Stratum deformation analysis and excavation sequence optimization for four-line parallel shield tunnels

The multi-line parallel tunnels belong to a complex layout in the underground space that has emerged in the wake of the continuous development of metro construction. When a new tunnel that travels through the existing ones in parallel with over a long distance is constructed, not only an adverse impact will produce on existing parallel tunnels, but also surface subsidence will be occurred. Contrapose the construction pattern that four-line parallel shield tunnels breakthrough soft soil stratum, a 3D elastic-plastic finite element dynamic model is built to simulate and analyze the whole process of four-line parallel shield construction. Study shows that, in the process of shield excavation, the interactive effects between horizontal lines are relatively weak, but in the vertical direction, it presents more intense; after the completion of the excavation for four-line parallel tunnels, the surface subsiders are not symmetrical, but appear right above the last excavation line; first excavation should run from the upper tunnels, followed by the lower tunnels, since it is conducive to the surface settlement control and reducing the interactive effects between various lines. In this paper, the findings can provide a theoretical basis and prophase guidance for such construction in the future.

Keywords: *Four-line parallel, shield tunnel, soil deformation, excavation sequence, finite element analysis*

1. Introduction

In the wake of the rapid development of urban subway construction in China, the rail transit network gets more mature now. In some ways, the urban underground space exploitation also constantly expands. Shield construction in some cities where soils often seriously has been more challenging followed by constant popularity and maturity. It will continue to evolve toward such pattern as ultra-depth, acute curve, long haul, and full diameter. As the contradiction between the supply and demand for lands in urban areas becomes sharper, the crossingc onstruction of multi-track tunnels and long-haul shield parallel construction are getting more and more popular [1-3]. Restricted by geological conditions and construction level, shield excavation will inevitably cause disturbances to the adjacent soil, which in turn leads to ground surface subsidence, cracks, damage or even collapse of building sand structures [4]. Therefore, it is more significant for us to predict and control the disturbance deformation during the short-distance (parallel or vertical) construction of multi-track tunnels, so as to minimize its adverse impact on the stratum environment.

Aiming at the parallel tunnel shield construction, scholars at home and abroad made some studies on the deformationon adjacent parallel tunnels caused by disturbances mainly using numerical simulation, lab experiments, field tests and theoretical analysis, etc. In this regard, they have obtained certain research results. Soliman et al. conducted 2D and 3D finite element studies on near-spacing parallel tunnels.When the stratum loss was not given, they analyzed the relationship between inter-tunnel inter-active effect and the tunnel spacing [5]. Lo et al. made an exhaustive explanation on the on-site measurement for inter-action among multiple tunnels. For the four-hole parallel tunnels, the horizontal displacement and vertical settlement of soil, ground surface subsidence, pore water pressure, vibration, lining structure stress and other parameters were measured using in clinometer, pore piezometer, stand pipe, stress detector, and straingauge, etc., based on which the inter-action between porous tunnels was deeply explored [6]. Ngetal., carried out a series of systematic 3D coupled finite element analysis on the inter-action between large parallel twin bore tunnels in hard clay during construction [7]. Chapman et al. investigated the law of short-term surface move ment caused during construction for twin bore parallel tunnels in kaolin clay by a string of small-scale (1:50) lab model tests [8]. Li Xuefeng et al. used the 3D finite-difference model to analyze the inter-active effect between lines at the time of shallow buried large-diameter close-distance shield tunnel construction on the background of cross-river tunnel project in Renmin Road, Shanghai, and compared the numerical simulation results with the actual values measured on site [9]. Wei Gang, based on the 2D analytical solution for the soil deformation caused by the horizontal parallel double-track shield construction as proposed by the existing literature, derived a 3D analytical

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solution for the soild formation [10]. Wang Huaning et al. simulated the rheological properties of wall rock using a visco elastic model, and obtained an inference from theoretical solutions to incremental displacement and stress caused by a circular section double-track tunnel excavation using the complex variable function, Laplace transform, and visco elasticity super position principle [11]. Bai Xuefeng et al., given that the new double-track parallel tunnel produced super position effect on surrounding soil layers and existing tunnels during the construction, proposed a two-phase analysis method for predicting the longitudinal deformation of adjacent tunnels caused by the new tunnels [12].

We will easily discover that the existing literature at home and abroad generally focuses on double-track tunnels with relatively single objects, but seldom involves three-track, four-track or even multi-track parallel overlaps (Wuhan Metro Lines 2 and 4) [13] that have emerged as a hot spot recently. There is a lack of sufficient and profound studies on the surface subsidence, strata stress, excess pore pressure and other mechanisms caused by ground disturbances during multi-track parallel tunnel shield construction, especially extremely scarce on the law of inter-active effect between multi-track parallel tunnels.

This paper makes a modelling analysis on the soild formation and excavation sequence caused by four-line parallel tunnel boring based on the large finite elements of tware ABAQUS, involving lateral surface settlement and base tunnel deformation, as monitored, caused by different excavation sequences in detail. The results from numerical simulation and calculated by Peck formula based on the principle of super position are compared to reasonably optimize the excavation sequence for four-track parallel shield tunnels as a theoretical reference for similar projects in the future.

2. 3D Dynamic elastic-plastic finite element numerical model

2.1 Tunnelling process simulation

The shield tunnelling process simulation adopts the element birth and death technology in the ABAQUS, a large-scale common finite element of tware, and variables of the material parameters. Variables (size of shield tail interspace, ultra-deep clearance, operation clearance, grouting filling extent, tunnel walls oil disturbance extent, etc.) that are strongly linked to construction but hardly quantified are equivalent to equipollent layer with homogeneity and equal thickness [14], so that these unquantized factors can be implemented in the computation model. The concrete finite element implementation process of shield tunnelling simulation is shown in Fig.1.

2.2 3D finite element model

In order to analyze the inter-active effect among tunnels during excavation, a 3D finite element model is first built for shield excavation of four-track parallel tunnels, and each is numbered, as shown in Fig.2: where the Y-axis is the tunnelling direction and X-axis is the lateral surface direction and the Z-axis is the soil mass direction. The model X is 60m wide, and Y takes the length of 14.4m as 12 loop segments are. Z direction is 60m deep. The whole model is: X×Y×Z = 60m×14.4m×60m. The depths of the 1# and 2# tunnels take 8.0m; 3#, and 4# tunnels have a depth of 19.5m. The clear distance between the tunnels is 5.0m, distributed symmetrically in space. After mapped meshing, there are 24,480 model units and 26,750 nodes.

In this FEM numerical analysis, the relative locations among the four-track parallel tunnels as considered are shown in Fig.3.

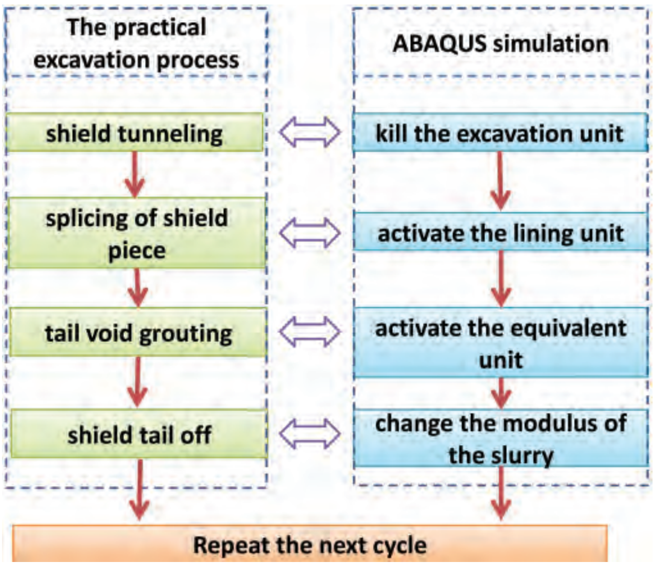

Fig.1 Schematic diagram of simulation process

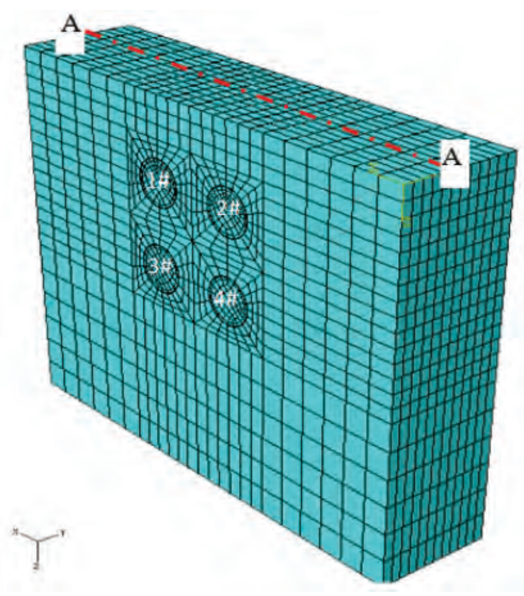

Fig.2 Integral model for finite element discretization

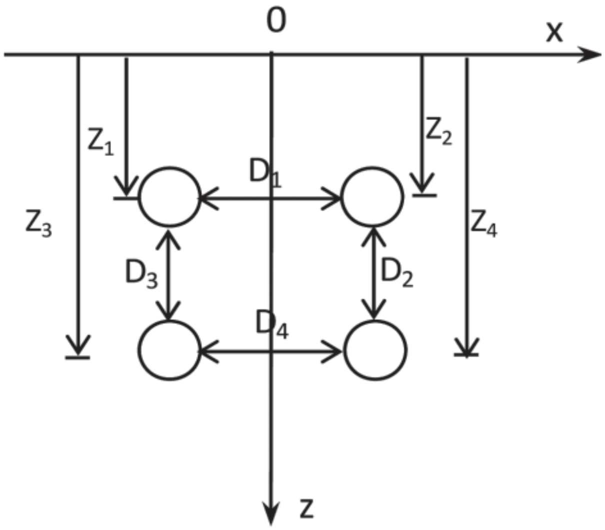

Fig.3 Relative location of four-track tunnels

2.3 Material parameters

For the sake of convenience, the soil mass stratification is not concerned in this paper. In the model, the soil element uses the 3D hexahedral eight-node pore pressure element C 3D 8P. The inter-action between the soil and the lining is simulated by the contact surface, and soil constitutive model is Drucker-Prager; concrete lining structure adopts the linear elastic model; lining element is the 3D hexahedron eight-node solid element C 3D 8R. Some material parameters are shown in Tables 1 and 2.

Table 1 Physical parameters of soil and lining

Name	μ	E/MPa	r'/kN·m^{-3}	c/kPa	φ/(°)	K/m·s^{-1}
Soil	0.25	11.65	7.8	14.3	15.2	0.023×10^{-7}
lining	0.21	30500				

Table 2 Parameters for equipollent layers

Equipollent layers	Step 1	Step 2	Step 3
E/MPa	0.2	2.0	18.0
K/m·s^{-1}	1.1×10^{-8}	0.6×10^{-8}	0.2×10^{-8}

Note: In Tables 1 and 2, μ is the Poisson ratio; E is the elasticity modulus; r 'is the buoyant unit weight; c is the cohesion force; φ is the cohesion force; K is the permeability coefficient.

3. Analysis of numerical simulation results

In the study, we carry out the shield excavation from the upper tunnels, and the non-lower tunnels, that is, when the excavation sequence is 1→2→3→4, the inter-active effect among the tunnels and the ground surface subsidence is measured. During the simulation, take 2.4m as an excavation length (width of two rings) when advancing with the stiffness migration, the lateral location on the surface above the ring 6 of each tunnel (i.e. the survey line A-A settlement, as shown in Fig.3) and the survey point below the ring 6 of the tunnel as the study objects, monitor the lateral displacement of the ground surface at the completion of each line and measure how the subsidence of each survey point is subjected to change with excavation step in the whole process of excavation, and how the displaces of final ground surface lateral location and survey point change over time after completion, so as to determine what are the inter-active effect among all lines during shield excavation and the stratum disturbance caused by this process.

3.1 Analysis of Impact of excavation of four-track parallel tunnels

The ground surface settlement clouds after completion of each line excavation are shown in Fig.4. It is obvious that after the excavation for each line, the surface settlement between the 1# and 2# on the above area is relatively larger, and unlike the single-line excavation, the soil at the bottom of the excavation surface does not seem rising, but shows the subsidence resulting from the stratum loss caused by the excavation of the 3# and 4# lines below; the soil above the excavation surfaces of the 3# and 4# lines sinks during the excavation, while the soil below rises, which coincides with the stratum displacement caused by the excavation of a single line, but differs in size.

During the excavation, the transverse subsidence of the ground surface on each line at the sixth ring and the change of surface subsidence after excavation of each line are shown in Figs.5 and 6, respectively. In the whole excavation process, the settlement of each survey point is shown in Fig.7.

As shown in Figs.5 and 6, when the 1# line shield excavation moves on to the 6th ring, ground surface above the 1# lines inks about 7.5mm, and continues to increase to 10mm when the 1 #line excavation is completed; when the 2#

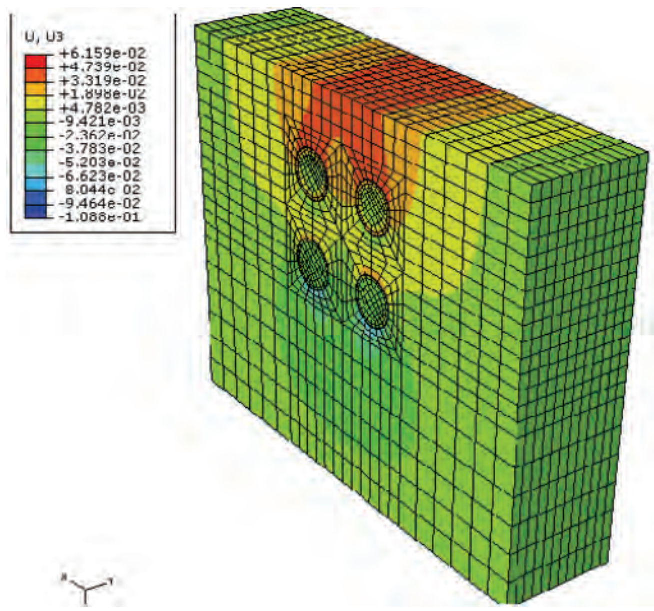

Fig.4 Sedigraph of ground surface after completion of excavation

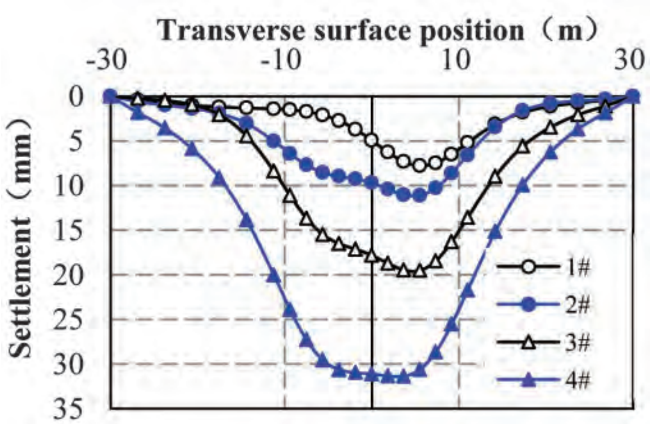

Fig.5 Transverse line A-A transient settlement curve of the ground surface at the 6th ring of each line excavated

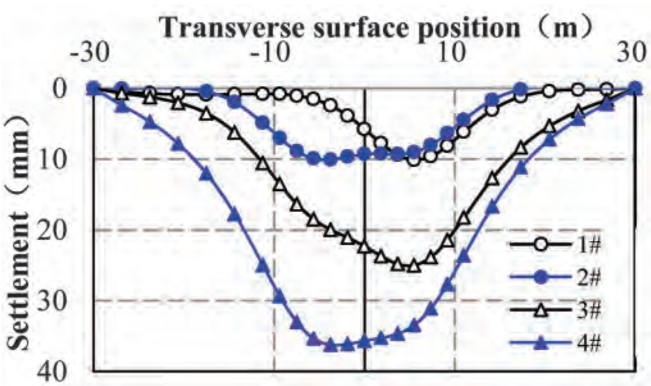

Fig.6 Transverse line A-A settlement curve of the ground surface after each line excavation is completed

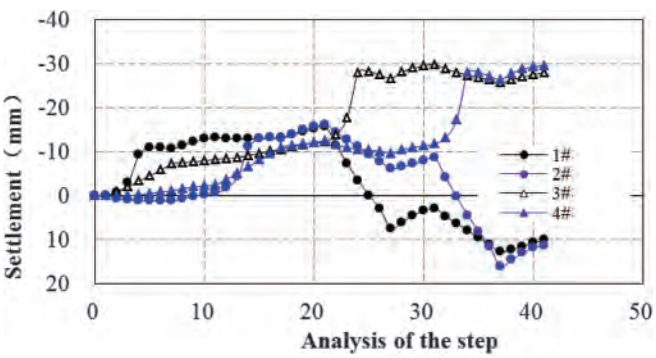

Fig.7 Curve of displacement of each survey point as a function of time

line reaches the 6th ring, the maximum surface settlement still lies above the 1# line, but has a tendency to shift to the 2# line, just 8mm right above it. The ground surface settlement above 2# line is 1mm higher than that above 1# line after the excavation of 2# line, which perhaps is attributed to the secondary stratum disturbance occurred during the excavation of the 2# line; when 3# and 4# lines travel to the 6th ring and after the excavations, the lateral settlements of ground surfaces how alike. However, numerically, the final surface settlement above the 3# line is 25mm, while that above the 4# line is 36mm, higher than that caused by the shield excavation for the 1# and 2# lines. This reveals that in the excavation process, the inter-active effect between the lines is weak in horizontal direction, and intense vertically, which attributes to the fact that thin-bedded and constitutive properties formed in the soil sedimentation process cause greater strength in horizontal direction than in the vertical direction.

As shown in Fig.7, the stress path that each survey point passes by in the excavation process is mapped. 1# survey point rises by 11mm at the base when 1# line goes up to the 6th ring due to the release of the crustal stress. During the 2# line excavation, the 1# line survey point is vulnerable, and the rising increases by about 2.5mm. When the 3# line is excavated, the rise of 1# survey point gradually decreases due to the unloading effect caused by it. The subsidence appears 6.5mm after the ring 6 excavation. The solidification of the grouting body in the 3# line excavation section controls the sinking pattern and makes it slightly rebound. Then 4# line excavation in the lower right side also leads 1# line survey point to sinking by 4.5mm. The sinks of 2#, 3# and 4# survey points correspond to the excavation sequence and present rising or sinking phenomenon. As longitudinal stiffness of the tunnel is relatively large, it can be supposed that the final settlement of each survey point represents that on each tunnel. It turns out that the 1# and 2# lines are unloaded due to the excavation at the bottom tunnel, and the tunnels sink. There is no unloading effect at the bottom of the 3# and 4# lines, but both rise because the crustal stress released below is greater than the top.

In order to analyze the inter-active effect between the lines, the results calculated by the Peck formula that corresponds to the super position principle but ignores the inter-active effect between the lines are shown in Fig.8.

As shown in Fig.8, when the inter-active effect between the lines is not given, the final surface subsiders are symmetrical, and the maximum settlement on the surface is 20mm,16mm lower than that calculated by numerical simulation, which attributes to the fact that Peck formula

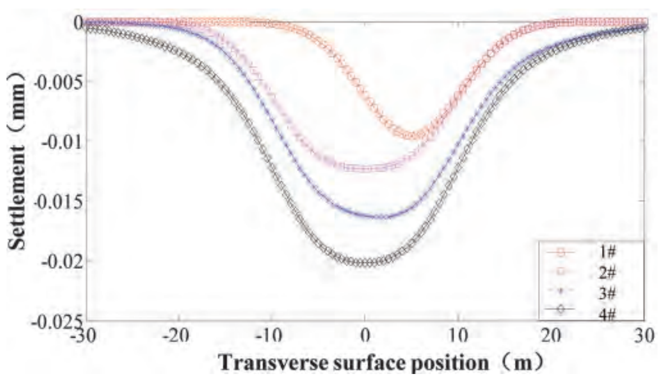

Fig.8 Curve of transverse surface settlement calculated by Peck formula

ignores the inter-active effect between the lines during the whole shield excavation process. Under different stress paths, the soild formations also differ and the plastic deformation in soil elasto-plastic nature is not recoverable. It follows that only when we analyze the entire process of shield excavation can we draw a reasonable conclusion under involvement of inter-active effect.

The actual stratum disturbance caused by the excavation of the four-track parallel tunnels is not a simple super position of the strata losses done by such construction, but attributes to this fact that the inter-active effect between the lines during the excavation process makes the ground surface subsiders asymmetrical after completion of such excavation, but appear just above the last excavation line because excavation process corresponds to the stress path. In this process, since the soil is a typical elasto-plastic medium, the above phenomenon is attributed to its diverse properties shown in different stress paths. In this regard, this inter-active effect between the lines in the horizontal direction is less, while the impact of the lower lines on the upperlines decreases with the increase of the distance.

3.2 Optimization of the excavation sequence of four-track parallel tunnels

Due to the particularity of space layout, the shield tunnelling of four-track parallel intersecting tunnels presents the characteristics different from single-hole tunnels and parallel double-hole tunnels. The interaction between tunnels is less in the horizontal direction but strong in the vertical direction. For this reason, it is necessary to study the law of stratum disturbance under different excavation sequences in attempt to obtain the optimal excavation effect. According to the permutation and combination knowledge, six types of different excavation sequences are designed, given the spatial position symmetry of the model. The excavation sequences under various working conditions are shown in Table 3.

Table 3 Excavation sequences under various working conditions

Condition 1	Condition 2	Condition 3	Condition 4	Condition 5	Condition 6
1-2-3-4	1-3-2-4	1-4-2-3	3-1-4-2	4-1-3-2	4-3-2-1

Under the six different excavation sequences, the final lateral surface settlement and the displacements of survey points below the ring 6 of each tunnel are shown in Figs.9 and 13:

As shown in Fig.9, when the excavation sequences are 1→2→3→4 and 1→4→2→3, the surface settlement reaches the minimum, about 36mm; when the excavation sequences are 4→1→3→2 and 4→3→2→1, the surface settlement is the maximum, about 42mm.

As shown in Figs.10~13, the 1# and the 2# lines show ink phenomena under different excavation sequences, but when it is 1→2→3→4, the maximum settlement of 1# and 2 lines

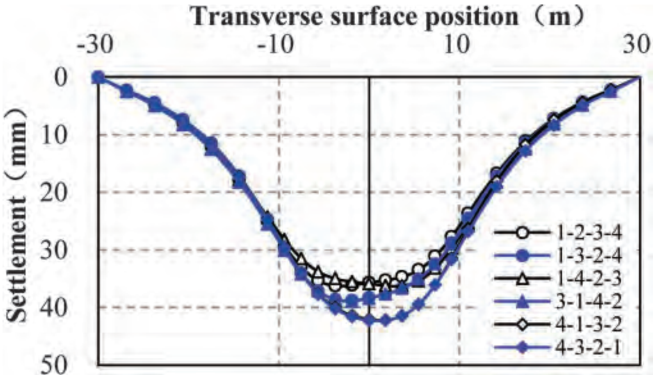

Fig.9 Final settlement of ground surface under different excavation sequences

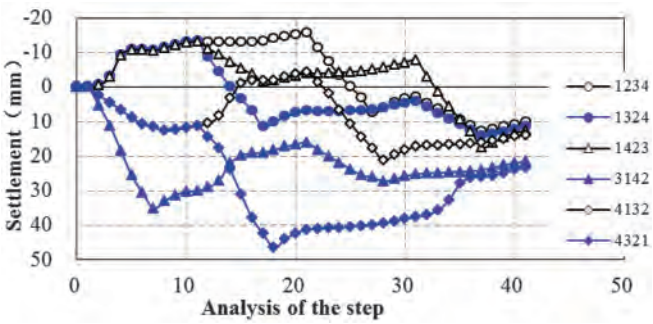

Fig.10 Settlement of 1# survey point under different excavation sequences

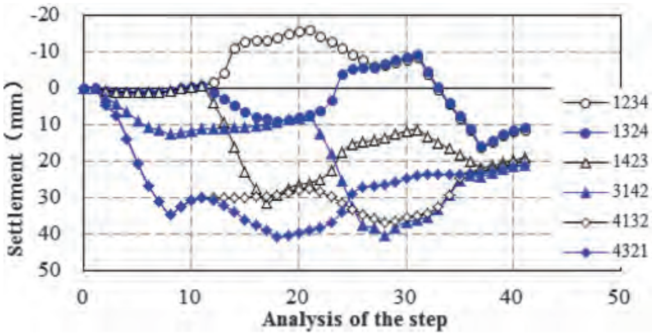

Fig.11 Settlement of 2# survey point under different excavation sequences

reaches about 14mm. When it is 4→3→2→1, the maximum settlement of both is 46mm or so; lines #3 and #4 all rise under different excavation sequences, that is, when it is 4→3→2→1, the maximum rise of the #3 and the #4 lines is about 30mm, about 2.5mm higher than that in 1→2→3→4 order.

As described above, in different excavation orders, the surface settlement and the rising and sinking values on each line during the excavation process all differ. It is thus clear that the practice that the upper tunnels are excavated before the lower tunnels under the conditions of four-track parallel tunnels will help control the settlement of the ground surface and reduce the inter-active effect between the lines. This is because the crustal stress released from lower tunnel excavation is partially borne by the tunnel segment itself that

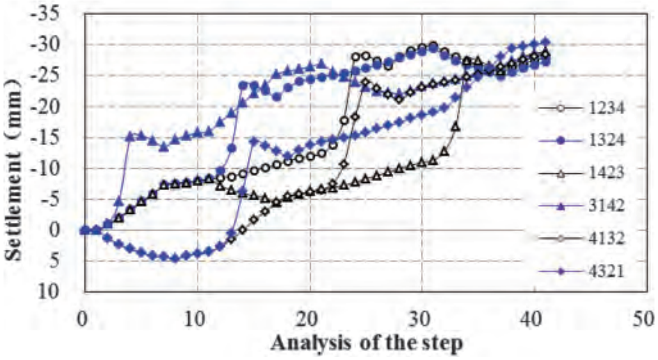

Fig.12 Settlement of 3# survey point under different excavation sequences

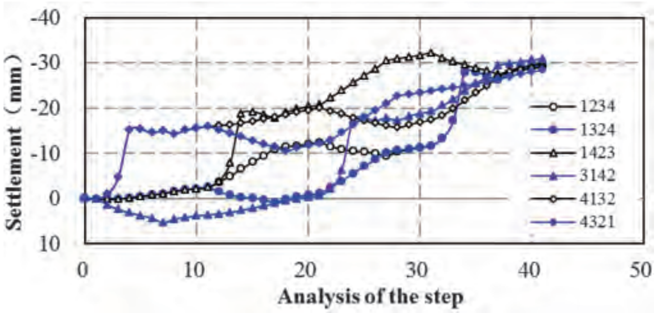

Fig.13 Settlement of 4# survey point under different excavation sequences

subjected to its stiffness effect after the upper tunnels are excavated, which reduces the disturbance to the stratum. However, the excavation of the lower tunnels is likely to cause uneven stress on the upper tunnel, resulting in fracture of the segment. For this purpose, it is required to make a comprehensive analysis of many factors in order to design a suitable strength for the segment and select the appropriate excavation sequence in the actual construction.

4. Conclusions

This paper conducts the finite element simulation on the construction process of the four-line parallel shield tunnels and analyzes the lateral surface settlement and the deformation as monitored under the tunnel that are caused by different excavation sequences, so that the excavation sequence of such construction process in the soft soil layer is optimized reasonably. The main conclusions are drawn as follow:

1. In the process of shield boring, the mutual impact between lines is relatively weak in the horizontal direction, but in tense in the vertical direction, which attributes to the fact that thin-bedded and constitutive properties formed in the soil sedimentation process cause greater strength in horizontal direction than in the vertical direction.
2. The actual stratum disturbance caused by the excavation of the four-track parallel tunnels is not a simple super position for the strata losses done by such construction, but attributes to this fact that the inter-active effect between the lines during the excavation process makes the ground surface subsiders asymmetrical after completion of such excavation, but appear just above the last excavation line.
3. In the different excavation orders, the four-line parallel tunnels have different ground surface settlements and line displacements. The practice that the upper tunnels are excavated before the lower tunnel will be conducive to controlling the ground surface subsidence and minimizing the inter-active effect between lines.

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