Soil Deformation Induced by Underground Tunnel Construction

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ABSTRACT: Development and utilization of underground railways can effectively ease the problem of urban traffic congestion. However, surrounding soil disturbance during tunnel excavation is likely to cause serious accidents. Thus, analyzing soil deformation during tunnel excavation is important. Through numerical simulation, this paper analyzes the influence of the step distance of a single-bore tunnel on the disturbance of the surrounding soil. Based on research on a single-bore tunnel, this paper further examines the effects of various spacing, locations, and excavation methods on the deformation of surrounding soils during parallel tunnel excavation. The results show that longer excavation steps lead to more intense disturbance to the surrounding soils. The most intense disturbance occurs at the ends of the tunnel. During new tunnel excavation, the tunnel crossing angle has stronger influence than the tunnel spacing on the original tunnel. Among the four excavation methods, single-bore advanced through is the most secure, whereas simultaneous excavation from opposite directions can cause the most intense disturbance to the surrounding soils. In practical operations, corresponding excavation methods can be employed according to specific conditions. Moreover, in-situ monitoring at key positions should be enhanced to avoid accidents.

KEYWORDS: Parallel tunnels; Numerical simulation; Excavation space; Tunnel spacing; Tunnel crossing angle; Soil deformation

1. INTRODUCTION

With the rapid increase in urban population, traffic congestion is worsening. Conventional ground road facilities can no longer satisfy the need of public transportation. Underground rail transport has been becoming the inevitable choice to address urban traffic congestion because of its vast construction space, good security, and strong carrying capacity. However, tunnel excavation may cause large deformation of surrounding buildings. Large deformations may cause serious accidents and economic losses. Therefore, the influence of underground tunnel excavation on surrounding soils is of great importance. The frequently-used methods to analyze the deformation of soil are empirical formulas, theoretical analyses, numerical calculations, and physical model tests. Peck theory (1969) is considered to be the foundation to predict ground deformation during engineering construction based on adequate in-situ monitoring data. Taking the horizontal curve of ground settlement as presenting normal distribution, Atwell (1974, 1982, 1986) introduced a calculation formulae for calculating the maximum settlement. O'Reilly and New (1982, 1992, 1991) and Mair (1993, 1995, 1996) simplified Peck's formula by utilizing engineering examples. With respect to theoretical studies, Tao and Hou (1986) and Hisashi (1992) analyzed circular tunnel from different aspects. However, neither empirical prediction nor theory analysis can quantitatively analyze the soil deformation under different construction schemes and complex soil conditions. Numerical simulation is capable to various conditions and complicated soil layers. At present, numerical simulation often employs 2D models to simulate single-bore tunnel excavation. Zhao et al. (2013) employed finite element software to simulate 2D parallel tunnel excavation, and analyzed the influence of the parallel tunnel arrangement and grouting on the surface settlement of soil. Chen (2002) employed finite element software ANASYS to simulate 2D parallel tunnel excavation, and the influences of the excavation methods on the surface settlement of the soil and the settlement of the tunnel vault are analyzed. Liu et al. (2013) employed the finite element software ABAQUS to analyze on pipe-soil interaction. Song et al. (2013) simulated single-bore tunnel excavation through the finite element analysis software ABAQUS using a 3D model and quantify the influencing range of the constructing tunnel. With regard to parallel tunnel excavation, Jia et al. (2006) conducted 3D simulation using finite element software *3D-б* to analyze the surface settlement of soils. These studies indicate that numerical simulation has unique advantages in analyzing complex conditions.

Physical model tests have been widely used to validate numerical results. Kimura et al. (1981) analyzed the influence of tunnel excavation on the deformation of surrounding cohesive soils and adjacent pile foundation by centrifuge model tests. Wu et al. (1998) studied cohesive soil displacement and collapse mechanism under the influence of single-arch and parallel tunnels. They found that numerical simulation contributes to the analysis on tunnel excavation. Previous studies mainly concentrated on the vertical displacement of tunnel. However, the influence of constructing tunnel on vertical displacement of surrounding soils is rarely analyzed.

In this paper, the horizontal displacements of tunnels are analyzed. The effects of single-bore tunnel excavation space on the disturbance of the surrounding soil are investigated through the finite element analysis software MIDAS/GTS. Also, this study further analyzes the influence of various spacing, locations, and excavation methods on the deformation of surrounding soils during parallel tunnel excavation. The results are favorable for tunnel constructions in the future.

2. EFFECT OF SINGLE-BORE TUNNEL EXCAVATION SPACE ON SOIL DEFORMATION

2.1 Single-bore tunnel modeling

Single-bore tunnel, a basic form of tunnel engineering, is an essential part of the complex tunnel engineering construction, such as parallel and cross tunnels. Excavation space is a key factor that affects safety during construction. This study examines the influence of different excavation spaces on underground tunnel excavation under the assumption that tunnels are built in homogeneous cohesive soil, in which the ground water is 2 m deep, the excavation section is circular, and the radius is 3 m. To simulate the excavation process more realistically and avoid the influence of boundary effect, that the distance from the center line of the tunnel to both sides of the model is assumed as 30 m; the height of the model is 46 m; and the length and depth of the tunnel are 30 and 10 m, respectively. The grouting area with a length, inner diameter, and outer diameter of 30, 3, and 3.5 m, respectively, is lined out in advance to consider the effect of preliminary support. The soil constitutive model used is modified Mohr–Coulomb model. Primary support consists of lining, shotcrete, and anchor. The equivalent thickness of lining and shotcrete is 0.45 m; the length and radius of the anchor are 2 and 0.025 m, respectively. The upper boundary is the ground and set as free surface, four sides are normal constraints, and the bottom is fixed constraint (Figure 1). The parameters of soil and other material parameters are shown in Table 1.

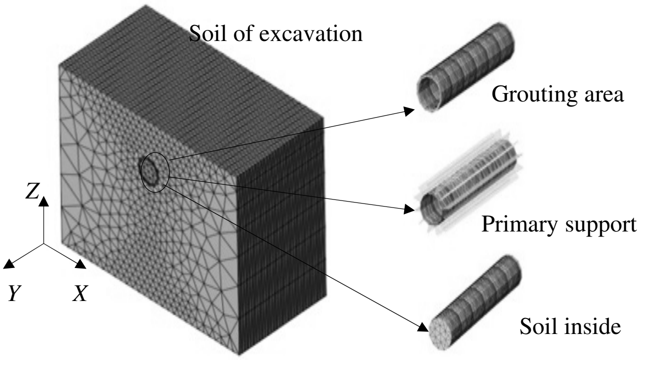


Figure 1 Mesh of finite element model

Table 1 Mechanical parameters of calculation model

Material name	Density ρ (kg/m^3)	Modulus of elasticity E_0 (MPa)	Consolidated quick shearing	
			c (kPa)	φ (°)
Soil	1800	20	25	25
Shotcrete + primary support	2400	25000	-	-
Grouting	2100	40	35	35
Anchor	7700	206000	-	-

The tunnel excavation method used in this study is whole section (2013), which involves excavating along the Y direction, grouting in advance of excavation, and making primary support immediately after each excavation step while conducting the next phase of excavation. Five excavation spaces of 0.5, 1, 1.5, 2, and 2.5 m are simulated. The surface settlement of soil (S_0), tunnel vault settlement (S_v), tunnel lift of inverted arch (S_b), horizontal displacement of the tunnel vault (H_v), and horizontal displacement of the inverted arch (H_b) are observed. Interval tunnel excavation, distance between two tunnels, tunnel crossing angle, and tunnel diameter are represented by B, L, θ, and D, respectively.

2.2 Analysis of single-bore tunnel excavation calculation results

For the single-bore tunnel, the surface settlement of soil, tunnel vault settlement, and inverted arch lift capacity are the keys for construction controlling. Research on the vertical displacement of different positions is conducted. The vertical displacement in the original excavation face of 0.5 m excavation space is taken as an example. The vertical displacements of 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12 o'clock in the original excavation face are listed (Figure 2).

Figure 2 shows that the settlement of tunnel vault (S_v) is the largest among the 12 positions during the excavation. At the same time, the lift of tunnel inverted arch (S_b) is also the largest among the 12 positions. Using the calculation and analysis under different excavation spaces to obtain $S_{0y=0}$ (the surface settlement of soil in the original excavation face), $S_{vy=0}$ (the settlement of the tunnel vault in the original excavation face), and $S_{by=0}$ (the lift of the tunnel inverted arch in the original excavation face), which are in accordance with the excavation steps on the initial section of the tunnel (Figure 3).

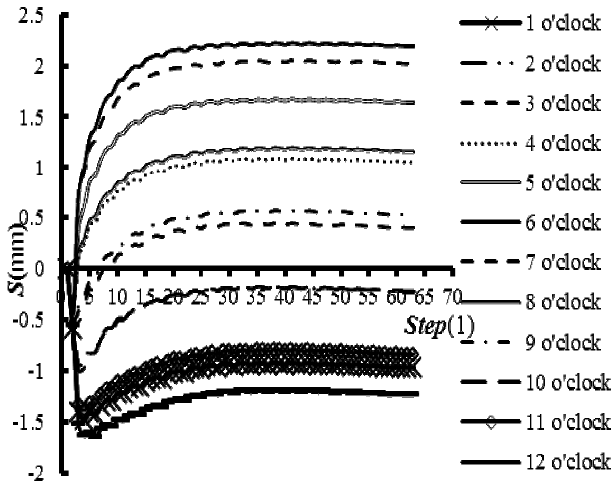


Figure 2 Vertical displacement of different orientations in original excavation face

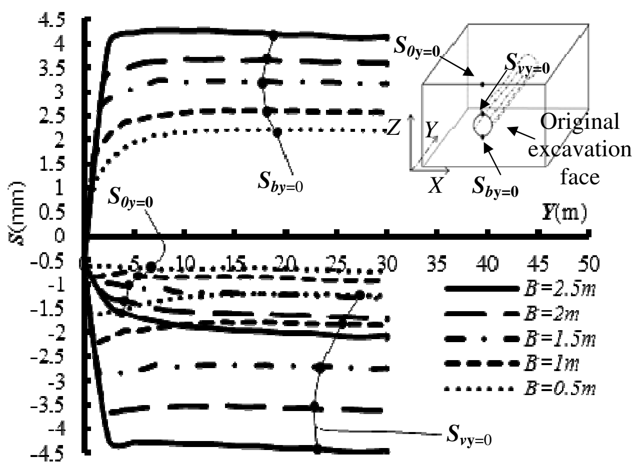


Figure 3 Schematic of $S_{0y=0}$, $S_{vy=0}$, $S_{by=0}$

Figure 3 illustrates that the settlement grows gradually with the increasing excavation space. The steps required to complete the tunnel excavation are also reduced with increasing excavation space. At the same time, the soil disturbance caused by excavation becomes increasingly intense. Thus, achieving a stable value would be difficult for the surface settlement. $S_{vy=0}$ changes more significantly than $S_{0y=0}$, while the overall changing trends of the two parameters are the same. That means both settlements gradually increase with the increases of excavation space, and the growth of the settlement is largest when the excavation space increases from 1 m to 1.5 m.

$S_{by=0}$ has a similar trend of change along excavation with $S_{vy=0}$ and $S_{0y=0}$, which grows with the increases of excavation space. $S_{by=0}$ and $S_{vy=0}$ have similar amplitudes of changes, and the settlement of the surface soil, tunnel vault, and inverted arch tunnel in the initial stage are caused by grouting. A larger excavation step occurs with more significant disturbance of surrounding soils in single-bore tunnel excavation, and the changes in $S_{vy=0}$ and $S_{by=0}$ are most obvious. Thus, particular attention should be paid to the safety of the tunnel vault and inverted arch during tunnel excavation.

The change curves of S_v and S_b are drawn for further studying the deformation variation at various points along the tunnel during tunnel excavation (Figure 4).

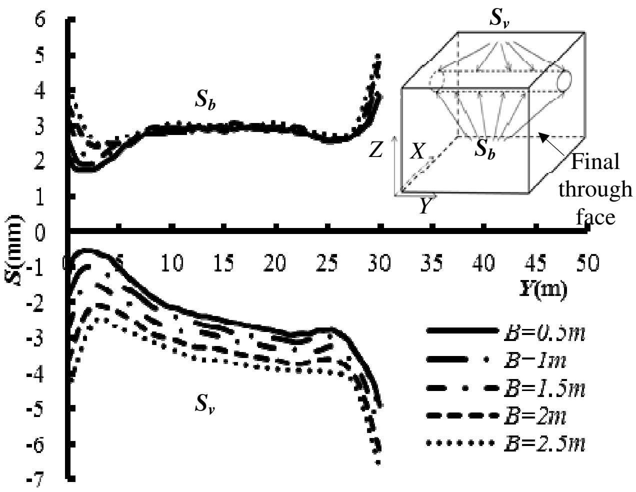


Figure 4 Settlement of vault and uplift of bottom along tunnel

Figure 4 shows that for the tunnel vault, the settlements at original excavation face and final through face of the tunnel are the largest, and the S_v along the entire tunnel gradually increases with the advance of the constraints. At the same time, the settlement increases with increasing excavation space. Therefore, the changes in S_v at the original excavation face and final through face are the key factors that must be considered during the process of construction. The changes in S_b are similar to those in S_v. These changes are most obvious in the original tunnel excavation face and final through face. With the development of constraint, S_b increases at the beginning of the excavation and then decreases before finally leveling off. The amount of lift decreases again at approximately 8 m to the tunnel final through face and then rapidly grows. Such a situation explains that the tunnel original excavation face and final through face are the most vulnerable to the danger of tunnel collapse and other accidents. They are also the most important places that must be considered during tunnel excavation.

During tunnel excavation, the impact on the surrounding soil is not limited to the soil near the tunnel, and the impact on the surface is a problem that must be solved. Uneven settlement on the surface of the earth can cause enormous damage to the existing buildings and ground traffic. The impact of different excavation spaces on the surface settlement of the soil is analyzed as follows. The cross-sectional tunnel center is taken as the research object, and then the surface settlement is extracted by each interval of 2 m to construct the curve of the ground settlement (Figure 5).

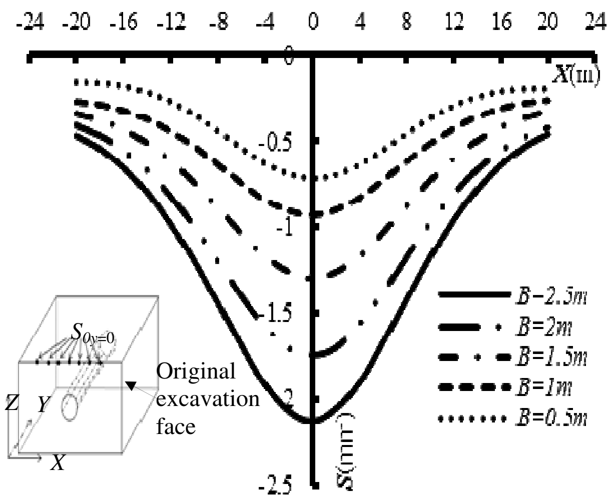


Figure 5 Settlement of surface soil

As shown in Figure 5, the distribution of the surface settlement above the tunnel is symmetrical, and the settlement gradually decreases with increasing distance from the tunnel axis. The surface settlement value stabilizes when the distance from the center of the tunnel is 3.5 D. The ground settlement and scope of influence around the transverse surface decrease correspondingly with decreasing excavation space, and the settlement significantly grows when the interval changes from 1 m to 1.5 m. Therefore, reducing the excavation space is crucial for the safety of the tunnel construction.

3. ANALYSIS OF IMPACT OF NEW TUNNEL ON EXISTING TUNNEL

The impact of a new tunnel excavation on the existing tunnel has become a security issue that must be considered in underground engineering. Modeling tunnel is under the premise of fixed single-bore tunnel calculation parameters (Figure 6). According to this model, the impact of new tunnel excavation on an existing tunnel with different spacing and positions is analyzed.

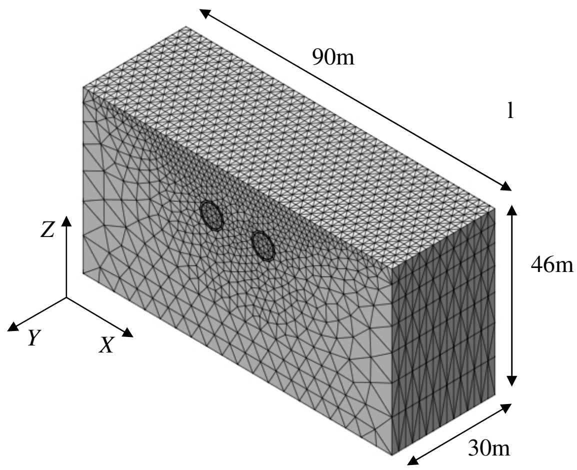


Figure 6 Mesh of parallel tunnel model

3.1 Analysis of impact of parallel tunnel spacing on surrounding soil

The parallel tunnel was dug with five different spacing of 2D, 2.5D, 3D, 3.5D, and 4D from the existing tunnel centerline; the tunnel excavation sp was 2 m. The changes in S_v and S_b along the existing tunnel are presented in Figure 7. The changes in single-bore tunnel excavation with the same excavation space are also shown in Figure 7 for comparison.

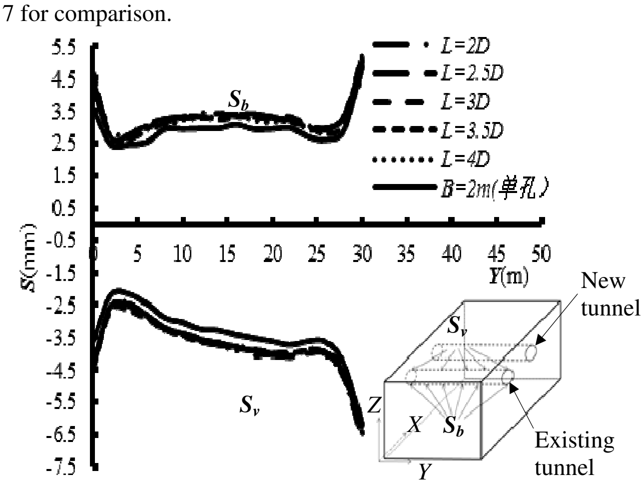
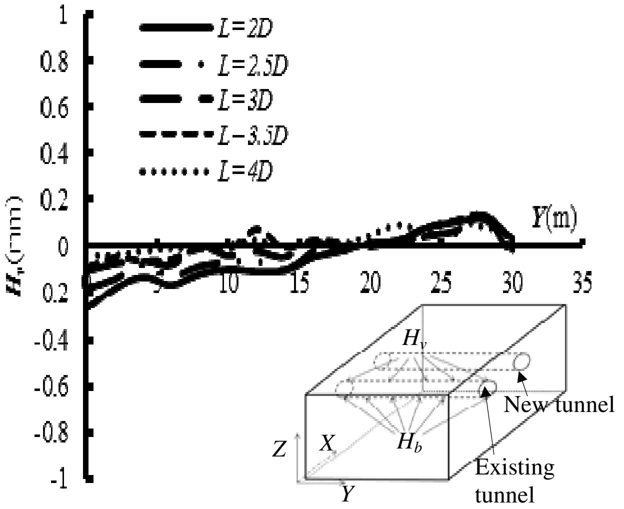


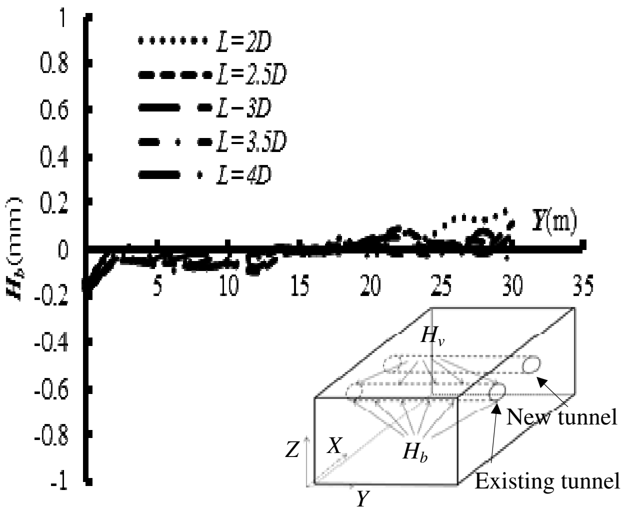
Figure 7 Displacement of original tunnel vault and bottom in vertical direction

Figure 7 shows that both S_v and S_b increase upon completion of the new tunnel excavation. The deformation trend is the same as that of a single-bore tunnel, which is most significant at two ends of the tunnel, and the deformation gradually increases along the direction of the tunnel excavation in the middle area. By contrast, the different parallel tunnel spacing has minimal difference from the impact on the S_v and S_b of the existing tunnel.

Figure 8 shows the curves of H_v and H_b along the original tunnel when the parallel tunnel excavation is completed.



(a) Horizontal displacement of existing tunnel's vault



(b) Horizontal displacement of existing tunnel's inverted arch

Figure 8 Displacement of original tunnel vault and bottom in horizontal direction

Figure 8 illustrates that the influence of new tunnel excavation on H_v and H_b of the existing tunnel is almost negligible.

The preceding analysis shows that different tunnel spacing has slightly more influence on S_v and S_b than the single-bore tunnel. However, different tunnel spacing has an almost negligible effect on the H_v and H_b of the existing tunnel. New tunnel excavation is not limited to the position in which two tunnels are at the same horizontal plane. The different orientations of new tunnel excavation are then analyzed.

3.2 Influence of parallel tunnel orientation

When the tunnel spacing is fixed, a new parallel tunnel excavated in the different orientation of the existing tunnel exerts different effects on the existing one. Taking the existing tunnel center as the center of the circle and 2.5 D as the radius, this study analyzes the changes in S_v, S_b, H_v, and H_b along the existing tunnel when the new tunnel is at 15°, 30°, 45°, 60° and 75° angles to the existing tunnel. Figure 9 shows the orientation of the new tunnel.

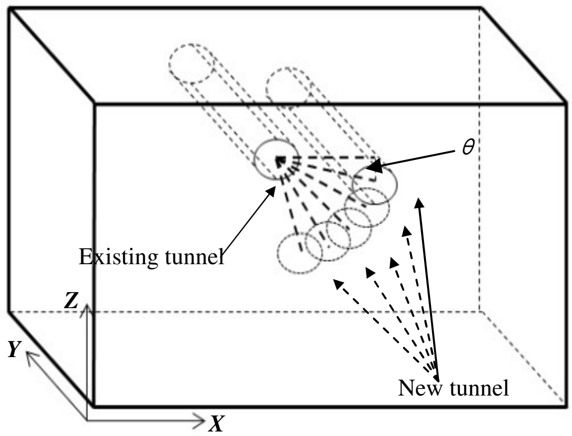


Figure 9 Schematic of new tunnel

Figure 10 illustrates the impact of the new tunnel on the vertical displacement of the existing tunnel vault and inverted arch.

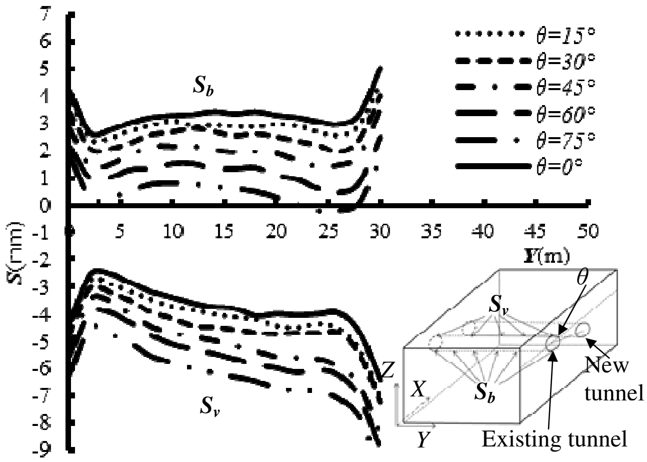


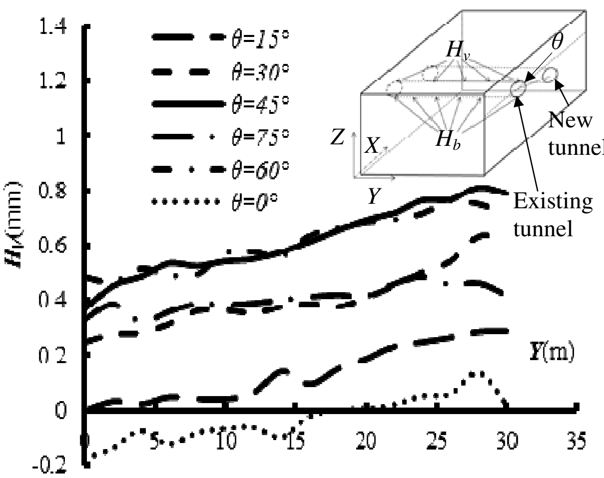
Figure 10 Displacement of original tunnel vault and bottom in vertical direction

Figure 10 shows that the changes in S_v and S_b along the tunnel excavation direction do not change over the tunnel angle. At the same time, S_v gradually increases with the increase of angle between the two tunnels, whereas S_b decreases with the angle increasing.

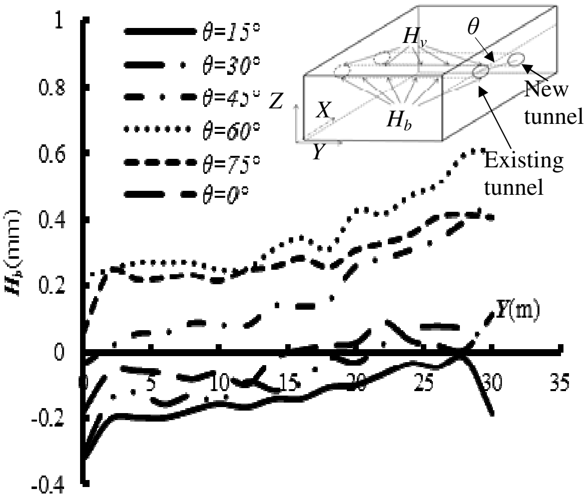
Figure 11 shows the curves of H_v and H_b along the existing tunnel after excavation of the parallel tunnels.

Figure 11 shows the H_v and H_b along the direction of excavation. According to the above figures the H_v and H_b of the existing tunnel are significantly less than the S_v and S_b of the existing tunnel. The variation in the horizontal displacement is relatively small; in addition, the variation is not monotonous with the increase in tunnel angle similar to the variation in vertical displacement. The variation in the horizontal displacement increases with increasing tunnel angle, peaks reach when the angle of the two tunnels is 60°, and then gradually decreases. The horizontal displacement has a large increase when the angle of the two tunnels is 45°.

If construction conditions allow, the distance between the two tunnels and the angle of the two tunnels should increase as far as possible to safely complete the excavation work.



(a) Horizontal displacement of existing tunnel's vault



(b) Horizontal displacement of existing tunnel's inverted arch

Figure 11 Displacement of original tunnel vault and bottom in horizontal direction

4. ANALYSIS OF MUTUAL EFFECT OF TWO PARALLEL TUNNELS BUILT SIMULTANEOUSLY

Four excavation methods of two parallel tunnels on the same horizontal plane are studied. The first excavation method is DE, which involves excavation with the same direction and the same excavation space. The second one is DA, which involves excavating in one tunnel with temporary support in the other one under the premise of excavation in the same direction with the same excavation space. The third one is OE, which involves excavation in opposite directions with the same excavation space. The fourth one is ST, which involves starting by excavating the single-bore tunnel and then excavating the other one after the breakthrough of the previous one.

4.1 Analysis of soil deformation surrounding tunnel

This paper presents the analysis results of tunnel A because of model symmetry. Figure 12 shows the curves of Sv and Sb along the excavation direction of tunnel A after the construction.

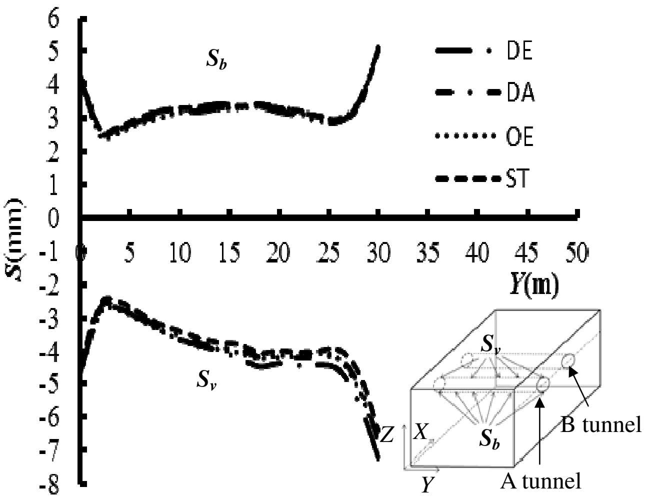


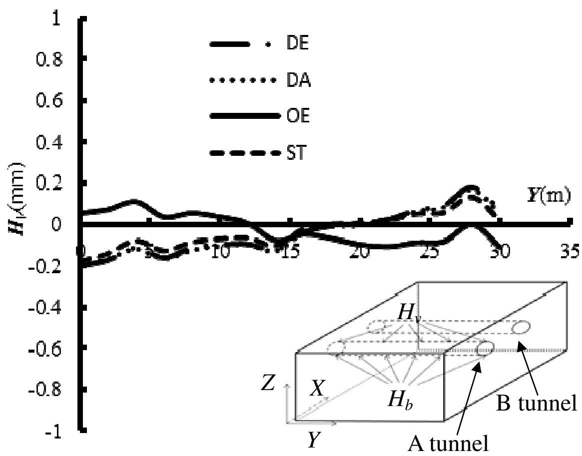
Figure 12 Displacement of A tunnel vault and bottom in vertical direction

Figure 12 shows that the diverse excavation methods exert minimal effects on S_v and S_b. The setting volume of S_v is smaller under the ST method than the amount under another three methods, but the changes in S_v are the same under the four methods. The changes in S_b obtained from the different excavation methods are almost the same.

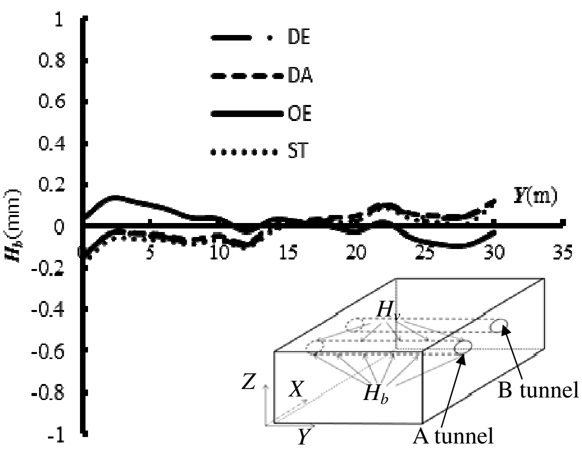
Figure 13 illustrates the curves of H_v and H_b along the tunnel after the excavation of the parallel tunnels.

Figure 13 shows that the influence of the different excavation methods for H_v and H_b is almost negligible compared with the vertical displacement.

The preceding analysis indicates that the excavation methods have slightly effect on the magnitude of the vertical displacement and the horizontal displacement of the soil around the tunnel. The effect of the excavation methods on the ground soil settlement is analyzed in the following section.



(a) Displacement of A tunnel vault in horizontal direction

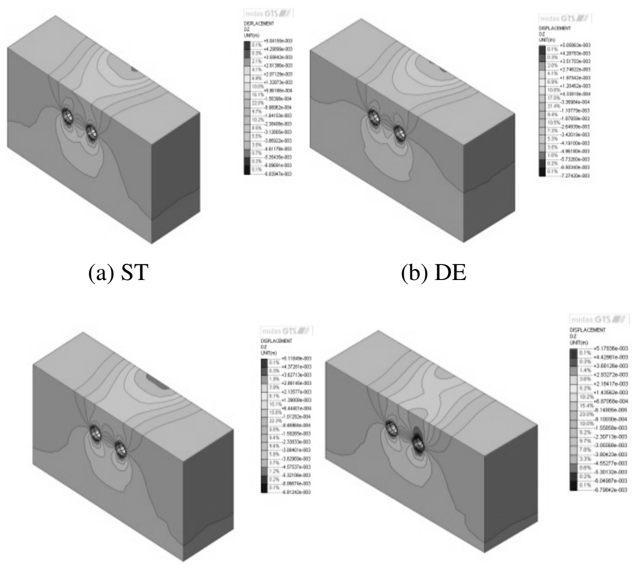


(b) Displacement of A tunnel inverted arch in horizontal direction

Figure 13 Displacement of A tunnel vault and inverted arch in horizontal direction

4.2 Analysis of surface settlement of soil

Different excavation methods have different degrees of disturbance to the surrounding soil. Figure 14 shows the cloud chart of soil settlement using four different excavation methods.



(a) ST (b) DE

(c) DA (d) OE

Figure 14 Cloud chart of soil settlement with different excavation methods

Figure 14(a) shows the cloud chart of soil settlement with the ST excavation method when the construction was finished. In this figure, tunnel A, which was excavated before tunnel B, is on the left side. The excavation of tunnel B not only changes the original symmetric distribution of the surface settlement but also further increases the settlement of soil upper tunnel A when compared with the cloud chart of the soil settlement in the single-bore tunnel. However, Figure 14(b) shows that the distribution of the surface soil settlement is relatively uniform using the DE excavation method when the construction is finished. The overall situation is that the soil surface settlement gradually increases from the initial tunnel excavation face and eventually peaks at the tunnel through the surface. The DA and DE excavation methods also have different effects on the surface soil settlement. Figure 14(c) illustrates that the DA excavation method has a stronger influence on soil disturbance and more significant soil settlement than the DE excavation method, although the changing trends of the two methods are similar. All of the three excavation methods are under the condition that the excavation direction is uniform. However, the influence of the excavation method with the opposite excavation direction on the soil disturbance is different from that of the aforementioned three methods. Figure 14(d) shows the surface settlement peaks at the final through faces of the two tunnels. In addition, the overall shape of the surface settlement resembles that of the number 8.

Therefore, ST is the safest and DE is the most dangerous among the four excavation methods.

5. CONCLUSION

The disturbance of surrounding soils caused by three excavating methods, namely, single-bore tunnel excavation, new tunnel excavation, and co-building tunnel excavation have been analyzed using finite element software MIDAS/GTS. The results are summarized as follows:

(1) For the single-bore tunnel excavation, longer step distance means more severe disturbance of the surrounding soil. Such a disturbance is manifested as the difficulty of the soil deformation to be stable, vertical displacements of the tunnel vault, and obvious extension of the inverted arch. For the entire tunnel, the maximum impact occurs at the initial excavation face and the final through face.

(2) For the new parallel tunnel, no obvious difference is observed between the impact of diverse tunnel spacing on the original tunnel vault and inverted arch vertical displacements. The overall displacement variation trend along the tunnel excavation direction is the same as that of the single-bore tunnel. However, the numerical value slightly increases, and excavation exerts minimal influence on the horizontal displacement of the original tunnel vault and inverted arch.

(3) For the co-building parallel tunnel, the minimal impact on tunnel deformation is exerted by the ST method, whereas the maximum impact on the ground surface settlement is exerted by the OE method.

Thus, in-situ monitoring during tunnel construction should be reinforced, and the appropriate excavation method should be selected based on the specific geological conditions.

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