column pouring connection, the structural internal force analysis of the excavation stage is carried out. Combined with the calculation and analysis model proposed above, SAP2000 software is used to calculate the stress of diaphragm wall and cover plate system. The bending moment increment of the diaphragm wall on both sides of the foundation pit in each excavation stage is shown in Fig. 4.



(a) Cover excavation side (b) Open-cut side

Fig. 4 The bending moment increment curve of diaphragm wall in each stage

From Fig. 4, it can be concluded that the maximum bending moment increment of the diaphragm wall on the cover and excavation side of the first stage is 889.32 kN·m, and the open excavation side is -483.67 kN·m; in the second stage, the maximum bending moment increment of the diaphragm wall on the cover excavation side is 188.23 kN·m, and the open excavation side is -169.83 kN·m; in the third stage, the maximum bending moment increment of the cover excavation side is 164.25 kN·m, and the open excavation side is -133.87 kN·m; in the fourth stage, the maximum bending moment increment of the cover excavation side is 178.63 kN·m, and the open excavation side is -171.28 kN·m; in the fifth stage, the maximum bending moment increment of the cover excavation side is 513.27 kN·m, and the open excavation side is -498.85 kN·m.

It can also be seen from Fig. 6 that the maximum bending moment increment occurs in the first stage, that is, when the excavation reaches 5.5 m deep, the incremental load causes the diaphragm wall to produce a large bending moment. The maximum bending moment of the diaphragm wall on the cover-excavation side is 889.32 kN·m, 1077.55 kN·m, 1206.35 kN·m, 1384.98 kN·m and 1559.63 kN·m, respectively. The maximum bending moment of the open-cut side is -483.67 kN·m, 618.28 kN·m, 737.84 kN·m, 881.23 kN·m and 1030.87 kN·m, respectively. It can be found that the bending moment increment of the diaphragm wall on the cover-excavation side is significantly larger than that on the open-cut side. The following conclusions are drawn : The main reason for this phenomenon is that the foundation pit constructed by the semi-covered excavation method has obvious vehicle bias load. The vertical load on the cover plate and the vehicle load on the side of the foundation pit on the cover excavation side make the diaphragm wall on the cover excavation side have large displacement deformation, and the bending moment value is also larger than that on the open excavation side.

The bending moment increment curve of each excavation cover plate is shown in Figure.7.

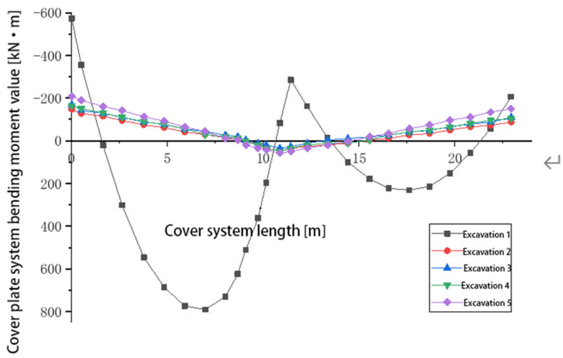


Fig.5 Bending moment increment curve of cover plate in each excavation stage

From Fig.5, it can be seen that the cover plate system is affected by the upper load, and the bending moment increment generated in the first stage of excavation is the largest. The maximum positive bending moment is 791.25 kN·m, and the maximum negative bending moment is -573.75 kN·m. In the other excavation stages, the bending moment is small because the load increment is no longer considered on the cover plate, and the maximum positive and negative bending moment is about 200 kN·m. From the increment of bending moment in each stage, it is found that the lower part of the cover plate is tensioned and the maximum positive bending moment is decreasing. The main reason for this phenomenon is that during the excavation of the foundation pit, the earth pressure and the elastic resistance released by the excavation are increasing. At the same time, the action on the cover plate system causes the tensile area on the upper side of the cover plate. In the support design and construction of the semi-covered excavation foundation pit, targeted strengthening measures should be proposed for this phenomenon.

4. Summary

The general situation of the project is summarized, and the engineering characteristics of the semi-covered excavation construction of the subway station, the characteristics of the foundation pit deformation and the corresponding deformation mechanism are analyzed, such as the displacement deformation of the diaphragm wall, the surface settlement, the temporary intermediate column uplift and the elastic-plastic deformation of the bottom of the pit. Based on the incremental method, the stress calculation and analysis model of the semi-covered structure is established. In addition to the soil pressure and the elastic resistance released by excavation, the load increment in the model also takes into account the effect of the vertical load increment on the cover plate. The bending moment increment of the diaphragm wall and the cover plate system in each excavation stage is calculated. The maximum bending moment increment of the diaphragm wall on the cover excavation side is 889.32kN·m, which is greater than 483.67 kN·m on the open excavation side. The maximum bending moment increment of the cover plate system is 791.25 kN·m. The bearing capacity of the diaphragm wall and the cover plate reinforcement is calculated according to the rectangular bending member, which meets the strength requirements.

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