Analysis of Shield Tunneling Section between Lianhu Park and Zuchongzhilu Stations on Suzhou Metro Line 11

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Abstract. The Suzhou Metro Line 11 is a planned urban rail transit line in Suzhou City. The efficient and safe construction of Line 11 will effectively alleviate the traffic pressure in the urban area, provide convenient and efficient public transportation options, improve traffic congestion, and enhance the convenience and efficiency of citizens' travel. Based on the geological survey, considering the engineering geological and hydrogeological conditions of the tunnel section between Lianhu Park and Zuchongzhi Road stations on Suzhou Metro Line 11, combined with the experience of similar projects, the construction method of shield tunneling with earth pressure balance technique was determined for the tunnel section. To ensure safe and efficient construction, attention points during shield tunneling construction were also addressed. Based on the cross-sectional diagram of the shield tunnel structure, a calculation model for the segment of the shield tunnel was proposed, determining the reinforcement, reinforcement area, and reinforcement ratio for segments at different burial depths. During the specific construction process, a construction monitoring plan was established for different areas within the major impact zone, minor impact zone, and potential impact zone. Shield tunneling construction in urban environments requires meticulous monitoring to ensure construction quality, mitigate risks to the surrounding environment, and safeguard public safety. Therefore, construction monitoring data points were accordingly arranged. This paper presents an analysis of shield tunneling construction for Suzhou Metro Line 11, focusing on the geological conditions, construction methodologies, and monitoring strategies employed. Through comprehensive monitoring and analysis, the study aims to understand the dynamic changes in soil and water pressure during tunnel excavation, assess the impact of construction on surrounding structures, and optimize construction techniques and parameters. The findings provide valuable insights for future urban tunneling projects, highlighting the importance of proactive monitoring and adaptive construction strategies.

Keywords: Metro system; Shield Tunneling Section; analysis and evaluation; shield tunnel segments; construction monitoring

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1 INTRODUCTION

Urban rail transit projects play a vital role in modern transportation infrastructure, facilitating efficient mobility and sustainable urban development [1-2]. The construction of underground tunnels, particularly through shield tunneling methods, presents unique challenges due to the complex geological and environmental conditions of urban areas [3]. Suzhou Metro Line 11, as a significant transportation initiative, necessitates thorough planning and execution to ensure construction quality, minimize environmental impacts, and ensure public safety. The Suzhou Rail Transit Line 11, formerly known as the Suzhou Rail Transit S1 Line, is a rail transit line under construction in Suzhou City, Jiangsu Province, China. The Suzhou Rail Transit Line 11 starts at Weiting Town in the Industrial Park, connecting with Suzhou Rail Transit Line 3, and passes through the western new town of Kunshan, the core area of the central urban area, the eastern economic and technological development zone, Lu Jia Town, Huaqiao International Business District. It terminates at Shanghai Metro Line 11, connecting important transportation hubs such as Yangcheng Lake Station and Huaqiao Station of the Shanghai-Nanjing Intercity Railway, as well as cultural and artistic centers, western medical centers, Yushan Square, civic activity centers, Kunshan City Government, eastern medical centers, international convention and exhibition centers, Shimao Square, Huaqiao International Exhibition Center, and other important passenger flow hubs. The starting point reserves conditions for through connection with Suzhou Line 3, and the terminal reserves conditions for through connection with Shanghai Line 11. A branch line to Taicang South Station is reserved for the future, with a length of about 13 km and 5 stations. As shown in Figure 1, the total length of this line is 41.25 km, with 28 stations. It starts from Weiting Station of Suzhou Rail Transit Line 3, enters Kunshan City to the east, and finally reaches Huaqiao Station of Shanghai Rail Transit Line 11. A branch line to Taicang City is planned. This line is positioned as a major corridor for east-west transportation in Kunshan, connecting Suzhou, Kunshan, and Shanghai [4]. The line started construction on November 27, 2018, and is expected to be opened for traffic on June 28, 2023, with a total investment of approximately 29.451 billion yuan. Line 11 enhances the radiation capacity of the central urban areas of Suzhou and Kunshan, guides the optimization of urban spatial layout, leads the construction of new urbanization, promotes the integration of transportation, industry, and space layout, and realizes the coordinated development of the Yangtze River Delta urban agglomeration, with extremely important demonstration significance [5].

This paper focuses on the shield tunneling construction analysis and evaluation for Suzhou Metro Line 11, with a particular emphasis on the geological characteristics of the construction site, the selection of appropriate tunneling methodologies, and the implementation of effective monitoring measures. By examining the geological profiles, construction methodologies, and monitoring strategies, this study aims to provide insights into the challenges and opportunities associated with urban shield tunneling projects.

Fig. 1. Engineering Planar Diagram of Suzhou Rail Transit Line 11

2 ENGINEERING GEOLOGICAL OVERVIEW

Based on the stratum structure, lithological characteristics, burial conditions, and physical mechanical properties revealed by exploration holes, combined with the "Suzhou Metro Survey Standard Stratum", the site exploration depth can be divided into 8 major layers such as ①, ②, ③, ④, ⑤, ⑥, ⑦, ⑪, and further subdivided into 20 sub-layers. Each lithostratigraphic layer is described according to lithostratigraphic code, lithostratigraphic name, age genesis, and lithological description. The composition of rocks and soils, stratigraphic ages, thicknesses, and elevations within the exploration depth and range are detailed in Table 1 "Ground Soil Layer Division Table".

The terrain of the project site is relatively flat, and the ground foundation soil is mainly composed of clay, loess, and sand, generally distributed horizontally. The impact of ground settlement on the project is minimal, and harmful gases such as shallow natural gas distribution have not been found. There are no liquefiable soil layers in the proposed construction site, so the geological conditions of the site are stable. After proper foundation treatment, it is relatively suitable for constructing the proposed tunnel of this project. Combining with the geological profile of the project section and the longitudinal section of the design route, the main soil layers involved in the shield tunneling at the project site are ②y layer silt clay, ③1 layer clay, ③2 layer clay, ④2 layer loess with sandy loam, ④2a layer loess with clay, ④3 layer sandy loam, ⑤1 layer clay, locally involving ⑤2a layer loess, ⑤2 layer sandy loam. The soil layers along the tunnel bottom vary greatly, and the shield working face encounters multiple layers of soil simultaneously. A comprehensive evaluation indicates that the shield foundation belongs to uneven ground. The main floor of the connecting passage is mainly located on the ⑤2a loess layer, which has a relatively stable stratum and good uniformity of the foundation soil.

Table 1. Subdivision of foundation soil layers

Layer No.	Soil layer name	Layer Thickness (m) Minimum ~ Maximum	Layer Top Burial Depth (m) Minimum ~ Maximum	Layer Top Elevation (m) Minimum ~ Maximum	Distribution Situation
①0	Gravel fill	0.80～3.30	0.00～0.00	2.17～2.64	Mainly distributed below roads
①2	Natural soil	0.50～3.10	0.00～2.00	0.17～2.45	Widespread distribution
②1	Silty clay	0.80～3.80	1.60～3.30	-1.06～1.02	Widespread distribution
②y	Silty clay with silt	1.00～14.00	1.50～5.00	-2.76～1.00	Localized distribution
③1	Silty clay	1.70～8.30	1.80～14.70	-12.29～0.68	Widespread distribution
③2	Silty clay	0.80～5.80	5.40～17.30	-14.89～-3.00	Localized distribution
④2	Silty sand interbedded with silt	2.30～10.70	7.00～18.30	-15.95～-4.60	Uniform distribution
④2a	Silty clay interbedded with silt	0.70～2.20	15.70～17.40	-15.00～-13.43	Localized distribution
④3	Silt interbedded with sandy silt	0.90～7.30	13.70～21.00	-18.73～-11.21	Uniform distribution
⑤1	Silty clay	1.20～4.80	18.40～21.30	-18.81～-15.86	Localized distribution
⑤2a	Silt	0.90～7.80	18.30～25.00	-22.52～-15.95	Major distribution
⑤2	Sandy silt	2.20～10.00	21.30～28.20	-25.55～-18.89	Localized distribution
⑤3	Silty clay	2.40～3.50	21.30～22.60	-20.36～-18.86	Scattered distribution
⑥1	Silty clay	2.20～8.00	22.50～29.20	-26.77～-20.23	Major distribution
⑦1	Silty clay	1.60～14.90	29.20～37.10	-34.75～-26.66	Localized distribution
⑦2-1	Silt	1.10～10.70	28.00～49.00	-46.67～-25.76	Major distribution
⑦2-2	Silty sand interbedded with silt	1.60～10.70	31.30～47.90	-45.60～-29.11	Major distribution
⑦3a	Silty clay interbedded with silt	1.00～4.90	41.00～50.30	-47.97～-38.76	Minor distribution
⑦4	Laminated silt	3.00～11.80	38.00～52.00	-49.70～-35.71	Deep hole exposure

⑪	Sandy silt	1.20～14.90	45.10～58.10	-55.75～-42.86	Deep hole exposure

3 ANALYSIS AND EVALUATION OF SHIELD TUNNELING SECTION

3.1 Shield Tunneling Method Selection

Based on the longitudinal section provided by the design unit, this report involves shield tunneling construction in the tunnel section with a route mileage range from YCK10+072.489 to YCK11+037.726. According to the design longitudinal section, the shield tunnel diameter is designed to be 6.7 meters, and the typical depth of the shield tunnel bottom is between 16.06 and 22.4 meters. To meet the stability requirements of the excavation face, prevent water seepage leading to sand or soil flow, and avoid excessive ground settlement, the selection of shield tunneling method should refer to the national standard "Subway Design Code" (GB50157-2013) and industry standard "Railway Tunnel Design Code" (TB10003-2016), combined with the engineering geological and hydrogeological conditions of this section and experience from similar projects [6-8].

It is proposed to use shield tunneling method for this section, and based on domestic experience from similar projects, both slurry balance and earth pressure balance shield tunnel boring machines are suitable for the hydrogeological and engineering geological conditions of this section. The main soil layers encountered in the shield tunneling range for this section include silt clay of layer ②y, clay of layer ③1, clay of layer ③2, loess with sandy loam of layer ④2, loess with clay of layer ④2a, sandy loam of layer ④3, and clay of layer ⑤1, with local involvement of loess of layer ⑤2a and sandy loam of layer ⑤2. According to the shield tunneling experience in the surrounding areas of Suzhou, the earth pressure balance construction method is generally used, with partial application of the slurry balance method. The earth pressure balance construction method is suitable for excavating different types of soft soil layers. Subways in Shanghai, Suzhou, Wuxi, Changzhou, and other areas are mostly constructed (or under construction) using earth pressure balance shield tunnel boring machines. Therefore, it is recommended to select the shield tunneling method for this section as the more economical earth pressure balance shield tunneling method.

3.2 Considerations for Shield Tunnel Design and Construction

(1) During the construction of the shield tunnel for this project, attention should be paid to the following issues due to the presence of Forward West Road, underground pipelines, rivers, etc., above the tunnel:

a. Control of ground settlement: The main causes of ground settlement caused by shield tunnel construction are stratum loss and reshaping and reconsolidation of the surrounding soil due to disturbance or shear damage. Based on the construction experience of existing subway projects, reinforcement methods such as synchronous grouting and secondary grouting can be adopted to effectively control excessive ground settlement.

b. Control of longitudinal uneven settlement: To control the impact of longitudinal uneven settlement of the tunnel, attention should be paid to differential settlement at the connections of subway stations and tunnel sections.

c. Monitoring of tunnel settlement and ground settlement should be conducted during tunnel construction, as well as deformation monitoring of surface structures and underground pipelines.

d. In the section of this project where the tunnel passes under the Huangni River Bridge pile, the design should consider the influence of important pipelines and existing building foundations on the section tunnel, determine a reasonable route plan, evaluate the risk level of the surrounding environment, and take corresponding design and construction control measures according to the risk level.

e. When the tunnel passes under rivers and several open streams, attention should be paid during design to ensure an adequate safety distance between the tunnel roof and the riverbed, and tunnel waterproofing should be reinforced to prevent water leakage into the tunnel.

(2) Influence of Surrounding Environment on the Tunnel

The current ground along the proposed site is suburban residential areas, and attention should be paid to the influence of the surrounding environment (especially the construction of planned buildings and structures) on the tunnel.

(3) Impact of Survey and Construction on the Tunnel

Some of the survey boreholes for this survey are located within the scope of shield tunnel excavation. Although grouting has been carried out to seal them after the survey, there are still deficiencies. Therefore, attention should be paid during design and construction.

4 CALCULATION OF SEGMENTAL LINING FOR SECTIONAL SHIELD TUNNEL

The cross-section of the shield tunnel is circular, with an internal diameter limited to 5900mm. Considering construction errors, measurement errors, structural deformation, and the effects of later settlement, combined with factors such as engineering geological conditions and burial depth, the inner diameter of the tunnel segment is 5.9m, and the outer diameter is 6.6m. The shield tunnel structure adopts prefabricated C50 reinforced concrete segments, with a segment thickness of 350mm and a width of 1200mm. The entire cross-section is divided into 6 segments. The segments are connected by bent bolts, assembled with staggered joints, as shown in Figure 2.

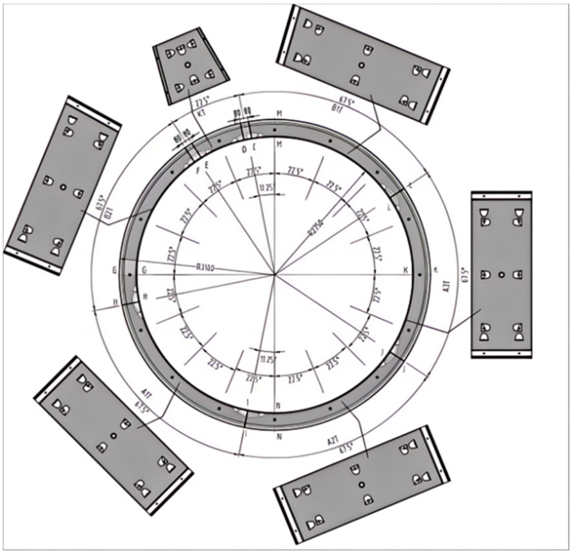

Fig. 2. Structural Cross-Section diagram of Shield Tunnel

Commonly used "load-structure" calculation models include the modified conventional method. This method considers the joint effect of equivalent stiffness rings, introduces the effective utilization rate of bending stiffness, and the rate of increase of bending moments. Generally, reinforced concrete segments are connected by long bolts, and empirical values are taken. The calculation model of the modified conventional method is shown in Figure 3.

After calculating the internal forces of the segments at YDK10+265 section (division point at 13m burial depth), YDK10+558 section (maximum burial depth at 15.95m), and YDK10+865 section (river crossing section), the results of segment reinforcement calculation are provided in the Table 2.

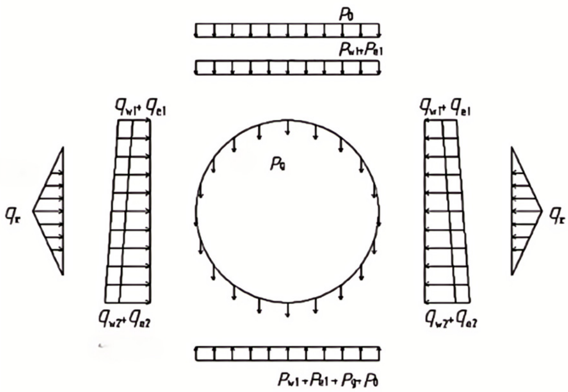

Fig. 3. Revised empirical calculation model diagram

Table 2. Reinforcement calculation for tunnel lining segments

<table>
<tr><th colspan="3" rowspan="2">Burial depth/m</th><th colspan="2">Design value</th><th rowspan="2">Required reinforcement area/mm^2</th><th rowspan="2">Recommended reinforcement</th><th rowspan="2">Reinforcement area/mm^2</th><th rowspan="2">Reinforcement ratio</th></tr>
<tr><th>Quasi-permanent combination</th><th>Basic combination</th></tr>
<tr><td rowspan="6">Boundary point at 13m depth</td><td rowspan="3">Inner side</td><td>M(kN.m)</td><td>74.58</td><td>135.84</td><td rowspan="3">1254</td><td rowspan="3">8@20</td><td rowspan="3">2513</td><td rowspan="3">0.60%</td></tr>
<tr><td>N(kN)</td><td>845.9</td><td>1209.6</td></tr>
<tr><td>Q(kN)</td><td>66.40</td><td>94.96</td></tr>
<tr><td rowspan="3">Outer side</td><td>M(kN.m)</td><td>54.59</td><td>98.53</td><td rowspan="3">934</td><td rowspan="3">10@16</td><td rowspan="3">2011</td><td rowspan="3">0.48%</td></tr>
<tr><td>N(kN)</td><td>1006.3</td><td>1485.6</td></tr>
<tr><td>Q(kN)</td><td>75.92</td><td>123.60</td></tr>
<tr><td rowspan="6">Maximum depth point at 15.95m</td><td rowspan="3">Inner side</td><td>M(kN.m)</td><td>79.56</td><td>142.92</td><td rowspan="3">1321</td><td rowspan="3">8@22</td><td rowspan="3">3041</td><td rowspan="3">0.72%</td></tr>
<tr><td>N(kN)</td><td>1050.7</td><td>1502.4</td></tr>
<tr><td>Q(kN)</td><td>82.48</td><td>117.95</td></tr>
<tr><td rowspan="3">Outer side</td><td>M(kN.m)</td><td>58.54</td><td>101.26</td><td rowspan="3">961</td><td rowspan="3">10@18</td><td rowspan="3">2545</td><td rowspan="3">0.61%</td></tr>
<tr><td>N(kN)</td><td>1507.0</td><td>1825.2</td></tr>
<tr><td>Q(kN)</td><td>106.38</td><td>145.56</td></tr>
<tr><td rowspan="6">At the river crossing section</td><td rowspan="3">Inner side</td><td>M(kN.m)</td><td>68.04</td><td>126.48</td><td rowspan="3">1166</td><td rowspan="3">8@20</td><td rowspan="3">2513</td><td rowspan="3">0.60%</td></tr>
<tr><td>N(kN)</td><td>693.8</td><td>992.5</td></tr>
<tr><td>Q(kN)</td><td>54.48</td><td>77.90</td></tr>
<tr><td rowspan="3">Outer side</td><td>M(kN.m)</td><td>52.68</td><td>99.44</td><td rowspan="3">943</td><td rowspan="3">10@16</td><td rowspan="3">2011</td><td rowspan="3">0.48%</td></tr>
<tr><td>N(kN)</td><td>1507.0</td><td>1233.6</td></tr>
<tr><td>Q(kN)</td><td>66.42</td><td>105.60</td></tr>
</table>

5 SHIELD TUNNELING CONSTRUCTION MONITORING

To ensure the construction quality of urban rail transit projects, ensure the safety of the surrounding environment, ensure the project construction proceeds as scheduled, safeguard the lives and property of the people, and further reduce the probability of accidents, it is particularly necessary to carry out monitoring during the construction of urban rail transit. Monitoring is an informatized construction method, and monitoring results are used to optimize design, guide construction, ensure construction safety and controllability, economic rationality, investment savings, and orderly management. During shield tunneling construction, various monitoring and analysis work is carried out on the dynamics of the strata and changes in surrounding environmental conditions. Through monitoring and analysis, the safety and stability of the strata and the degree of construction impact on the surrounding environment are grasped, and observation results are promptly fed back to reasonably determine construction techniques and parameter guidance for construction. The purposes include:

(1) Understanding the changes in water and soil pressure and deformation during shield tunnel excavation, clarifying the degree of engineering construction's impact on

the strata and identifying potential adverse geological sections and weak links prone to instability.

(2) Understanding the degree of engineering construction's impact on surrounding buildings to ensure they remain in a safe working condition.

(3) Comparing monitoring data with predicted values to assess whether the previous construction techniques and parameters meet expected requirements, to determine and adjust subsequent construction.

(4) Promptly feeding back on-site measurement data and analysis results to optimize design, achieving the objectives of high-quality, safe, economically reasonable, and expedited construction.

The bottom depth of the shield tunnel section from Lianhu Park Station to Zhuchongzhi Road Station ranges from 16.1 to 22.5 meters. After comprehensive analysis, it was decided to take the larger range as the basis. The engineering impact zoning is as follows:

(1) Major Impact Zone: Within a 15.8-meter range directly above and outside the tunnel;

(2) Minor Impact Zone: Within a 15.8 to 22.5-meter range outside the tunnel;

(3) Potential Impact Zone: Within a 22.5 to 35.75-meter range outside the tunnel.

6 CONCLUSION

The construction of Suzhou Metro Line 11 will have a positive impact on the city's sustainable development, residents' travel needs, and the enhancement of the city's image. It is also one of the important measures for Suzhou to promote urban modernization. The analysis of shield tunneling construction for Suzhou Metro Line 11 underscores the importance of proactive monitoring and adaptive construction techniques in ensuring project success. Through comprehensive geological analysis, careful selection of tunneling methodologies, and rigorous monitoring practices, the project aims to mitigate construction risks, minimize environmental impacts, and ensure the safety and stability of surrounding structures.

The findings of this study offer valuable insights for future urban tunneling projects, emphasizing the importance of integrating geological considerations, construction methodologies, and monitoring strategies to achieve efficient, safe, and sustainable transportation infrastructure. As urbanization continues to accelerate, the lessons learned from Suzhou Metro Line 11 will be invaluable for informing future urban rail transit projects worldwide. Based on the characteristics of engineering geology, hydrogeology, and similar project experience in the section from Lianhu Park to Zuchongzhi Road of Suzhou Metro Line 11, the following conclusions are drawn:

(1) The construction method adopted for the section from Lianhu Park to Zuchongzhi Road is soil pressure balanced shield tunneling.

(2) Combining with the cross-sectional diagram of the shield tunnel structure, a calculation model for segmental lining is proposed, determining reinforcement, reinforcement area, and reinforcement ratio for segments at different depths.

(3) The main impact area, secondary impact area, and potential impact area are determined, and a construction monitoring plan is established with corresponding monitoring data points arranged accordingly.

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