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Shallow Tunneling Method and Control Measure for Ground Surface Settlement

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Abstract: In order to ensure that the tunnel deformation and surface settlement are controlled within the allowable range during the construction process, the design unit has compiled technical measures and monitoring schemes for ground settlement control of this project. Based on the example of a shallow tunneling project on Subway line 8, this paper analyzes and discusses the shallow tunneling method in detail and puts forward corresponding technical measures for ground settlement control.

Keywords: Shallow tunneling; Ground surface settlement control; Advance ductule

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1. Introduction

With the rapid development of China's economy and the continuous acceleration of urbanization, the construction of urban rail transit has attracted greater attention. The shallow tunneling method is used mostly and preferably in urban rail transit construction. However, this method cannot be used for construction in some areas due to the limitations of economic and technical conditions; hence, the open-and-cut method is used. As a consequence of the limited land area for urban construction, the construction of underground works can only be carried out on the ground. Certain hidden safety hazards and engineering quality problems have emerged during the construction process as a result of influencing factors such as stratum, geological conditions, construction methods, and environmental conditions [1-3].

2. Project overview

The total length of the subway station line in this project is 1,180 m. The Tuling-Beijie stations section is a newly built tunnel located in an urban area. It passes through many existing subway lines, such as lines 1, 2, 4, and 7. The project subway line crosses line 1, whereas line 2 crosses line 7 in the Tuling-Beijie stations section. The strata that the section tunnel crosses are mainly argillaceous siltstone, and the overlying soil layer is mainly silty clay, with a small amount of medium sand in some parts. The buried depth of the tunnel is relatively shallow (about 15–20 m). The tunnel passes through the existing buildings, where the bearing capacity of the foundation for the existing buildings is 200 kPa, and the maximum settlement is only 5 mm.

2.1. Technical difficulty: Shallow buried depth and complex formation

This project is a tunnel evacuated with the shallow tunneling method, and the buried depth of the interval tunnel is relatively shallow (about 15–20 m). It is a rare tunnel in an urban area, as the buried depth is relatively shallow compared to other urban areas, and the settlement control requirements for the ground surface and buildings are relatively high. The overlying strata where the project is located are mainly silty clay and a small amount of medium sand, and the thickness of argillaceous siltstone is about 15–20 m. Among them, the silty clay is up to 30 m thick and partially contains a small amount of medium sand, while the overlying soil layer is mainly silty clay and a small amount of medium sand. Under such complex geological conditions, construction is difficult, and the safety risks are high.

2.2. Technical difficulty: Inclusion of buildings and strict requirements for ground surface settlement control

Considering many existing buildings and pipelines included in this project, where most of them are located in the city center, the requirements for the control of ground surface settlement are relatively high during the construction process. According to data, the maximum ground settlement value of the Beijing Subway tunnel project is -50 mm, and the maximum ground surface settlement value is -20 mm, while the maximum settlement value of this project is only 5 mm. In addition, the buildings traversed by this project are all old buildings of different degrees, some with long durability, and the current building foundations are in poor condition, so the impact on them should be minimized during construction. Meanwhile, the project passes through multiple existing subway lines such as Lines 1, 2, 4, and 7, and the crossing point is located in the center of the city, so the control requirements for land settlement are more stringent.

3. Construction technology of shallow tunneling

3.1. Construction plan

The center cross diaphragm (CRD) method was applied for this project, where it began with the excavation of the pilot tunnel, followed by the implementation of the primary support and the construction of the secondary lining. This can effectively prevent surface settlement and tunnel deformation. During the excavation of the pilot tunnel, the excavation method of short distance, dense interval, and short steps, which defines the principle of "shallow, dense, and short," was adopted. The face of the tunnel was supported in time after excavation. The stabilization time took up to 1.5–3 days, and the construction of the next step could only be carried out after the face of the tunnel was stable. To ensure the construction safety of the pilot tunnel, the construction methods of advanced curtain grouting to strengthen the ground, small conduit advance support, large pipe shed and small conduit joint support, and timely follow-up of an inverted arch and secondary lining were adopted during the excavation of the pilot tunnel. The section size of the tunnel is 10.68 m × 9.72 m, of which the excavation section is 81.42 m long; the pilot tunnels on both sides are 21.1 m long, and the side pilot tunnels are 30.0 m long. The height of the upper and lower steps of the tunnel section is 3.0 m, that is, the height of the upper step is 11.95 m, and the height of the lower step is 9.93 m. The arch of the tunnel structure was constructed using the three-step method, where the upper and lower steps were alternately carried out in cycles of upper, middle, and lower construction steps; the maximum excavation step distance is 12.1 m. In the construction of the three-step method of the arch, the excavation of the pilot tunnel was carried out in the order from nearest to furthest. According to the ground surface settlement monitoring results, the maximum settlement of the tunnel vault is 30 mm when the construction is symmetrical from the surface to the tunnel arch, whereas the maximum settlement of the tunnel vault is 40 mm when the construction is symmetrical from the vault to both sides of the tunnel. Therefore, it is essential to be attentive to closing the tunnel face in time during tunnel excavation. When the CRD method was used for construction, the arch, secondary lining, and primary support (arch shotcrete + secondary lining) were supported in time after the excavation of the pilot tunnel, and primary concrete was poured in the pilot tunnel. At the same time, monitoring and measurement were strengthened, and construction parameters were adjusted promptly at each stage. With the stability of the tunnel face and the increase in the strength of the initial support concrete, each process was adjusted and optimized in time.

3.2. Shallow tunneling construction

The characteristic of the shallow tunneling method is that the excavation section is small, and the arch is the main part. When the arch is excavated, the secondary lining should be applied as soon as possible. Under normal circumstances, when the soil layer is thick, the construction of the partition wall can be carried out immediately after the construction of the upper steps is completed. However, when the soil layer is thin, the construction of the partition wall can be carried out after the construction of the upper steps is completed. Since the main structure of the station is located in the Yangtze River, special technical measures were taken to ensure that the station structure is not affected by the river water. In order to avoid accidents during construction due to water level changes, the construction and maintenance of temporary drainage systems must be done in time [4-6]. Meanwhile, the surrounding rock deformation and settlement must be strictly controlled when excavating the station. During the construction of the secondary lining, it is necessary to ensure its good combination with the primary support to prevent cracks. After the construction of the station structure is completed, the construction of the secondary lining is required.

3.3. Advance ductule grouting construction

The arch part of the standard section of the primary branch tunnel adopts a single row of advance ductule, DN 32 × 3.25 mm steel welded pipes, the circumferential distance is 0.3 m, the arch part is drilled within 180 degrees, the angle is 16 degrees, and the length is 2.0 m. Each structure was calibrated as mentioned, and a schematic diagram of a single row of advance ductules is shown in **Figure 1**.

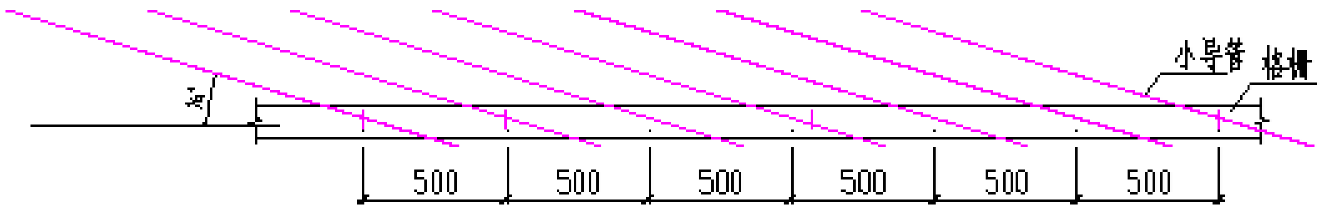

Figure 1. Schematic diagram of laying a single row of small catheters with primary branch structure. Translation (from left to right) Advance ductule, Grille

3.3.1. Manufacturing of small catheters

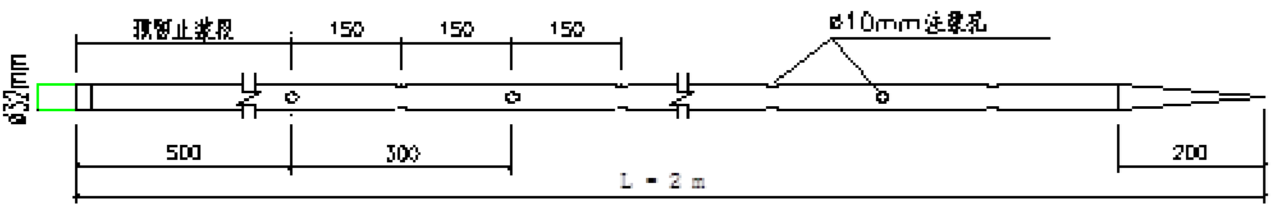

Figure 2. Grouting pipe processing diagram. Translation (from left to right): Reserved for grout stop, Grouting hole

The advance ductule is made of DN 32 × 3.25 mm welded steel pipe, and the front end of the advance ductule is processed into a tapered shape to facilitate insertion and prevent slurry from rushing forward. Drill holes with a diameter of 6–10 mm in the middle of the advance ductule, arranged in a plum blossom shape (to prevent dead angles in grouting), with a spacing of 150 mm, and no holes are drilled within 0.5

m of the tail to prevent grout leakage (**Figure 2**).

3.3.2. Layout and installation of advance ductule

For tunnel excavation, DN 32 × 3.25 mm welded steel pipes are used for advanced grouting to strengthen the formation. The advance ductules pass through the arch grid and are connected to the grid by spot welding. The circumferential distance is 0.3 m, the arch is drilled within 120°, and the elevation and extrapolation angles are 16°.

The advance ductule is constructed by the jacking method, and the ductule is directly jacked manually using a hand-held pneumatic drill. For sandy soil, if there is hole blocking, use a 32 mm diameter steel pipe to make a blowpipe, slowly insert the blowpipe into the soil, perforate with high-pressure air, insert a small ductule after the hole is formed, and seal the nozzle with a cotton cloth.

3.3.3. Grouting

The grouting is mainly made of cement water glass slurry. Fifty mm thick C25 concrete is sprayed on the working face outside the core soil of the upper step to seal and prevent grout leakage, followed by cleaning up the accumulation in the small ductule with high-pressure air. The grouting sequence is from the bottom to the top, and it can be either single-pipe or multi-pipe parallel grouting.

3.4. Advanced curtain grouting construction

The construction steps of the advanced curtain grouting process can be divided into construction preparation, drilling, and grouting, adjustment of grouting amount, bolt grouting sealing and grouting reinforcement, etc., according to the above project overview and conditions, respectively.

3.4.1. Construction preparation

After the tunnel excavation is completed, to ensure the construction quality and safety, it is necessary to carry out pre-grouting construction in front of the tunnel and carry out geological exploration in advance. Before construction, it is necessary to measure the ground surface, underground obstacles, and groundwater level in the site, as well as establish a relevant coordinate system. After the tunnel is penetrated, all boreholes can be treated uniformly to ensure the stability of the front wall structure of the tunnel and meet the requirements of the overall construction and geological conditions. After the tunnel is excavated to the design depth, all drilling rigs are stopped at the same time, and on the premise of completing all the drilling holes, water injection is performed on the remaining undrilled holes [7].

3.4.2. Drilling and grouting

The orifice should be uniform, the maximum rate should not exceed 30 cm, and ensure that there is no water leakage in all holes. When the mud pump needs to be lifted to be flushed with the drill pipe for drilling in the broken ground, the height of the mud pump should be kept consistent. When the drilling is completed, the drill bit should be drilled to a depth of 15–20 cm from the grouting hole.

3.4.3. Adjustment of drilling grouting volume

During the construction process, grouting fluid from the lower part of the borehole is poured with clean water and injected into the formation cracks. When the grouting fluid is injected, it is enough to form a continuous structure. The grouting pressure is generally 0.2 MPa. Both ends of the hole need to be grouted to the surroundings, and each hole must have enough cement slurry to fill the hole. As the amount of grouting in each section of drilling is different, grouting in stages and directions are required, and differential pressure control must be applied during grouting to achieve the purpose of a uniform and consistent pressure.

3.4.4. Anchorage grouting

After the drilling is completed, steel wire rope or lead wire rope is used to tighten the hole wall, followed by arranging each anchor cable evenly in the hole in the form of a single anchor with a length of 1.5–2 m. When anchoring, the size of the hole must be strictly controlled to ensure it forms a whole, and at the same time reserve a row spacing of 2 to 3 mm in the hole wall, so that the number of anchor cables can be accurately laid out when drilling. The hole's diameter is not less than 25 mm, the length of the steel bar should not exceed 3 m, and the spacing should not be less than 1 m. Steel wires should be high-quality steel wires with a tensile strength greater than or equal to 500 MPa (grade 2). During production and installation, they should be evenly distributed within 50–100 mm from the center of the drilling hole to prevent cracks on the hole wall, where each cable joint shall be firmly connected and meet the design requirements (tensile strength not less than 50 MPa), and no less than 2 test operations (drilling for more than 30 d or working pressure greater than 1.0 MPa) must be performed during installation. Before grouting, lime powder is put in the hole (amount of 40–50 kg/m^3), followed by putting it into the mud pool, adding a small amount of water to dissolve it, and then drill into the hole for circulating grouting.

3.4.5. Bolt grouting sealing and grouting reinforcement

Before excavation and support, the prestressed anchor (φ12) is grouted in the "integral + segmented" way, and grouting holes are set on the grouting section of the prestressed anchor (φ12). The quality of anchor bolt grouting can be found through observation. The grouting resistance and grout flow rate of the anchor (Φ12) grouting hole are related to the viscosity of the injected grout and the viscosity of the grout. With the increase of the drilling depth, the injection pressure gradually increases. In order to prevent ground settlement and water gushing from endangering adjacent buildings, a layer of the hose should be laid at the bottom of the pit to connect the slurry discharge pipe and a row of slurry holes should be set. The slurry discharge hole and the slurry discharge pipe are connected at a distance of about 200 m from the bottom of the pit. When the aquifer on the ground is discharged, the slurry discharge pipe should be blocked in time.

4. Ground settlement control measures

The ground settlement control measures include the following:

(1) Strictly control the deformation of the surrounding rock and support structure during construction, and strictly control the grouting pressure and grouting volume when carrying out soil nailing support on the excavation surface. According to the surrounding rock, stratum, hydrogeological conditions, and buried depth of the tunnel, the surrounding rock of this project is mainly silt, fine sand, and muddy clay, where the stratum is soft, the bearing capacity is low, and the self-stabilization ability is poor. Therefore, the composite lining structure is used in the construction to provide secondary support for the surrounding rock and the supporting structure. Meanwhile, strengthen the connection grouting between primary support and secondary lining. The primary support uses small ductules to pre-grout in advance to strengthen the formation [8-10].

(2) Strengthen construction management and monitoring and measurement work. Real-time monitoring of the deformation of tunnels, ground surfaces, and pipelines during the construction process through construction monitoring and measurement, and timely analysis and summary, to take measures to ensure the normal use and operation safety of the ground surface and pipelines.

(3) During the construction process, protective measures shall be taken for ground buildings to control the occurrence of ground settlement . Before the construction of the tunnel between Tuling-Beijie stations, the surrounding buildings, and pipelines shall be investigated and reinforced, and then the tunnel

construction shall be carried out. In order to ensure the normal use and operation safety of surrounding buildings and pipelines, the following measures are taken in this project: (1) reinforcement of surface buildings through the use high-pressure rotary grouting piles for reinforcement, while strengthen the monitoring of the surface buildings during the construction process, and if the surface settlement is too large or unstable then the excavation is stopped immediately and dealt with it in time; (2) pipeline reinforcement through the use of high-pressure rotary grouting piles to reinforce the pipelines around the subway tunnel, effectively reducing the impact of subway tunnel construction on pipelines; and (3) pipeline protection measures, where the underground diaphragm wall is used to close the ground surface settlement area around the subway tunnel during the construction process, which its sealing effect is to reduce the disturbance to the surface buildings during the excavation of the subway tunnel, thereby controlling the ground settlement .

5. Conclusion

In the construction of urban rail transit, the shallow tunneling and underground excavation method is a construction method suitable for better strata, smaller sections, and poor surrounding rock. The shallow burial and underground excavation method in the construction of urban rail transit must be designed following the actual geological conditions, reasonable selection, and improvement of construction methods and processes while monitoring work to ensure the safety and smooth completion of the construction process. Meantime, the construction of urban rail transit projects has a great impact on the surrounding environment, and the control of ground settlement during the construction process is the key. The safety of the tunnel structure and the surrounding environment can be ensured through a reasonable selection of control technical measures and monitoring methods, as well as the use of information-based construction technology.

Disclosure statement

The authors declare no conflict of interest.

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