Shallow tunnelling method (STM) for subway station construction in soft ground

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1. Introduction

The New Austrian Tunnelling Method (NATM) has become very popular for tunnel construction all over the world due to its technical feasibility, safety and economic competitiveness. This method is based on the principles established by Rabcewicz (1964, 1965) for the use of shotcrete as a support system in tunnel construction, together with observational method to determine whether the support system is sufficient. The use of NATM in soft ground was largely pioneered by Professor Müller for the Frankfurt Metro construction in 1968 and was later further developed by London Underground in the early 1990s.

Although the NATM has achieved remarkable successes (Taunertunnel, Arlberg tunnel, Inntal tunnel, metro Rankfurt, Schweikheim tunnel, Tarbela caverns) all over the world (Kolymbas, 2005), as many of the NATM’s recommendations were already in use, there exists some confusions and conflicts (Karakus and Fowell, 2004). One debate of the NATM is whether it is suitable for soft ground construction (Brown, 1981). It is widely accepted that one of the major principles of the NATM is the deliberate mobilization of the strength of the ground around a tunnel to the maximum possible extent by allowing a controlled ground deformation (Brown, 1981; Sauer, 1988; Will, 1989; Health and Safety Executive, 1996). Institution of Civil Engineers (ICE) claimed that any soft ground application of NATM is associated with the following principal measures: (1) Excavation stages must be sufficiently short, both in terms of dimensions and duration. (2) Completion of primary support—in particular, closure of the sprayed concrete “ring” must not be delayed. Since these two measures are not compatible with the original NATM philosophy for soft ground, ICE proposed a different title of Sprayed Concrete Lining (SCL) instead of NATM for soft ground tunnelling (ICE, 1996).

The NATM was first introduced to China at the end of 1960s. It was widely used after the construction of the Dayaoshan railway tunnel (double track, 14.3 km in length, constructed from January 1981 to November 1988). This method was first adopted for soft ground excavation in the construction of the Jundushan railway tunnel (double track, 8.5 km in length, constructed from January 1985 to August 1988). This method was first used for shallow subway tunnel construction in the Fuxingmen U-turn project (445 m single track, 262 m double track, 7.0–14.9 m tunnel span, 9–12 m soil overburden, constructed from May 1986 to May 1987). These three projects are regarded as the milestones for the NATM used in China. During the Fuxingmen U-turn project construction, tunnelling in shallowly buried soft ground was found to be greatly different from tunnelling in solid or fair rock, although the
construction techniques adopted for these two ground conditions were more or less the same. Therefore the name “shallow tunnelling method” (STM) was assigned by the Ministry of Construction of the People’s Republic of China in 1987 to distinguish it from the NATM. This method has been widely used in subway construction in densely built urban areas in many cities in China since then, such as Beijing, Shanghai, Guangzhou, Shenzhen and Hangzhou.

Although great construction achievements have been made by using the STM, limited research papers on this topic have been published in international journals (Xiang et al., 2005; Fang et al., 2011). In order to bridge the gap between practice and research, this paper provides an in-depth illustration of the STM. In this paper, the two mechanical characteristics of the STM which distinguish it from the NATM are first illustrated. The two necessary preconditions of the STM are then explained. Next the auxiliary methods which are used to guarantee the two preconditions of the STM are demonstrated. After that the underlying principles of

Table 1
Classification of typical auxiliary methods.

<table>
<thead>
<tr>
<th>Method</th>
<th>Construction safety</th>
<th>Environmental safety</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crown stabilization</td>
<td>Cutting face stabilization</td>
</tr>
<tr>
<td>Precoring</td>
<td>〇</td>
<td>〇</td>
</tr>
<tr>
<td>Pipe roof</td>
<td>〇</td>
<td>〇</td>
</tr>
<tr>
<td>Horizontal jet grouting</td>
<td>〇</td>
<td>〇</td>
</tr>
<tr>
<td>Are-shaped top heading with support core remained</td>
<td>〇</td>
<td>〇</td>
</tr>
<tr>
<td>Face shotcrete</td>
<td>〇</td>
<td>〇</td>
</tr>
<tr>
<td>Face bolt</td>
<td>〇</td>
<td>〇</td>
</tr>
<tr>
<td>Face grouting</td>
<td>〇</td>
<td>〇</td>
</tr>
<tr>
<td>Footing reinforcement bolt</td>
<td>〇</td>
<td>〇</td>
</tr>
<tr>
<td>Footing reinforcement pile</td>
<td>〇</td>
<td>〇</td>
</tr>
<tr>
<td>Footing grouting</td>
<td>〇</td>
<td>〇</td>
</tr>
<tr>
<td>Temporary invert</td>
<td>〇</td>
<td>〇</td>
</tr>
<tr>
<td>Water inflow control</td>
<td>Drainage</td>
<td>Above the ground surface</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inside the tunnel</td>
</tr>
<tr>
<td>Rock reinforcement</td>
<td>Growing</td>
<td>〇</td>
</tr>
<tr>
<td></td>
<td>Freezing</td>
<td>〇</td>
</tr>
<tr>
<td>Contact grouting</td>
<td>〇</td>
<td>〇</td>
</tr>
<tr>
<td>Ground reinforcement</td>
<td>Pull-face grouting</td>
<td>〇</td>
</tr>
<tr>
<td></td>
<td>Compensation grouting in the tunnel</td>
<td>〇</td>
</tr>
<tr>
<td></td>
<td>Pre-grouting above the ground surface</td>
<td>〇</td>
</tr>
</tbody>
</table>

〇: Useful methods for construction safety  ●: Useful methods for environmental safety
the STM based on the engineering practices are elaborated. Furthermore nine subway stations using typical sequential excavation approaches of the STM together with their on-site monitoring results are shown respectively. Finally numerical simulation results are presented to compare various sequential excavation approaches.

2. Insights into the STM

In China, soft ground tunnels are generally shallowly buried, particularly common for urban subway construction in soft ground. The associated tunnelling techniques dominated by using manpower-excavation are collectively referred as STM.

The STM is a concept or philosophy for tunnelling in soft ground rather than a set of excavation and support techniques. It is different from the NATM with regard to the design philosophy, although the former also adopts some of the widely used techniques such as sequential excavation, ground reinforcement, shotcreting, monitoring as in the NATM.

The critical overburden depth, which distinguishes the shallowly buried conditions from the deeply buried conditions, is obtained by considering whether the arching effect can be adequately developed. Under deeply buried conditions, the arching zone heights are assumed to be unchangeable. While for shallowly buried conditions, the failure zones are easy to extend to the

Fig. 3. Example of forepoling.

Fig. 4. Typical layout of footing reinforcement pile.

Fig. 5. Typical layout of pipe roof protection.
ground surface. According to the Code for Design on Tunnel of Railway (TB10003-2005, 2005), the critical overburden depth is considered to be 2.5 times of the arching zone height obtained by the deeply buried conditions. In practice, this critical overburden depth is commonly considered to be 4–6 times of the tunnel diameter as the arching zone height varies with different soil conditions. The arching effect is illustrated in detail below.

2.1. The mechanical characteristics of the STM

2.1.1. Limited arching effect

Arching effect is one of the most universal phenomena encountered in soils both in the field and in the laboratory (Terzaghi, 1943). Arching can be best described as a transfer of stresses between a yielding mass of geomaterial and the adjoining stationary members induced by stress redistribution. The shearing resistance tends to keep the yielding mass in its original position resulting in a change of the pressure on both of the yielding part’s support and the adjoining medium. The concept of arching is illustrated in Fig. 1 (Terzaghi, 1946). Due to arching, the height of the relatively loose overburden above the tunnel roof resulting from the excavation of the tunnel is D (the height of the arching zone) instead of H (the overburden depth). The limitation of this practice is that it lowers the strength of the rock mass and permits a significant roof convergence, which mobilizes a zone of loosened rock mass above the tunnel roof. Despite all these limitations, arching effect does play an important role in reducing the load on the roof support of a deep tunnel. However, for a shallow tunnel in soft ground, the arching effect may not be adequately developed to enable an arch to be self-supporting above the excavation. Therefore, under this condition, the support may actually carry a significant portion of the ground directly above the roof.

2.1.2. Limited ground strength mobilization

The philosophy of the NATM relies on the mobilization of the strength of the ground by allowing a controlled deformation. For the STM, however, the ground settlement should be strictly controlled instead of being readily mobilized. This is of paramount importance for shallow tunnelling under densely built urban area, since excessive ground settlement may cause tunnel cave-in, and bring negative effects or even damages to the existing nearby structures and utilities. Therefore the key principle for the STM is to control the ground deformation in order to guarantee the tunnel stability and the environmental safety.
and the resulting convergence for a section of the support in the longitudinal direction of the tunnel. By making a significant and possibly debatable assumption that the support application does not change the ground response, the tunnel-support system reaches equilibrium at the point where the GRC and the SCC intersect. The curve GRC I in Fig. 2 represents the condition of natural ground. The beginning point O of GRC I represents the condition that for the internal pressure equal to the far-field stress $\sigma_0$. As there is no change in the initial stress and strain state around the void, the radial displacement of the wall is zero. With a decrease of the internal pressure, the radial displacement of the wall increases. The initial deformation is linear. It becomes curvilinear upon reaching point A, which indicates the onset of plastic deformation. Beyond point B, with excessive displacement, the disintegration of the surrounding ground may cause cave-in and hence disasters. Therefore, under this condition, it is necessary to take
suitable ground reinforcement measures before tunnelling to guarantee its stability. The GRC II is derived in the presence of ground reinforcement, where “detrimental loosening” is prevented. With the installation of ground reinforcement, the ground deformation and the load on the support can be greatly reduced. Even though the ground is reinforced, a stiffer support with installation immediately after excavation is still preferred (SCC 1 is preferred to SCC 2 and SCC 3) for shallow tunnelling in soft ground, especially in the densely built areas, where strict ground deformation control is required.

2.2. Preconditions for the STM

Using specific construction techniques, the STM allows shallow tunnelling in soft ground conditions, such as silt, clay, sand and gravel. Two preconditions, namely stability of the cutting face and dry tunnelling condition, must be satisfied when using the STM.

2.2.1. Stability of the cutting face

Generally, the self-stability of the shallow tunnel in soft ground is very limited. It is impossible to tunnel through a cutting face with a very short stand-up time. Therefore, suitable measures should be taken to guarantee a long enough stand-up time for the cutting face and the unsupported span before the support takes action.

2.2.2. Dry tunnelling condition

For shallow tunnelling below the groundwater level or in the water-bearing ground, dry tunnelling condition should be guaranteed. Dry tunnelling condition is essential in maintaining the stability of the cutting face by avoiding the mechanical properties of the surrounding ground.
deterioration of the surrounding ground due to water inflow and increasing the effective stress of the surrounding ground. Furthermore, dry tunnelling condition could also improve the underground working environment, hence increasing the working efficiency and decreasing the unsupported time of the free span behind the cutting face.

In practice, these two preconditions cannot be always satisfied. Therefore, one or more auxiliary methods for the STM, which are illustrated below, should be adopted.

2.3. Auxiliary methods for the STM

An auxiliary method is a construction method of a secondary or special nature adopted to ensure tunnel construction safety and surrounding environmental safety, where either conventional support patterns or sequential excavation measures do not provide effective solutions or where they are not advantageous (Japan Society of Civil Engineers, 1996).

Table 1 lists some typical auxiliary methods currently used in the STM. These auxiliary methods are classified according to their objectives—crown stabilization, cutting face stabilization, footing stabilization, ground water control and ground (existing nearby}

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**Table 1**

<table>
<thead>
<tr>
<th>Method Description</th>
<th>Crown Stabilization</th>
<th>Cutting Face Stabilization</th>
<th>Footing Stabilization</th>
<th>Ground Water Control</th>
<th>Ground Stabilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backfill concrete</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Φ800 bored and cast-in-place pile</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Φ800 cylindrical steel column</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Φ121 roof pipe</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Φ32 grout pipe</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

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**Fig. 16. Cross-section of the Xuanwumen station.**

**Fig. 17. PBAA used in the Xuanwumen station.**

**Fig. 18. Measured ground surface settlements.**
structure) movement control. Most auxiliary methods have more than one function in the STM; and all these methods, except the drainage methods, serve the purpose of limiting ground settlement. More than one auxiliary method is often adopted simultaneously. Some auxiliary methods, such as forepoling, footing reinforcement bolt (pile), pipe roof, and contact grouting, are widely used in the STM due to their efficiency and cost-effectiveness. In this way, the auxiliary methods are not only auxiliary but also necessary for the STM. These “necessary” auxiliary methods are further discussed below.

2.3.1. Forepoling

Grouting type forepoling is commonly used in the STM. Forepoling pipes (Fig. 3a), steel, Φ42 (or Φ32), 2.5–3.5 m length, are driven at an angle of 10–30° with the tunnel longitudinal axis into the ground above the top heading arch ahead of the cutting face. The separation of the forepoling pipes in the tunnel cross section is

Fig. 19. Cross-section of the Huangzhuang station in Line 10.

(a) Stage 1  (b) Stage 2  (c) Stage 3

(d) Stage 4  (e) Stage 5  (f) Stage 6

Fig. 20. DPCAA used in the Huangzhuang station in Line 10.

Fig. 21. Measured ground surface settlements.
about 0.3–0.5 m. The distance between the exposed ends of two adjacent loops of forepoling pipes along the tunnel is 1–1.5 m, which is 2 or 3 round lengths of the top heading. Fig. 3b shows a typical layout of forepoling. Forepoling is very effective to enhance the stability of the free span and prevent the failure from extending to the ground surface during construction.

2.3.2. Footing reinforcement bolt and pile

Footing reinforcement bolting and piling consists of installation of downward-facing small diameter steel pipes with grouting or bolts at the footing of the primary supports. Compared to footing reinforcement bolt, footing reinforcement pile is more commonly used in China. For the footing reinforcement piling, Φ42 steel grout pipes, 2.5–3.5 m in length, are driven diagonally downward into the side ground at the foot of the top heading primary support. Fig. 4 shows a typical layout of the footing reinforcement pile. This method is helpful to bring the support capability of the steel grid into full action soon after installation. It is also useful to prevent any potential collapse during the following bench excavation.

2.3.3. Pipe roof protection

The pipe roof protection consists of installing, prior to the tunnel excavation, a series of steel pipes, parallel (or at a certain angle) to the tunnel axis around the periphery of the tunnel. The steel pipes are installed by horizontally boring or ramming at portals.

![Fig. 22. Cross-section of the Jiaomen west station.](image)

![Fig. 23. MDA used in the Jiaomen west station.](image)

![Fig. 24. Measured ground surface settlements.](image)
The voids between the surrounding soils and pipes, and the pipes themselves are then grouted. Commonly, Φ108, Φ114, Φ127 and Φ159 pipes are used. However, large diameter pipes (e.g. Φ300, Φ600) may sometimes be adopted. An individual pipe of the pipe roof is either a single pipe or assembled by welding or screwing multiple pipes together. The pipe roof should be longer than 10 m in view of the efficiency and cost-effectiveness. The maximum length of a pipe roof can be up to 150 m, which means that the entire subway station is under the protection of the pipe roof. Fig. 5 shows a typical layout of the pipe roof protection. This method plays an important role in controlling the potential cave-in during excavation and is very useful in reducing both the magnitude and the lateral extent of the ground settlement. This method is widely used at tunnel portals, other types of tunnel junctions and for the protection of neighboring structures such as buildings, pipelines, and existing tunnels.

2.3.4. Contact grouting

Grouting is used for various purposes during shallow tunnelling in soft ground. Among which, contact grouting, which plays an important role in controlling ground settlement, is highly recommended. Contact grouting is the process of filling voids that are unintentionally created during tunnelling. As the voids induced by the STM generally occur between the primary lining and the surrounding ground, and between the primary lining and the secondary lining, there are two types of contact grouting.
One type of contact grouting involves grouting between the primary lining (or temporary lining) and the surrounding soils using pre-embedded pipes (Fig. 6). Since lattice girder and wire mesh are used in the primary lining, the shotcrete must be sprayed through the girder and the mesh. Due to uneven spraying and rebounding of some shotcrete off the bars, voids are inevitably left behind the individual bars, especially on the tunnel crown. These existing voids may extend and collapse in the course of tunnelling, which will lead to a disturbance to the ground above. Moreover, stress concentration induced around these voids may crack the primary lining locally. This kind of contact grouting is helpful in stabilizing the ground above the tunnel crown during construction and ensuring the primary lining in full contact with the surrounding ground to allow an effective load transfer.

Another type of contact grouting involves injecting grout between the primary lining (waterproofing membrane, to be more accurate) and the secondary lining (Fig. 6). Due to the gravity-driven flow of the casted secondary lining before hardening and the shrinkage of the concrete, a crescent-shaped void is unavoidably created between the primary lining and the secondary lining on the tunnel crown. By a subsequent contact grouting from pre-embedded pipes through the secondary lining, the structural integrity and waterproofing ability of the lining can be enhanced.

2.4. Principles of the STM

Since the STM is mainly used for tunnelling under densely built urban area, the primary aim of this method is to control the ground deformation in order to guarantee the tunnel stability as well as the environmental safety. The underlying principles of the STM based on the engineering practices are elaborated below.
Proper auxiliary methods: Proper auxiliary methods should be selected for the shallow tunnelling after carefully evaluating their effectiveness, economic efficiency and compatibility with the particular conditions of the tunnel.

Sequential excavation with short advance length: The tunnel should be driven in stages such that the area of each face is small enough to control. The entire excavation area is divided into multiple small drifts by temporary support, if necessary. Each drift can then be excavated by using full-face excavation or top heading (with support core)-bench-invert (if necessary) sequential excavation. The drift height varies from about 2.5 m to 6 m and the height of the sequential excavation part varies from about 1.5 m to 3 m. The advance length (free span) should be strictly restricted to the distance between two adjacent lattice girders along the tunnel axis, which is about 0.5–0.75 m. One of the many alternative ways of achieving this principle is illustrated in Fig. 3.

Rigid support with quick installation: Early strength sprayed concrete is preferred with two layers of welded wire mesh and lattice girder for the primary lining. Support measures should be adopted once available after excavation.

Short ring closure time: It is imperative to close the primary lining to a complete ring at a short distance behind the face as soon as possible. Sometimes, temporary invert and temporary side walls are adopted for shortening the ring closure time and enhancing the support capability.

Systematic deformation monitoring: Deformation monitoring in tunnelling projects should always be properly performed with instruments installed or operated either from the ground surface or from inside the tunnel. Observations and measurements as shown in Figs. 31 and 32.
are used to: (1) Assess the stability of the tunnel and existing nearby structures. (2) Verify the assumptions made during the design period. (3) Adjust the construction techniques, mostly auxiliary methods. (4) Improve the ground model for further calculation. (5) Accumulate experiences for the following similar projects.

It can be concluded from this section that the major difference between the philosophy of NATM and STM is whether the strength of the ground should be mobilized by allowing a controlled deformation. The STM utilizes some NATM construction techniques, but not necessarily NATM philosophy. Some typical subway stations in Beijing using the STM are shown below.

3. STM used in Beijing for subway station construction

3.1. Overview of the Beijing subway

Beijing subway is a rapid transit rail network that serves the urban and suburban districts of Beijing municipality. The subway’s first line (Line 1) was opened in 1971. The network has 14 lines, 198 stations (if stations linked with transfers are counted separately), and 339 km of tracks in operation by January 2011. Hundreds of kilometers of new lines and extension lines are currently under construction. By 2015, 19 lines with 561 km tracks will be in operation.

In this study, some typical stations of Line 4, Line 5 and Line 10 in Beijing using the STM are introduced. These three lines are
located in the Beijing downtown area. The STM deems to be more suitable in many stations as the heavy traffic above will not be interrupted by the subway construction. Table 2 lists some detailed information of these 3 Lines.

The geological and hydrogeological conditions of Beijing subway are very complicated, which are enormously different among different stations. A typical geological profile of the Beijing subway is shown in Fig. 7. It reveals that the ground is typically composed of backfill soil, sand, silty sand, silt, silty clay, clay, gravel, etc. Generally the soil layers are not continuous and are interbedded with each other. The typical physical and mechanical properties of soils are shown in Table 3. The ground water level, which varies with the geographic position and seasons, is about 10–25 m below the ground surface.

According to the construction characteristics and especially the construction sequences, the STM used in subway station construction in Beijing is categorized into five “approaches”, which are named as Middle Drift Approach (MDA), Side Drift Approach (SDA), Drift Column Approach (DCA), Pile Beam Arch Approach (PBAA) and Drift Pile Column Arch Approach (DPCAA), respectively. These approaches are used for the construction of both double-deck subway stations and single-deck subway stations. A particular approach may be adopted with some variations in different stations, while one station may use different approaches according to its specific conditions. These five approaches will be discussed in detail below.

### 3.2. Construction approaches for a double-deck station

#### 3.2.1. MDA for the single-arch–double-span station

MDA was adopted for the Puhuangyu station, which was a single-arch–double-span–double-deck station. The typical design cross-section is shown in Fig. 8. The MDA for the Puhuangyu station construction is shown in Fig. 9. A total of five stages are required to accomplish the excavation of the entire cross-section. It is noted that, for any two consecutive stages, the commencement of a later stage does not necessarily wait until the earlier stage is completed in order to improve the construction efficiency.
Therefore, when mentioning the time–deformation curves in the following paper, the consecutive stages that are not distinctly separated are grouped together.

The Arabic numbers labeled in the drifts indicate the designed excavation sequence. Any two drifts labeled with the same Arabic number will be excavated simultaneously. For the convenience of the following description, the labeled Arabic numbers are also referred as the identification of the drifts. For example, stage 1 in Fig. 9 is composed of four substeps, namely drift 1 excavation, drift 2 excavation, drift 3 excavation and drift 4 excavation respectively. Stage 3 is composed of drifts 5 excavation, drifts 6 excavation, drifts 7 excavation and drifts 8 excavation respectively. These explanations are also applicable to the following various stations.

According to the monitoring data, the ground surface settlement was mainly induced in the excavation stages (stage 1 and stage 3). In stage 1, the excavation of the upper two drifts accounted for about 80% of the settlement in this stage. The average ground surface settlement above the middle drifts in this stage was about 40 mm. In
stage 3, the excavation of the upper four drifts (drifts 5 and drifts 6) accounted for about 80% of the settlement induced in this stage. The average ground surface settlement above the side drifts on the left was about 90 mm, while that above the right side drifts was about 125 mm. The largest ground surface settlement value, which exceeded 235 mm, was reported at point R (Fig. 8) of one section.

(a) MDA for double-deck-single-arch station

(b) MDA for double-deck-triple-arch station

(c) PBAA for double-deck-triple-arch station

(d) DPCAA for double-deck-triple-arch station

(e) MDA for single-deck-triple-arch station

(f) SDA for single-deck-triple-arch station

(g) MDA for single-deck-single-arch station

(h) SDA for single-deck-single-arch station

Fig. 40. Simulated ground surface settlements.
So remedial measures, including temporary vertical steel bar support, were adopted after a certain length of drift 5 and drift 6 on the right side of this station, ground surface settlement above the single-deck part excavation respectively. Generally, ground surface settlements accounted for about 55–65% of the final settlements in stage 1. This value was about 5–15% for stage 2, 10–30% for stage 3 and stage 4, and 2–5% for the remaining two stages. The typical measured ground surface settlement curves of the three monitoring points (Fig. 17) are shown in Fig. 21.

3.3.2. SDA for triple-arch–triple-span station

SDA was adopted for the Huangzhuang station, which was a triple-arch–triple-span–single-deck station, in Line 4. The typical design cross-section is shown in Fig. 22. The SDA for the Huangzhuang station construction is shown in Fig. 23. A total of six stages are required to accomplish the excavation of the entire cross-section.

As the single-deck part of the Huangzhuang station in Line 4 was excavated after the construction of the double-deck parts of this station, ground surface settlement above the single-deck part was mainly induced by the former double-deck construction (Fang et al., 2011). The ground surface settlement curves of the three monitoring points (Fig. 25) in five different cross sections are shown in Fig. 27. The average ground surface settlement before construction accounted for about 74% of the average final settlements. Excluding the pre-settlement value, the average ground surface settlement in stage 1, stage 2, stage 3 and stage 4, and remaining two stages accounted for about 73%, 9%, 16%, and 3% of the average net settlement induced by the single-deck part excavation respectively.

3.3.3. MDA for single-arch–triple-span station

MDA was adopted for the Liujiayao station, which was a single-arch–triple-span–single-deck station, in Line 5. The typical design cross-section is shown in Fig. 28. The MDA for the Liujiayao station construction is shown in Fig. 29. A total of five stages are required to accomplish the excavation of the entire cross-section.

According to the monitoring data, ground surface settlement was mainly induced in stage 1 and stage 3. The typical measured ground surface settlement trough derived by the selected monitoring points (Fig. 16) of different construction stages are shown in Fig. 18.

3.2.4. DPCAA for triple-arch–triple-span station

DPCAA was adopted for the Huangzhuang station, which was a triple-arch–triple-span–double-deck station, in Line 10. The typical design cross-section is shown in Fig. 19. The DPCAA for the Huangzhuang station construction is shown in Fig. 20. A total of six stages are required to accomplish the excavation of the entire cross-section.

According to the monitoring data, the ground surface settlement was mainly induced in the excavation stages (stage 1 and stage 3). Generally, ground surface settlements accounted for about 55–65% of the final settlements in stage 1. This value was about 5–15% for stage 2, 10–30% for stage 3 and stage 4, and 2–5% for the remaining two stages. The typical measured ground surface settlement curves of the three monitoring points (Fig. 19) are shown in Fig. 21.

3.3. Construction approaches for single-deck station

3.3.1. MDA for triple-arch–triple-span station

MDA was adopted for the Jiaomen west station, which was a triple-arch–triple-span–single-deck station, in Line 4. The typical design cross-section is shown in Fig. 22. The MDA for the Jiaomen west station construction is shown in Fig. 23. A total of five stages are required to accomplish the excavation of the entire cross-section.

According to the monitoring data, ground surface settlement was mainly induced in stage 1 and stage 3. The typical measured ground surface settlement curves of the three monitoring points (Fig. 22) are shown in Fig. 24. Ground surface settlements accounted for about 55–85% of the final settlements in stage 1 and stage 2, and about 15–45% in the remaining three stages.

3.3.2. SDA for triple-arch–triple-span station

SDA was adopted for the Jiaomen west station, which was a triple-arch–triple-span–single-deck station, in Line 4. The typical design cross-section is shown in Fig. 25. The SDA for the Huangzhuang station construction is shown in Fig. 26. A total of six stages are required to accomplish the excavation of the entire cross-section.

As the single-deck part of the Huangzhuang station in Line 4 was excavated after the construction of the double-deck parts of this station, ground surface settlement above the single-deck part was mainly induced by the former double-deck construction (Fang et al., 2011). The ground surface settlement curves of the three monitoring points (Fig. 25) in five different cross sections are shown in Fig. 27. The average ground surface settlement before construction accounted for about 74% of the average final settlements. Excluding the pre-settlement value, the average ground surface settlement in stage 1, stage 2, stage 3 and stage 4, and remaining two stages accounted for about 73%, 9%, 16%, and 3% of the average net settlement induced by the single-deck part excavation respectively.

3.3.3. MDA for single-arch–triple-span station

MDA was adopted for the Liujiayao station, which was a single-arch–triple-span–single-deck station, in Line 5. The typical design cross-section is shown in Fig. 28. The MDA for the Liujiayao station construction is shown in Fig. 29. A total of five stages are required to accomplish the excavation of the entire cross-section.

According to the monitoring data, ground surface settlement was mainly induced in stage 1 and stage 3. The typical measured ground surface settlement trough derived by the selected monitoring points (Fig. 16) of different construction stages are shown in Fig. 18.

The measured ground surface settlement curves of the three monitoring points in this section are shown in Fig. 10. The abnormally large settlement value was mainly caused by the leakage of the nearby rainwater pipes. According to the site survey, there existed one Φ1200 rainwater pipe, 3 m above the right drift, which was connected with one rainwater pipe branch in the longitudinal direction and another rainwater pipe branch in the lateral direction by a vertical rainwater well (Fig. 11). The two rainwater pipe branches had very serious leakage problems, which liquified the surrounding silt. So remedial measures, including temporary vertical steel bar support (Fig. 12), installation of additional plastic pipes inside the leakage pipes, and compensation grouting on tunnel crown, were adopted after a certain length of drift 5 and drift 6 on the right site were excavated. These measures were proved to be effective for subsequent construction.

3.2.2. MDA for the triple-arch–triple-span station

MDA was adopted for the Tian Tan Dong men station, which was a triple-arch–triple-span–double-deck station, in Line 5. The typical design cross-section is shown in Fig. 13. The MDA for the Tian Tan Dong men station construction is shown in Fig. 14. A total of five stages are required to accomplish the excavation of the entire cross-section.

According to the monitoring data, the ground surface settlement was mainly induced in the excavation stages (stage 1 and stage 3). The average final ground surface deformations above the middle drifts and the side drifts were about 123 mm and 97 mm respectively. Ground surface settlements above the middle drifts accounted for about 70% of the final settlement in stage 1 and stage 2, while ground surface settlements above the side drifts accounted for about 50% of the final settlement in stage 1 and stage 2. The typical measured ground surface settlement curves of the three monitoring points (Fig. 13) are shown in Fig. 15.

3.2.3. PBAA for triple-arch–triple-span station

PBAA was adopted for the Xuanwumen station, which was a triple-arch–triple-span–double-deck station, in Line 4. The typical design cross-section is shown in Fig. 16. The PBAA for the Xuanwumen station construction is shown in Fig. 17. A total of five stages are required to accomplish the excavation of the entire cross-section.

According to the monitoring data, ground surface settlement was mainly induced in the first three stages. After stage 3, with the protection of the concrete arch above the tunnel crown, even though the remaining excavation area was about two times that of the former excavation area, limited ground surface settlement (less than 10 mm) was induced. The ground surface settlements in stage 1 accounted for about 45–55% of the final settlements and accounted for about 35–45% in stage 2 and stage 3. The typical measured ground surface settlement trough derived by the selected monitoring points (Fig. 16) of different construction stages are shown in Fig. 18.
installed with 21 ground surface settlement monitoring points (Fig. 28) were chosen for detailed monitoring. The largest ground surface settlement was reported to be about 53 mm in one of these three sections. The ground surface settlement troughs for different construction stages of this section are shown in Fig. 30. The ground surface settlements accounted for about 65–80% of the final settlements in stage 1, and about 20–35% in the remaining four stages.

3.3.4. SDA for single-arch–triple-span station

SDA was adopted for the Zhangzizhong station, which was a single-arch–triple-span–single-deck station, in Line 5. The typical design cross-section is shown in Fig. 31. The SDA for the Zhangzizhong station construction is shown in Fig. 32. A total of five stages are required to accomplish the excavation of the entire cross-section.

According to the monitoring data, ground surface settlement was mainly induced in stage 1 and stage 3. Three cross sections installed with thirteen ground surface settlement monitoring points installed (Fig. 31) were chosen for detailed monitoring. The largest ground surface settlement was reported to be nearly 70 mm in one of these three sections. The ground surface settlement troughs for different construction stages of this section are shown in Fig. 33. Ground surface settlements accounted for about 55–65% of the final settlements in stage 1, about 10–20% in stage 2, and about 15–30% in the remaining three stages.

3.3.5. DCA for single-arch–triple-span station

DCA was adopted for the Dongsi station, which was a single-arch–triple-span–single-deck station, in Line 5. The typical design cross-section is shown in Fig. 34. The DCA for the Dongsi station construction is shown in Fig. 35. A total of nine stages are required to accomplish the excavation of the entire cross-section.

According to the monitoring data, ground surface settlement was mainly induced in stage 1, stage 3 and stage 7. Two cross sections installed with eleven ground surface settlement monitoring points (Fig. 34) were chosen for detailed monitoring. The largest ground surface settlement was reported to be about 26 mm in one of these two sections. The ground surface settlement troughs for different construction stages of this section are shown in Fig. 36. The ground surface settlements accounted for about 60–70% of the final settlements in stage 1, about 10–20% in stage 2, and about 20%–30% in stage 7.

3.4. Statistical analysis of the ground surface settlement

A total of 342 ground surface settlement monitoring points with final monitored settlements of the nine above-mentioned stations
are chosen for further statistical analysis. These selected points were mainly within the boundary projection of the tunnel cross-section to the ground surface. Fig. 37 shows the histogram of the final ground surface settlements of the 342 points. Table 4 shows the statistical data of the ground surface settlements of the above-mentioned stations. According to the data, it can be concluded that: (1) The ground surface settlement values mainly fall into the range between 0 and 80 mm. A total of 282 points, which account for about 82.5% of the total points, are distributed in this range. The tail of the histogram extends further to the right due to a relatively small number of large settlements. (2) Ground surface settlements varied greatly among different stations. The maximum max-settlement (241.8 mm in the Puhuangyu station) is about 10 times the minimum max-settlement (24.6 mm in the Dongsi station). The maximum mean-settlement (97.7 mm in the Puhuangyu station) is about 6 times the minimum mean-settlement (16.8 mm in the Dongsi station). (3) Generally, the value of ground surface settlement due to the double-deck station construction is larger than that due to the single-deck station construction. (4) The monitored ground surface settlements of all stations, except for the Dongsi station, exceeded 30 mm, which is a universally-adopted ground surface settlement control standard in China. In fact, the construction and environmental safety of these stations were guaranteed even though the ground surface settlement was far larger than 30 mm. On the contrary, tunnel cave-in and pipeline collapse were induced in tunnels with a ground surface settlement less than 30 mm. Therefore, further study should be performed to evaluate the applicability of this 30 mm control standard. It is more preferable to develop specific standards for different stations and even different parts of one station considering the particular local conditions.

4. Numerical simulations of different STM approaches

4.1. Assumptions and descriptions of the numerical models

Due to the distinctly different geological conditions, construction techniques and construction qualities associated with different stations, it is unscientific to conclude which approach is better simply based on the monitoring data. Numerical simulation, using FLAC3D, a finite difference computer program, is employed to evaluate all these approaches by assuming these approaches are used under the same conditions. The dimensions of the numerical simulation models, the overburden depth and the surrounding soil parameters values are shown in Fig. 38. As the main purpose of the numerical analyses is to compare these different STM construction approaches by evaluating their ground surface deformation, only one meshed block is considered in the longitudinal direction to increase the computational efficiency. In these pseudo three-dimensional numerical simulations, the ground deformations prior to the support installation are calculated by using the hypothetical modulus of elastic (HME) soft lining method (Powell et al., 1997; Karakus and Fowell, 2005). The primary supports, modeled by using continuum elements, are installed immediately after excavation with their elastic modulus reduced to 0.2 GPa.

The simulations of the double-deck stations use the cross sections of the above-mentioned double-deck stations. In order to obtain a better comparison, the simulated two cross sections of single-deck stations with triple-arch are chosen based on the single-deck part of the Huangzhuang station in Line 4. In addition, the simulated three cross sections of single-deck stations with single-arch are chosen based on the single-deck part of the Zhangzihong station in Line 5. The detailed mesh shape and corresponding ground surface settlement monitoring points for the stations using different construction approaches are shown in Fig. 39.

4.2. Numerical simulation results

The simulated ground surface settlements of two particular points (point M and point L, Fig. 39) for different construction approaches used in different kinds of stations are shown in Fig. 40. The simulated ground surface settlement troughs for these approaches are shown in Fig. 41.

According to these numerical simulation results, the following conclusions can be obtained.

(1) The ground surface settlements induced by tunnelling vary according to different construction approaches used for different tunnel cross sections. Even for the same cross section, different construction approaches lead to different settlements. It implies that the construction approaches do have a significant effect on the ground surface settlements. The influence of excavation sequences on ground settlements must be taken into account, particularly in the case of a large tunnel span with a limited overburden depth.

(2) Generally, it is difficult to decide which construction approach is better with regard to the ground surface settlement control without considering its construction characteristics. For example, for the construction of the single-deck station with triple-arch and triple-span, the ground surface settlement value induced by MDA (maximum value: 58.8 mm) is slightly smaller than that induced by SDA (maximum value: 62.0 mm). On the contrary, for the construction of the single-deck station with single-arch and triple-span, the ground surface settlement value induced by MDA (maximum value: 94.2 mm) is much larger than that induced by SDA (maximum value: 51.8 mm). It shows that the optimum construction approach with regard to the ground surface settlement control is dependent on its particular construction situation.
5. Conclusions

This paper illustrates the use of the STM for tunnelling in the shallowly buried soft ground in China. According to the study, the following conclusions can be drawn:

1. The STM is a philosophy for tunnelling in the shallowly buried soft ground. Limited arching effect and limited ground strength mobilization are the two mechanical characteristics of this method. The stability of the cutting face and the dry tunnelling condition are the two prerequisites that must be satisfied for this method. Auxiliary methods, which are commonly adopted in the STM to guarantee these two prerequisites, are categorized according to their objectives. Some “necessary” auxiliary methods, such as forepoling, footing reinforcement pile, pipe roof protection and contact grouting, are highlighted. Proper auxiliary methods, sequential excavation with short advance length, rigid support with quick installation, short ring closure time and systematic deformation monitoring are summarized as five principles required to follow when using the STM.

2. MDA, SDA, DCA, PBAA, and DPCAA are summarized as the five major approaches, which are categorized mainly due to the construction sequences, adopted in subway station construction based on the STM in China. Nine typical stations in Beijing using these approaches together with the field monitoring data are used to illustrate the construction procedures, support measures and settlement characteristics associated with excavation. It provides useful references for similar projects in future.

3. The statistical analysis of the final settlement value of 342 ground surface settlement monitoring points of the nine stations reveals that the ground surface settlement values mainly fall into the range between 0 and 80 mm. The 30 mm ground surface settlement control standard is not applicable to subway station construction using the STM in Beijing. Ground surface settlements varied greatly among different stations. The value of ground surface settlement due to the double-deck station construction is generally larger than that due to the single-deck station construction.

4. Numerical simulations were conducted based on the assumption that these approaches are adopted under the same geological conditions and overburden depth. The numerical results reveal that the ground surface settlements induced by tunnelling vary according to the construction approaches used for different tunnel cross sections. Even for the same cross section, different construction approaches lead to different settlements. The optimum approach in ground settlement control should be judged by reasonable numerical simulations in view of particular tunnelling conditions. Comparing the numerical simulation results with the field monitoring results, one can conclude that numerical simulation is an effective means in predicting the ground surface settlement. The PBAA approach is proved to be better than other approaches at ground settlement control as revealed both by numerical simulation and field monitoring.

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Suitable numerical simulations should be performed to assess the competitive nature of different construction approaches with respect to the ground settlement control during the design phase.

In most cases, the simulated ground surface settlement trends, or the ratio of the settlement induced in one particular stage to the final settlement, agree well with the monitored ground surface settlement trends for the particular construction approach in different construction stages, for example, Tiantian Dongmen station using MDA, Xuanwumen station using PBAA, Huangzhuang station using DPCAA, etc. It indicates that the numerical simulation is very effective in predicting the settlement trends induced by different construction approaches, even though the overburden depth and the soil mechanical parameters adopted in the simulation may differ from those of the reality. Moreover, with the availability of some monitoring data collected from the early construction stages and using some numerical back analysis techniques, both the settlement trends and the settlement values can be more appropriately predicted.

Generally, the ground surface settlement value associated with a double-deck station construction is larger than that associated with a single-deck station construction. However, the ground surface settlement induced by PBAA used in a double-deck station construction is comparable to that due to the construction of some single-deck stations, and is about half of that due to the construction of the double-deck stations using other approaches. Considering the construction procedures (Fig. 17) and the predicted ground surface settlement curves in various stages (Fig. 40c), the ground surface settlement of PBAA is mainly due to the construction of the first three stages. After that, with the protection of the firm arch-pile-column support system, limited ground surface settlement is induced in the remaining two stages, even though the remaining excavation area is about two times that of the former excavation. Due to the merit of PBAA in controlling ground surface settlement, many variations of this approach have been proposed and put into practice (Fig. 42). DPCAA and DCA can also be deemed as two variations of PBAA.


