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Research on Combined Construction Technology for Cross-Subway Tunnels in Underground Spaces

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ABSTRACT

Given the increasingly notable segmentation of underground space by existing subway tunnels, it is difficult to effectively and adequately develop and utilize underground space in busy parts of a city. This study presents a combined construction technology that has been developed for use in underground spaces; it includes a deformation buffer layer, a special grouting technique, jump excavation by compartment, back-pressure portal frame technology, a reinforcement technique, and the technology of a steel portioning drum or plate. These technologies have been successfully used in practical engineering. The combined construction technology presented in this paper provides a new method of solving key technical problems in underground spaces in effectively used cross-subway tunnels. As this technology has achieved significant economic and social benefits, it has valuable future applications.

1. Introduction

Urban rail transit (URT) plays a key role in promoting economic development, improving the ecological environment, optimizing city structure, and sustaining city development. As an important part of urban infrastructure, URT development is directly linked to urban layout and development. Thus, URT supports all urban functions and improves citizens' quality of life. However, when urbanization occurs in a dramatically rapid manner, urban traffic plans become unstable: Either no extension engineering may exist in new subway lines, or the standards and conditions of extension engineering may be unsuitable. As a result, new lines are constructed near densely built areas and existing roads or subway lines, creating an engineering problem of new lines passing through existing structures. For newly developed areas in large cities, the URT construction plan is usually directly related to the layout and development of the city. Difficulty arises when different structures are constructed near or on top of subway tunnels. Any nearby engineering construction projects will affect the safety of operating subway tunnels. At present, most cities in China restrict new construction within the security zones of existing subway lines. This condition causes division in underground space and limits the effective use of space. From this perspective, dealing with the relationship between the safety of existing subway tunnels and the maximized usage of underground space in subway zones presents challenges. A new, economical, and efficient technology must be developed to solve such problems, thus justifying the significance of this paper [1–5].

2. Establishment of a technical system

With further development of urban infrastructure, the usage of underground space and subway construction will inevitably influence each other. A significant amount of research has focused on engineering problems that involve new lines passing through existing structures, and much progress has been made in this field. As urban space increasingly extends underground, the development and utilization of underground space attract increasing attention. URT is often built in city centers. Thus, numerous deep foundation pits may be located near or may cross above operating subway tunnels and stations, especially in new urban areas. Excavation of these deep foundation pits affects the surrounding environment. Therefore, to maintain subway operation during excavation, the displacement of station walls and structures must remain within the allowable range.

However, protection and construction techniques for the exploitation and utilization of underground space within the subway zones of existing subway lines remain insufficient. To ensure subway tunnel security, this study uses current theories and technologies regarding the settlement of underground structures that

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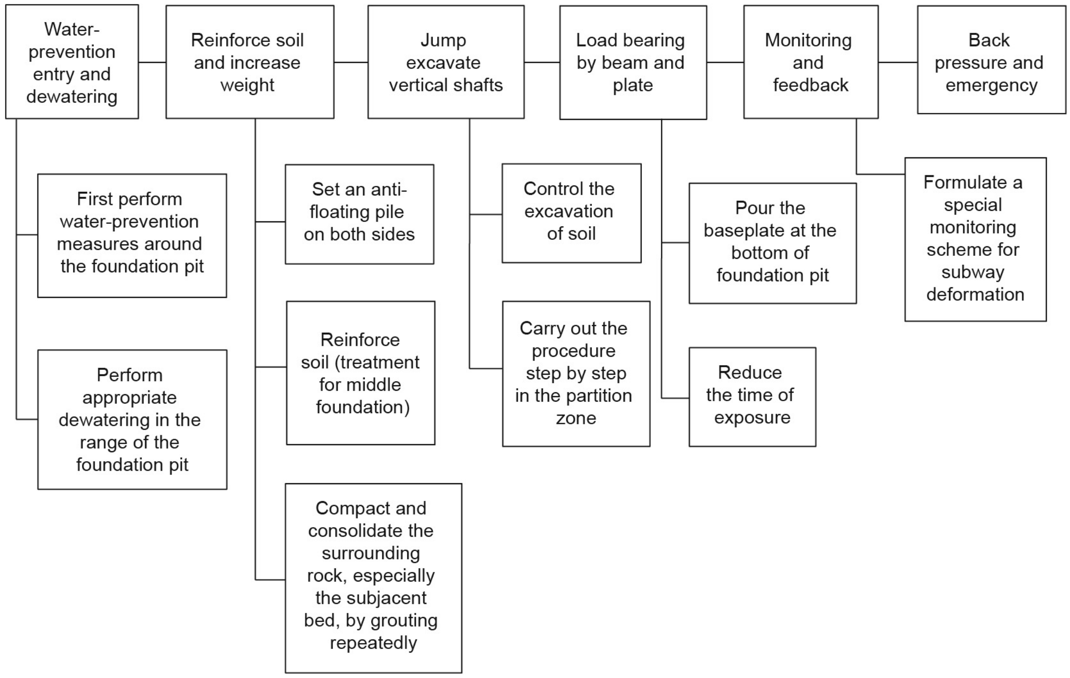

Fig. 1. A technology roadmap for the combined construction technology of a cross-subway tunnel in an underground space.

cross subway tunnels and independent operating tunnels. We put forward new techniques, including the following: establishing a deformation buffer layer between the top of the tunnel structure and the base plate of the underground space; using a steel partitioning drum or plate (PDP) near the two sides of the tunnel; using mud to protect bored piles after construction; using grouting reinforcement for the tunnel structure; controlling the water table; performing jump excavation by compartment; and using a back-pressure portal frame technology and a monitoring control system. A combination of a high-precision three-dimensional (3D) tunnel laser scanner and a robot is used during this process, and a precision real-time monitoring system for tunnel deformation is developed. Fig. 1 illustrates a technology road map for the combined construction technology of a cross-subway tunnel in an underground space.

3. Key technologies

With the continuous deepening of urban infrastructure construction, crossing engineering inevitably occurs in the development of urban underground space and subway construction, resulting in multiple close projects. Although many achievements have been made in the crossing engineering of subway construction, there is still a lack of effective protection measures for underground structures, such as operational subway tunnels, and of new construction techniques. Therefore, given the concept of the subsidence of underground structures in tunnel-crossing engineering being independent, the following key construction technologies were established: setting a deformation buffer in the space between the tunnel structure and the floor of the underground space; separating the deep foundation with a steel bucket or plate adjacent to both sides of the tunnel; and a post-construction retaining pile (wall).

3.1. The construction technique of the deformation buffer layer

3.1.1. Design principle

Based on an analysis of the large deformation characteristics of new construction crossing over the top of an existing subway tunnel, this study proposes a new combined supporting technology of bolt net and shotcrete with a buffer layer of U-shaped steel. A compressible bracket of U-shaped steel is added to provide stable friction resistance to a support basis of bolt net and shotcrete. High-compression foamed concrete is added between the surrounding rock and the U-shaped steel to guarantee the compression performance of the compressible bracket. Fig. 2 illustrates the proposed supporting technology.

The specific functions of each support unit area are as follows:

(1) The primary support, consisting of bolt net and shotcrete, acts as a combined support and includes the anchor-solidifying agent resin bolt (i.e., anchor cable), shotcrete, and mesh reinforcement. The supporting rock is sealed, and degradation of mechanical properties is avoided after sealing. At the same time, the primary support is closely integrated with the soft surrounding rock.

(2) The compressible bracket of U-shaped steel is completely closed to ensure unity of the supporting structure.

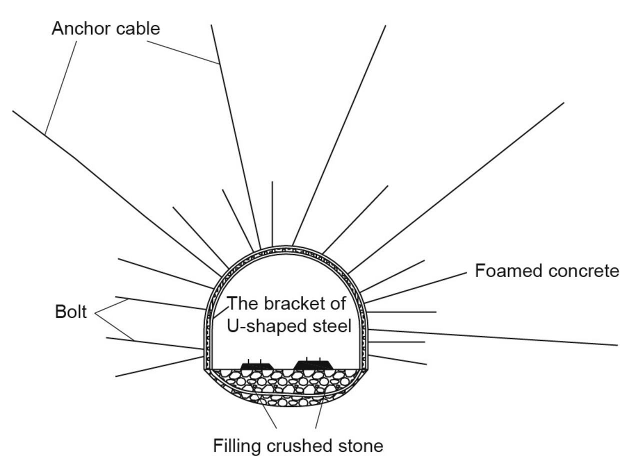

Fig. 2. Diagram of the presented combined supporting technology of bolt net and shotcrete with a deformation buffer layer of U-shaped steel.

(3) The foam in the foamed concrete buffer layer is mixed in a pumping system after adding a blowing agent. The foam and cement paste are then uniformly mixed and poured through the pumping system. A new, lightweight material with a large number of closed pores is subsequently formed after natural curing. The porosity of the foamed concrete gives it a low density and low elastic modulus. The foamed concrete also features good deformation capacity, and can easily absorb and disperse the shock load.

(4) The crushed stone layer ensures easy compression of the U-shaped steel and improves the overall stability.

Another deformation buffer layer or isolated deformation layer is set up between the existing tunnel and the baseplate of the underground space above the tunnel. This layer should be specially designed and constructed according to the type of surrounding structures. The deformation buffer layer can reduce the shock impact of subway operations on the underground space above it and can improve the quality of usable underground space above the tunnel to a reasonable level. The effect of structure settlement on the subway tunnel is thus decreased, the subway tunnel and the structures above it become independent, and the settlement and the subway exert no influence on each other.

3.1.2. Construction technique

Construction of bolt net and shotcrete

The array pitch of the bolts measures 800 mm × 1000 mm, with an error of ±100 mm. A single layer of mesh reinforcement is set up with an overlap length of one grid. The thickness of the shotcrete is 50 mm in total.

Setup of U-shaped steel shed and backfill in the baseplate

- **Fixing of bolts:** The head and tail of two sheds of the U-shaped steel should be fixed with bolts and a press plate. The bolts consist of four groups, with each group containing two bolts. Two groups of bolts are located in the haunch, and the other two groups are located in the inverted arch. An appropriate length of bolt should be exposed to fasten the U-shaped steel shed.
- **Setting up the U-shaped steel shed:** Construction of the U-shaped steel shed proceeds from the bottom up. First, the inverted arch should be laid and filled with crushed stones and sand. Second, the haunch should be set up. Last, the top arch should be constructed, and plastic mesh and plastic paper should be laid.
- **Filling with foamed concrete:** A double layer of plastic mesh and air duct cloth should be laid from the bottom up. The direction of the lay should be along the tunnel, and its length should be around 20 sheds. The depth of the double layer of plastic mesh and air duct cloth in the baseplate should be 500 mm; these materials should be laid alternately on two sides, and should feature an overlap length of 100 mm. When filling the space between the U-shaped steel shed and the arch by the foamed concrete, if the lay height ranges from 1 m to1.5 m, the average thickness of the foamed concrete should be 200 mm. The foamed concrete is filled from the bottom up. The two sides of the U-shaped steel shed should be filled alternately, and the lay height should consistently be 1 m. When the middle of the arch is being filled, three or four sheds should be filled simultaneously. The subsequent section can only be filled with foamed concrete once the current section is completed.

3.2. A reinforcement technique for the surrounding rock

3.2.1. Mixed proportion of clay grout

When grouting the underlying stratum near the surrounding rock of the subway tunnel, pore water is dissipated from the surrounding rock. The resistance of the surrounding rock then improves. This condition significantly reduces the consolidation settlement of the stratum. Repeated grouting of the double-liquid weathered granite results in a lower density after two repetitions. After a considerable number of field tests, we determined that the density and resistance of the surrounding rock improve significantly when clay-cement is used for grouting first, followed by double-liquid grouting.

After a considerable number of tests, the mix proportion and relevant parameters were determined to be as follows: The weights of clay and cement account for 75%–90% and 10%–20% of the solid weight, respectively; the percentage of admixture is 0%–5%, and the weight of water accounts for 43% of the total weight; the specific gravities of the clay grout and clay-cement grout are 1.18–1.28 and 1.25–1.35, respectively; and the relative viscosity of the clay grout measured by the Engler Viscometer is greater than or equal to 16 s, while that of the clay-cement grout is also 16 s. The plastic strength, P_m (kPa), of the clay-cement grout is determined as follows: $P_m = kG/h^2$, where k is the fitting coefficient, G (g) corresponds to the weight of the conical cup test, and h is the depth. If there is insufficient clay, fly ash can be used as an alternative. However, the percentage by weight of the fly ash should be less than 20%.

3.2.2. Design for grouting reinforcement of the tunnel

To increase the stiffness of the rock and soil layers near the subway tunnel and to improve the deformation resistance of the tunnel, grouting can be used for tunnel reinforcement. Steel floral tubes also exhibit an anchorage effect. Fig. 3 shows a typical grouting section in a tunnel.

3.2.3. Construction

Grouting for tunnel reinforcement involves the following steps:

(1) Fix the position of the grouting hole, and select the drill position so that it is located appropriately to hoist segments.

(2) Prepare the platform for grouting. Reserve a 4 cm thickness of concrete after drilling through the segment, based on the location of the hole for hoisting. The drill depth measures 3–5 m and can be adjusted according to the geological conditions.

(3) Adjust the mix proportions and grouting pressure as needed according to field tests.

(4) Insert a DN25 steel floral tube into the grouting holes, and fill the space between the tube and grouting holes with cotton yarn. Immediately after the installation of the grouting pipe, set up an orifice pipe with a ball check in the entrance of the grouting pipe to prevent ground water from entering.

(5) Reinforce the soil by grouting via the four grouting holes in every segment. Drilling at the ballast bed position requires no grouting. Leave the grouting pipe in the soil after grouting. Each segment only requires one section of grouting. Grouting for two symmetrical grouting holes of a segment should commence

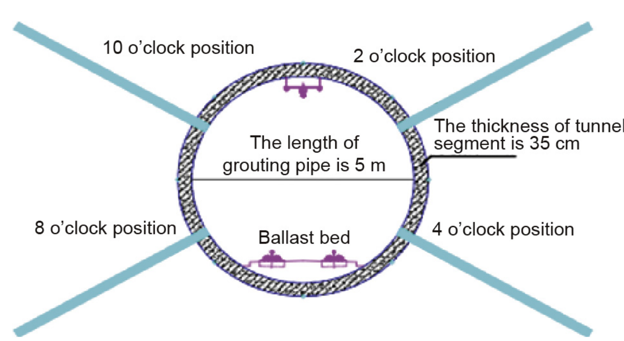

Fig. 3. A typical grouting section in a tunnel.

simultaneously for the same section of grouting, and the grouting pressure should not exceed 0.5 MPa.

3.3. Technology of a steel partitioning drum or plate for a deep foundation

3.3.1. Functions of the partitioning drum or plate in a deep foundation

(1) A PDP can reduce the maximum settlement value of the land outside the deep foundation pit. The PDP can simultaneously change the shape of the subsidence and decrease the corresponding area. The transverse angle variable of the nearby building also decreases. As a result, building damage caused by foundation pit excavation is decreased. With the PDP, the middle of the foundation pit wall experiences a more remarkable decreased settlement than the foundation pit corner.

(2) The PDP can reduce the horizontal displacement of the enclosure walls. A smaller distance between the enclosure wall and the PDP results in less horizontal displacement of the shallow soil.

(3) The soil pressure of the enclosure wall decreases under the influence of the PDP; this result shows that the PDP functions as a blocking enclosure wall. In addition, the PDP shows no effect on the uplift or distribution of soil.

3.3.2. Setup of the partitioning drum or plate

Appropriate amounts of PDP can be built between the structure and the tunnel when structures are located near underground construction. The aims of this arrangement are to prevent a foundation shift in the adjacent area and to improve the stability and safety of nearby buildings during excavation. The PDP mainly consists of a continuous underground wall, dug pile, and deep mixer; it also minimizes foundation deformation near the tunnel.

"Partitioning" refers to the reinforcement of the structure of the stratum by introducing structural units into the soil. The structural unit is not a part of the tunnel structure and is also unrelated to the protected structure; it can prevent the spread of surrounding rock stress due to tunnel excavation. Surrounding rock stress is transmitted to the bearing stratum through the PDP, which acts as a cutoff point in the transmission of deformation. This cutoff reduces the impact of accumulation and differential settlement on the foundation of buildings during excavation. A full-length steel sleeve was used in this study. Fig. 4 shows the construction of a PDP.

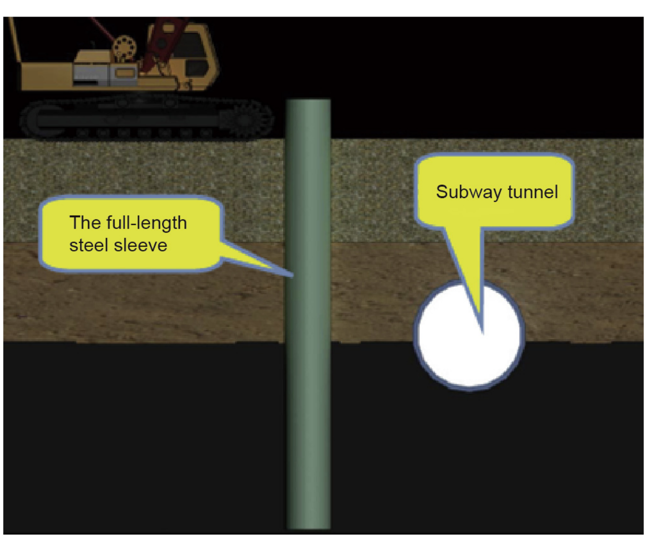

Fig. 4. Construction of a PDP.

3.3.3. Construction of a pile foundation near the subway tunnel

At the side of the subway tunnel where the engineering pile is constructed (Fig. 5), the use of an oscillatory casing drill can prevent excessive breakage and collapse of holes, and remarkably reduce the disturbance range of the rock surrounding the operating subway tunnel.

When the reinforced concrete pile is poured after drilling, the steel casing should be pulled out slowly after the initial set of the concrete. Simultaneously, clay grout is poured from the outside to form a clay layer around the pile and stratum. This results in a decreased influence of pile settlement being observed on the stratum and on the operating subway tunnel.

3.4. The technology of jump excavation by compartment above the subway

If a subway tunnel is buried deep with a shallow foundation pit existing above it, as shown in Fig. 6, it is possible to divide the foundation pit into a series of vertical shafts or compartments, where each compartment has a width of 15 m or less. The excavation and construction of each compartment is completed within a limited time, and is followed by the construction of the next compartment. This technology can reduce the rebound of the stratum caused by the excavation. Along with ballasting, the process of jump excavation by compartment over a certain period can effectively control the uplift of the foundation pit.

3.5. Back-pressure portal frame technology

After the PDP described in Section 3.3 is finished, construction of the cover plate should be carried out by means of jump excavation by compartment. The baseplate should be constructed after the excavation of the bottom of the compartment. As shown in Fig. 7, the pressure of the portal frame encompasses the cover plate, engineering pile, and structural pile. This technology prevents rebound of the stratum and uplift of the baseplate, thus guaranteeing tunnel safety.

Fig. 5. Construction with an oscillatory casing drill.

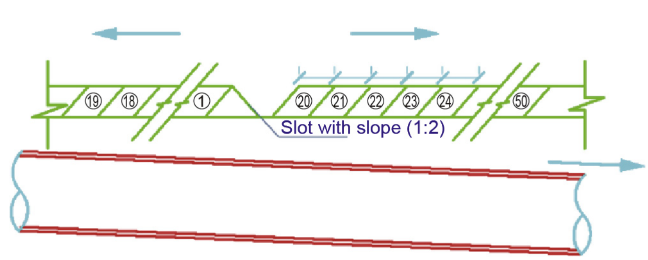

Fig. 6. Diagram of jump excavation by compartment above a subway.

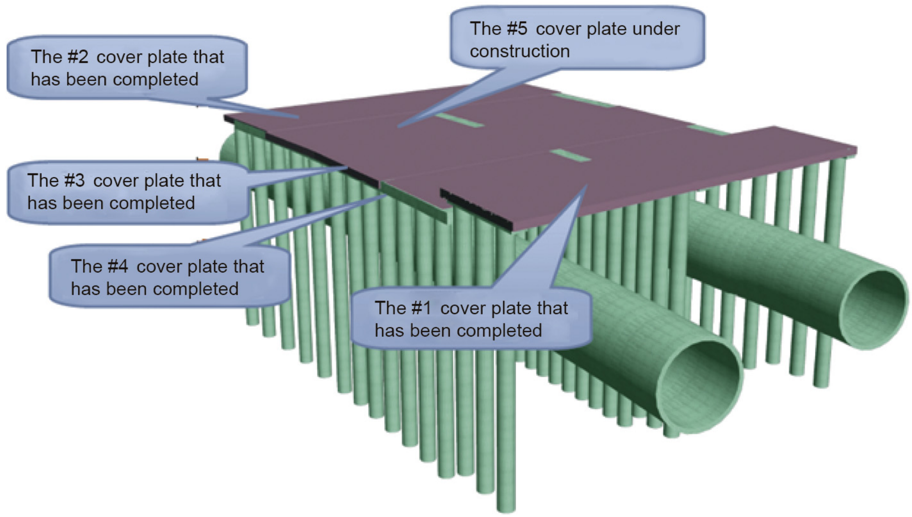

Fig. 7. Construction of the cover plate.

3.6. Novel grouting technology for tunnels below the groundwater table

3.6.1. Water-prevention measures

(1) Drilling a segment hole involves two steps. First, a hole with a diameter of 130 mm and a depth of 100 mm is made by a core machine in the upper tunnel. The position of this hole is located between two hand-holes. Second, a hole with a diameter of 75 mm and a depth of 160 mm is prepared with the same center of a circle (as shown in Fig. 8).

(2) Next, a device is installed in the segment hole to prevent water from entering; this device is installed in the segment hole. Fig. 9 shows a section where the water-prevention device has been installed.

(3) Finally, the ball check device is installed. The grouting pipe covers the designed depth through the flange plate of the device for water prevention. The ball check is then soldered to the grouting pipe. Closing the ball check stops the water, and the ball check is opened for grouting.

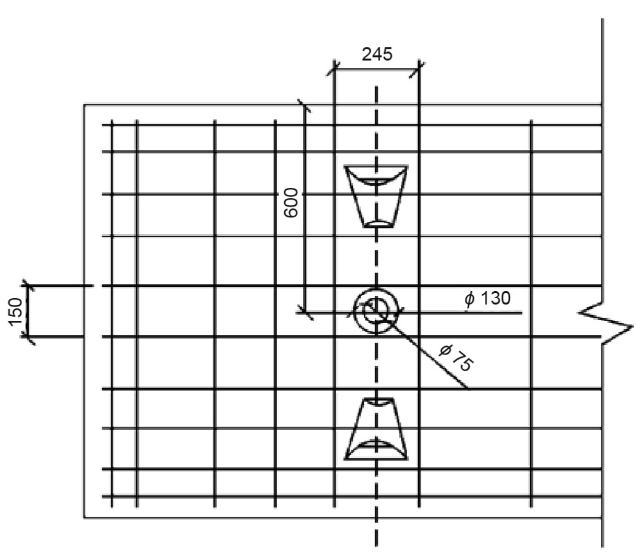

Fig. 8. Sketch map of the drilling position (unit: mm).

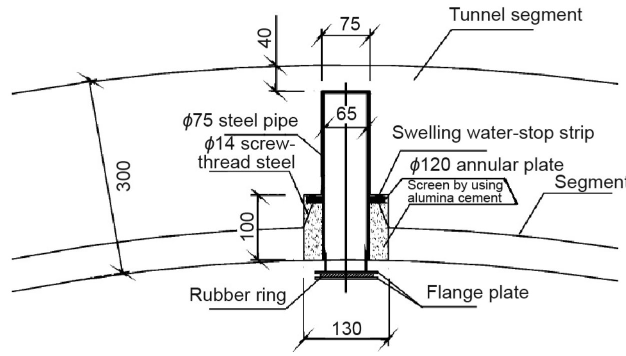

Fig. 9. Section with a water-prevention device (unit: mm).

3.6.2. Measures to control grouting pressure

Grouting pressure is the main parameter of grouting. The quality of the spread of the slurry, filling space, and grouting effect all depend on the grouting pressure. Grouting pressure relates to the degree of fracture of the surrounding rocks, water pressure, slurry material, and gel time. The grouting pressure formula is as follows: $P_0 + 2 \leq P \leq P_0 + 4$, where P and P_0 refer to grouting pressure and water pressure (MPa), respectively. The upper limit of the calculated value should be used during construction.

3.6.3. Sealing measures

The sealing measures are as follows:

(1) When the slurry strength has met the qualification after a seven-day test, remove the flange plate.

(2) Remove a part of the water-prevention pipe (50 mm within the inner arc of the segment) and the grouting bolt.

(3) Close the water-preventing steel plate by welding.

(4) Screen the space using alumina cement.

4. A high-precision real-time monitoring system for tunnel deformation

Automatic monitoring has unique advantages for large-scale tunnel construction: It can realize continuous automatic monitoring, rapidly acquire data, ensure correct data monitoring, and eliminate accidental errors. When the monitoring value exceeds the alarm settings and causes the automatic alarm system to operate, automatic monitoring can assist engineers and technicians to make the right decisions and guarantee timely engineering measurements. An automatic monitoring system can control tunnel engineering at all times and ensure safety in the event of malfunction.

4.1. Automatic monitoring system for tunnel deformation

The components of the automatic monitoring system presented here (Fig. 10) include a high-precision 3D tunnel laser scanner (Fig. 11), a Leica robot for measurement, monitoring stations, a computer control room, datum points, and deformation points. The remote computer can monitor and control the monitoring system through the Internet. Functions of the remote computer include observation, recording, processing, storage, preparation of deformation report forms, and automatic observation of deformation trends.

4.2. Achievement of high-precision displacement in real-time automatic monitoring

Under normal working conditions, the system can give instructions to the monitoring station through a remote computer, while the monitoring station monitors data stability and deformation. Construction-caused deformation of any point in the operating tunnel structure can be accurately monitored in real time through the high-precision 3D tunnel laser scanner. Monitoring and meteorological data are then sent to the control computer, and the data-processing system automatically corrects and estimates data quality. Figs. 12 and 13 illustrate the workflow of the automatic monitoring system.

4.3. Processing and sharing of automatic monitoring data

4.3.1. Data processing

The polar coordinate method, followed by differential processing, can be used to monitor data. Observation of each station can thus be accomplished within a short period. Datum and deformation points can be monitored simultaneously. Thus, the influence of external conditions on datum and deformation points can be considered relevantly. The differences in datum points can be added to the observation values for the deformation points; differential processing is then performed in order to obtain the 3D displacement of the deformation points.

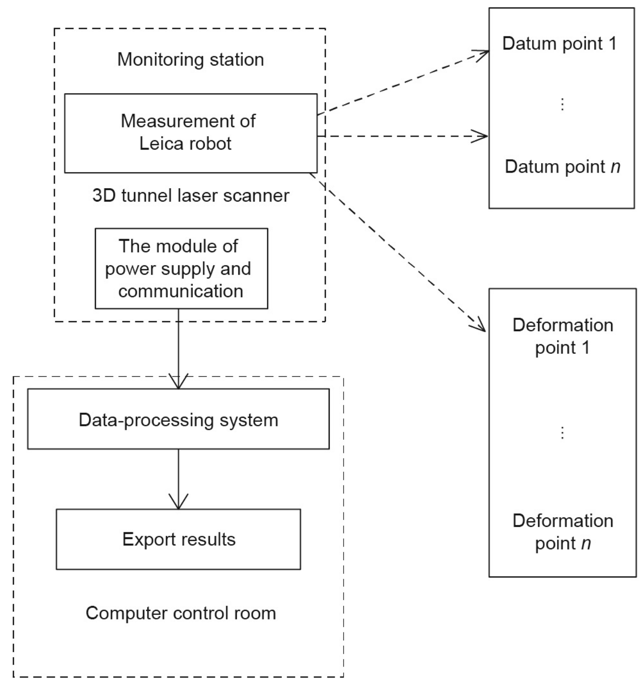

Fig. 10. Composition of the high-precision automatic monitoring system.

Fig. 11. Leica high-precision 3D tunnel laser scanner.

4.3.2. Display and sharing of automatic monitoring data

(1) Real-time monitoring mode. Real-time monitoring is used during grouting reinforcement and foundation pit excavation. The

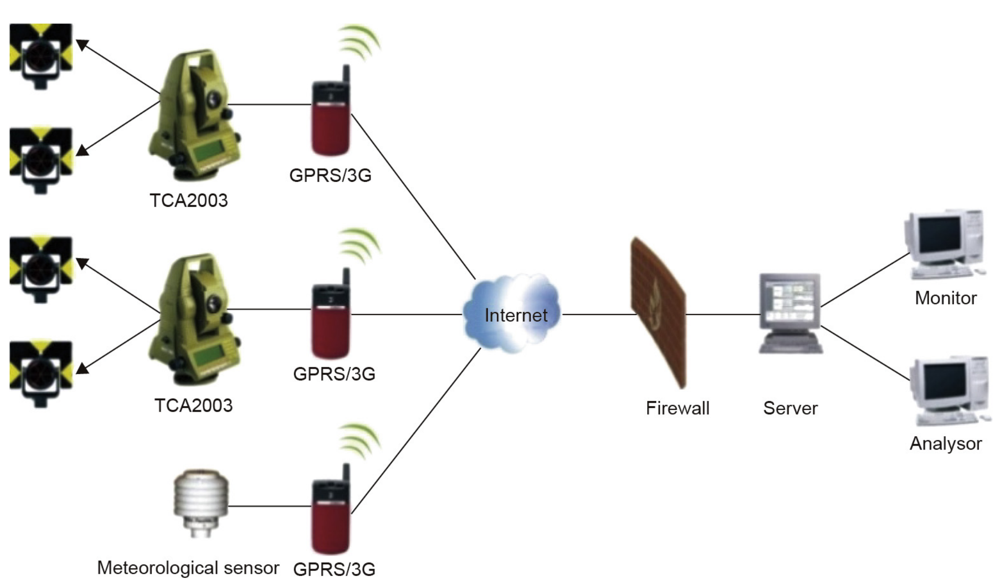

Fig. 12. Schematic diagram of the automatic monitoring system. GPRS: general packet radio service.

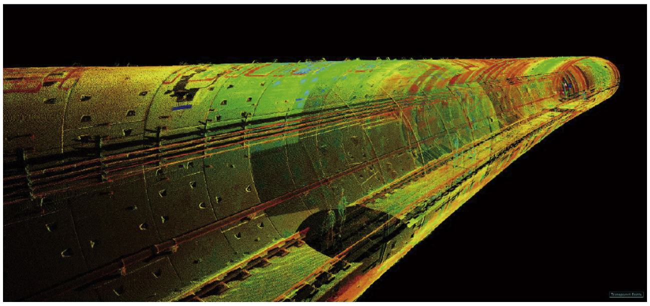

Fig. 13. Overall angle view of the scanning structure for the exchange square in Shenzhen Metro Line 1.

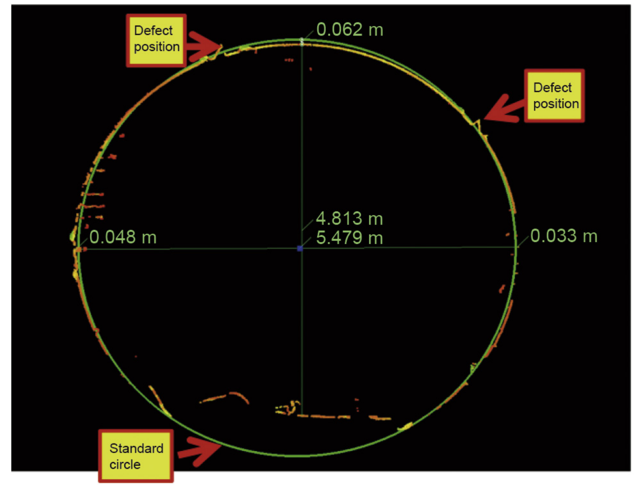

Fig. 14. A comparison of scanning results between the exchange square in Shenzhen Metro Line 1 and a standard tunnel.

monitoring time is monitored every two hours. The system calculates and displays the deformation curve of each point, and the automatic alarm systems run when the conditions exceed the alarm settings.

(2) Display of the information management platform. The unified management and sharing of data offers convenient searching, retrieval, and use of data. In this way, sizable amounts of monitoring data can be obtained. In addition, the oversight of misdescription and misstatement of monitoring data by managers can be avoided. The unified management and sharing of data can also improve work efficiency. In return, timely feedback can be provided in response to monitoring information, and monitoring reports can be created quickly (Fig. 14).

5. Engineering applications

5.1. Project overview

The project described here is located in the Qianhai Zone and Guiwan Zone of Shenzhen. Fig. 15 shows the planimetric position of the project, which has an area of 11 000 m^2. Many engineering construction projects surround the project in question. In addition, most of the project lies in the security zone of Metro Line 11. Figs. 16 and 17 show the relative position of the foundation pit and the subway tunnels.

5.2. Construction technique

The foundation pit of the project lies directly above or near the subway tunnel. Therefore, a key aim as well as unique difficulty of the project is to protect the existing subway tunnel. To protect the subway tunnel, the combined construction technology includes reinforcement of the surrounding rock, wall protection using an underground diaphragm wall, jump excavation by compartment, back-pressure portal frame technology, and a high-precision real-

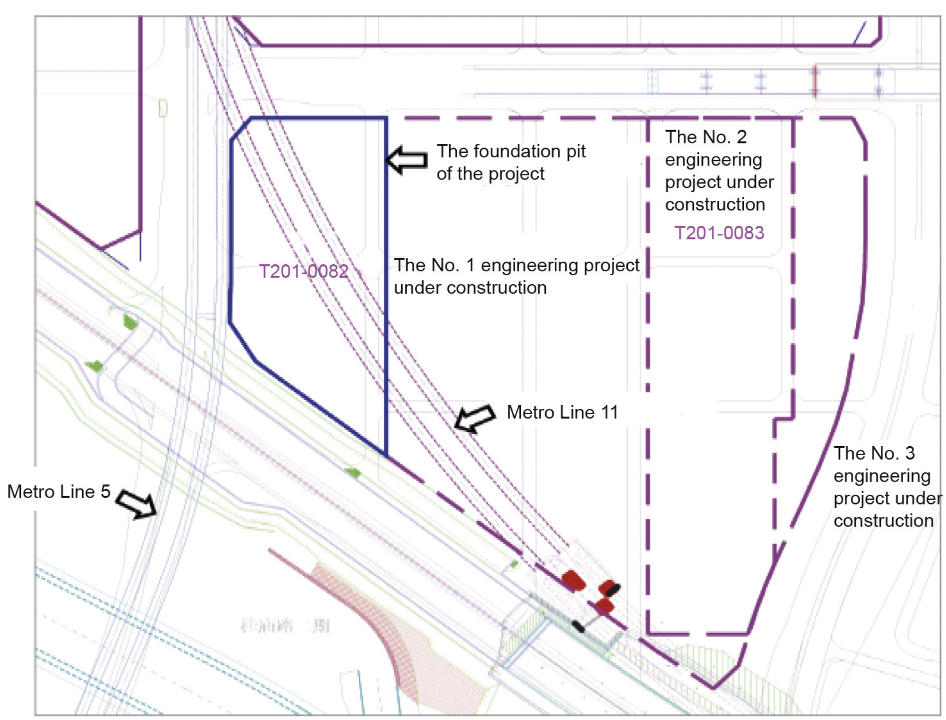

Fig. 15. Planimetric position of the project.

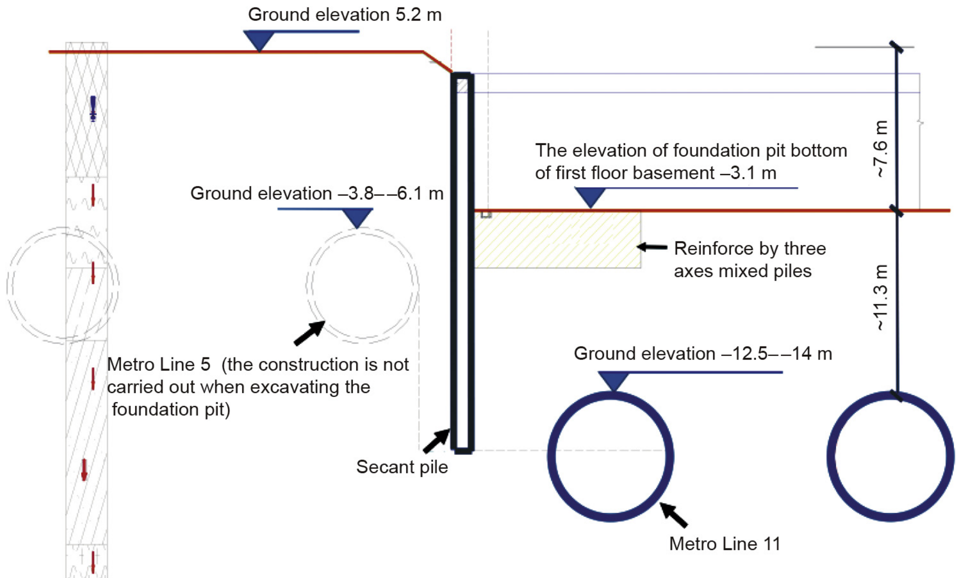

Fig. 16. Cross-section of the north foundation pit and subway tunnels.

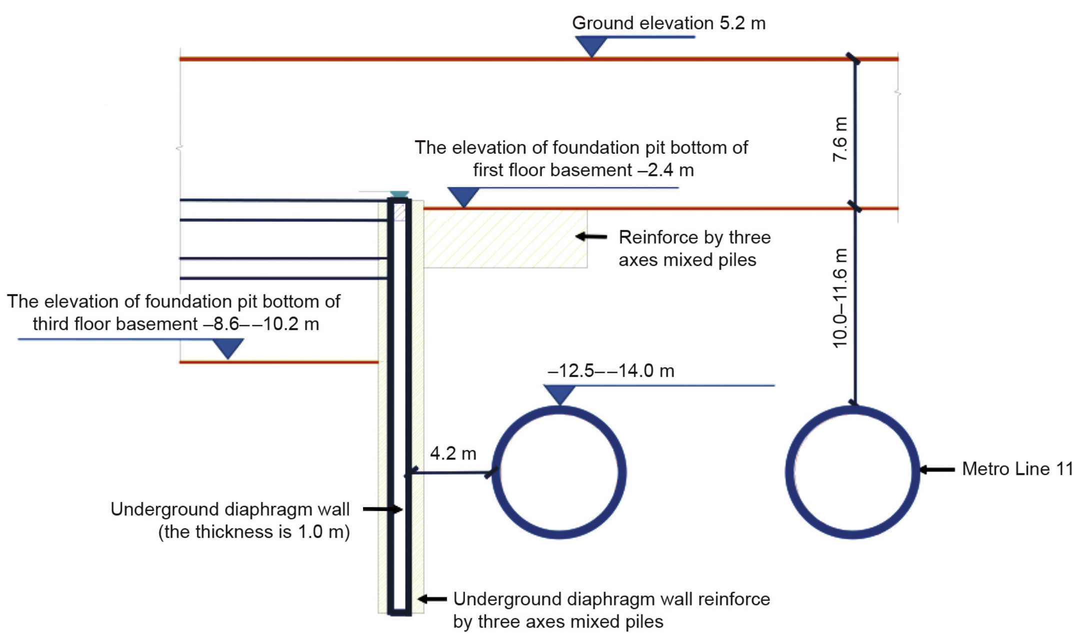

Fig. 17. Cross-section of the south foundation pit and subway tunnels.

time monitoring system. The results indicate a smooth excavation of the foundation pit and an effective project.

5.3. Use of the high-precision automatic monitoring system

The monitoring system used in this project records the real state and defect information of the tunnels, which may include marked areas of water seepage in a section, or damaged sections. Tunnel deformation can be understood by comparing the scanning results of the tunnel in different times. As Fig. 14 shows, the deviation between the tunnel and the design drawing is obtained. The results can effectively guide the construction and realize its informatization.

A relative amount of uplift and settlement in the left line changed remarkably. Figs. 18 and 19 show the curves of maximum uplift and settlement, respectively.

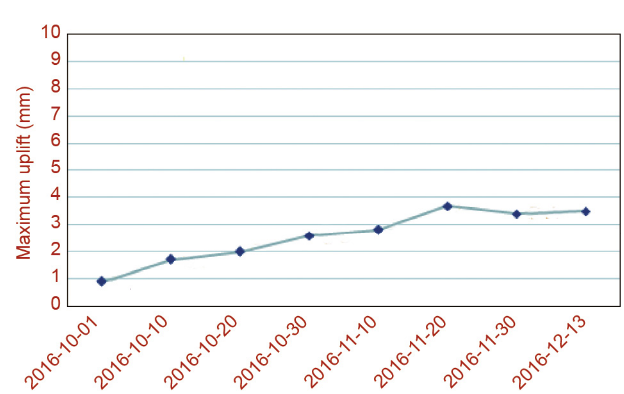

Fig. 18. Maximum uplift in the left line ZSK25 + 658.

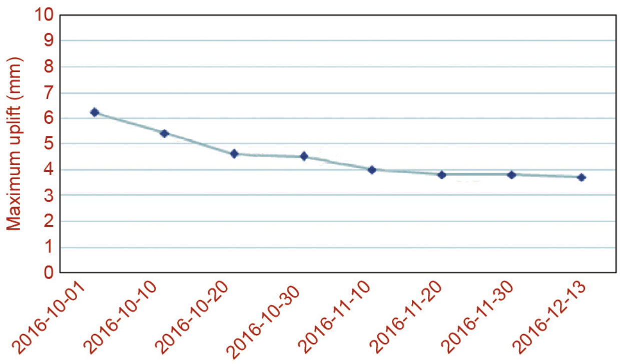

Fig. 19. Maximum settlement in the left line ZSK25 + 534.

6. Conclusions

Our research on the combined construction technology of cross-subway tunnels has yielded several innovations:

(1) A novel reinforcement technology for surrounding rock has been developed. This technology first uses clay-cement grout, followed by double-liquid grouting. An improved reinforcement effect is observed when compared with traditional methods.

(2) The combination of jump excavation by compartment and back-pressure portal frame technology has been found to effectively reduce stratum rebound, and ensures the safety of the operating tunnel.

(3) The concept of the deformation of underground structures (i.e., an independent cross-subway tunnel and tunnels) has been raised here for the first time. The goals of deformation in the early, medium, and late period of construction being independent of each other are achieved using reasonable scientific measures. The results show the remarkable effects of deformation at different periods.

(4) The first real-time high-precision monitoring system for the deformation of existing subway tunnels has been developed, based on a high-precision 3D tunnel laser scanner and a robot; this system provides an actual technological basis for the safety of tunnel operation during construction in underground spaces.

A combined construction technology for cross-subway tunnels in an underground space has been successfully applied in subway engineering in Shenzhen. This technology provides a breakthrough in the usage of underground space near subways under current domestic and foreign specifications. This technology provides a new way of solving key technical problems in the effective use of the underground space of cross-subway tunnels in order to achieve significant economic and social benefits. With this technology, the 1900 ha (1 ha = 10^4 m^2) of land divided by existing subways in the Qianhai Free-Trade Zones in Shenzhen can be utilized to achieve considerable economic and environmental benefits. These implications illustrate the important future applications in the underground space of cross-subway tunnels.

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