Numerical Simulation of Continuous Shield Tunneling based on a Dynamic Element-Deletion Technology

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Abstract. Currently, the finite-element (FE) simulation of tunnel excavation usually adopts the birth-to-death approach, which directly removes the soil element in the excavation region. This approach simplifies the dynamic process of continuous excavation to a transient process, which ignores the time-dependent response of soils in front of the excavation face as well as the soil–cutterhead interaction. This study presents a novel FE method to simulate the dynamic and continuous shield-tunneling process. In this method, the state variables are calculated based on either the stress or strain tensor of any arbitrary elements in which the elements that extrude into the excavation chamber can be identified and eliminated using the element-deletion technology. Therefore, the dynamic and continuous excavation process of a shield machine can be accurately simulated. Furthermore, the method can be used to analyze the influence of the cutterhead geometrical parameters as well as its rotary and propulsion speeds on the stability of the excavation face. By analyzing the key construction parameters such as shield-tunneling speed, cutterhead speed, and slurry pressure, the superiority of the dynamic simulation is demonstrated.

1. Introduction

The disturbance due to shield tunneling on the surrounding ground and nearby buildings is a major concern in practical engineering. Considerable efforts have been devoted to analyzing the shield-tunneling effects on the surrounding ground via model testing[1-4]. For example, based on the Chongming River Crossing Tunnel, Li et al. proposed a feasible scheme for a dynamic excavation-model test of a slurry balance shield and investigated the mechanism of excavation-face stability of a slurry pressure-balanced shield and distribution pattern of settlement during the shield advancement[11]. A number of theoretical models have also been proposed for face-stability analysis of shield tunnels based on limit-equilibrium conditions[5-10]. For instance, Leca, and Dormieux proposed a series of cone-instability models and used the limit-analysis method to analyze the stability of a shallow tunnel excavation face in sandy soil as well as other frictional media that obey the Mohr–Coulomb failure criterion[6].

However, the tunneling process can be affected by many variables that cannot be easily considered in both model testing and theoretical derivations. In this case, numerical simulation becomes a reliable alternative. Zhao et al. proposed a method that combined computational fluid dynamics and discrete-element method to simulate the behavior of the fluid–particle interaction in mining and geotechnical
engineering\textsuperscript{[11]}. Pan et al. studied the influence of pore water pressure on the stability of a tunnel face by combining the kinematic method and numerical simulation\textsuperscript{[12]}. Ukritchon et al. conducted both two- and three-dimensional finite-element (FE) analyses to assess the stability of a Bangkok underground tunnel without a drainage surface\textsuperscript{[13]}.

Currently, the birth-to-death element method is widely used in the numerical simulation of tunnel engineering, which directly removes the excavated soil to simulate the process of tunnel excavation. However, this method ignores the time-dependent ground response and fails to satisfy the needs for continuous prediction. To overcome these disadvantages, the present paper proposes a numerical-simulation technology of dynamic shield tunneling based on the element-deletion technology. This technology can obtain not only the dynamic information of stratum displacement but also the important parameters of shield-machine construction, which can provide more useful guides for practical engineering.

2. Numerical modeling

2.1 Geometric model

Figure 1 shows the geometry of the FE model developed in the FE software ABAQUS (v2020). To save calculation time, the size of the numerical model is set to that of the model test performed by Li\textsuperscript{[1]} to investigate the simulation accuracy. The specific model dimensions are as follows: 2400-mm long, 1200-mm wide, and 2000-mm high. The distance between the tunnel axis and ground surface is 1000 mm. The tunnel diameter is 400 mm, and the diameters of the cutterhead and shield shell of the shield machine are the same as that of the tunnel. The distance between the excavation face and right boundary of the model is 800 mm.

![Geometric model and mesh generation](image)

Figure 1 shows that the geometry of the model is composed of three parts: stratum, shield, and shell. Among them, the stratum is partitioned into three parts: soil at the workface, soil around the tunnel, and soil far from the workface. The stratum part contains 586,650 elements. Near the tunnel workface, the meshes are refined to more accurately capture the near-field ground response. The cutterhead is composed of the cutters and panel, as shown in Figure 2. The cutter is used to cut the soil element in the workface of the tunnel.
2.2 Constitutive models

The Drucker–Prager (DP) criterion and shear-damage model are used to describe the constitutive behavior of the soil. The DP model is an ideal elastic–plastic model that can better reflect the plastic behavior of soil, whereas the shear-damage model reflects the damage behavior of the disturbed soil under shear condition. When the cutterhead contacts the soil at its front, the soil is subjected to shearing. When the strain of the soil element reaches a specified limit, the state variable of the element changes from one to zero, which means that in this model, the elements has been deleted and no longer participates in the subsequent calculation steps. This technology can better simulate the effect of soil cutting by the cutterhead.

The parameters of the DP model are listed in Table 1-1. The shear-damage model parameters are listed in Table 1-2, and the contact parameters between the cutterhead and soil are listed in Table 3. Because the rigidities of the cutterhead and shield shell are much larger than that of the soil, the deformation of the cutterhead and shield shell is negligible compared with that of the soil. Therefore, the cutterhead and shield shell are considered as rigid bodies for simplicity. In the simulation, the motion state of the rigid body can be controlled by setting the displacement condition of the reference point. This model simulates the plastic behavior of soil by setting the hardening parameters of the DP criterion after the material enters the plastic stage. Its parameters are listed in Table 1-2.

Table 1-1 DP parameters of the soil

| Density (kg/m³) | Angle of friction/° | Flow stress ratio | Dilation angle | Young’s modulus/MPa | Poisson’s ratio |
|----------------|---------------------|-------------------|---------------|--------------------|---------------|
| 1800           | 35                  | 0.8               | 35            | 30                 | 0.35          |

Table 1-2 DP hardening parameters of the soil

| Yield stress/Pa | Absolute plastic strain | Yield stress/Pa | Absolute plastic strain |
|-----------------|-------------------------|-----------------|-------------------------|
| 8580000         | 0                       | 9490000         | 0.000583                |
| 8660000         | 0.000119                | 9620000         | 0.000601                |
| 8780000         | 0.000154                | 9680000         | 0.000797                |
| 9040000         | 0.000159                | 9750000         | 0.000895                |
| 9380000         | 0.000257                | 9840000         | 0.000984                |
| 9460000         | 0.000426                | 9950000         | 0.00105                 |
Table 2 Input parameters of the damage model

| Fracture strain | Damage evolution type | Displacement at failure |
|-----------------|-----------------------|-------------------------|
| 0.0015          | “displacement”        | 1                       |

* Displacement at failure refers to the ratio of node displacement to element size when the element fails.

Table 3 Contact between the soil and rigid body

| Normal behavior | Tangential behavior |
|-----------------|--------------------|
| hard contact    | “Penalty”:0.1(friction coefficient) |

*Hard contact: no penetration allowed from the master surface to the slave surface in the contact pairs.

2.3 Loads and boundary conditions

The loads of the model include gravity, surface water pressure, and slurry pressure on the excavation surface. The gravity load is 1 g. The surface water pressure is calculated according to the water-table level above the upper surface of the soil.

The slurry pressure acts on the soil in front of the excavation face. The filter cake is assumed to be well formed and can effectively transmit the slurry pressure. In the tunneling process, the excavation face always changes with time. Therefore, the slurry pressure acting on the nodes must be varied in real time according to the change in the excavation face.

In this model, the VDLOAD subroutine (available in ABAQUS and written in FORTRAN code) is used to dynamically control the loading of the slurry pressure. In each incremental step, the node elements in the area in front of the excavation face are detected. When horizontal distance $u$ between the node and excavation face satisfies $L_e < u < 2L_e$, a corresponding volume force is applied to the node ($L_e$ denotes the length of the element in the x direction, namely, the excavation direction). In this manner, the slurry pressure can be converted into a volume force that acts on the most forward layer of the excavation face. Therefore, the slurry pressure can be dynamically controlled.

2.4 Dynamic simulation of the tunneling process

At present, the mature FE simulation method of shield-tunnel excavation directly removes the shield using the birth-to-death element method and simultaneously installs the lining. This method simplifies the continuous advancement process of the shield machine into discrete excavation steps, which cannot accurately simulate the influence of shield tunneling on the surrounding strata and suffer from the difficulty of considering the influence of the shield-construction parameters on the tunneling. In particular, the rotating speed, advancing speed, and slurry-support pressure of the cutterhead in the shield machine induce a significant effect on the stability of the construction.

In this model, to reduce the interference of the other factors, the installation of tunnel-lining segments is ignored. The earth pressure around the tunnel is borne by the shield shell. When the shield shell contacts the surrounding soil, the soil is affected by the friction resistance from the stratum, and its reaction force affects the stratum.

The behavior of the cutterhead and shield shell is controlled by their respective reference points. We assume that the forward speed of the shield and rotation speed of the cutterhead are constant under the same working condition.
3. Results

3.1 Stress-field distribution

The stress field of the model after excavating for four min is shown in Fig. 3 (sliced in the middle of the model).

Figure 3 Stress contour of the soil close to the excavation face during shield tunneling

Figure 3 shows that the soil in front of the shield is sheared due to the rotation and jacking of the cutterhead during the tunneling process. When the sheared soil reaches a specified strain state, the element is removed. Therefore, the excavation surface becomes uneven. In addition, the stress-field distribution in Figure 3 shows that the stress-concentration phenomenon is most significant in front of the excavation face. The stress around the shield shell is not uniform with larger stresses existing near the excavation face than far from it.

3.2 Comparison with the model test

To verify the validity of the model, the simulation results are compared with the model-test results obtained by Li[1]. First, the parameters of the numerical model must be adjusted to be the same as those of the model test, such as the cutterhead speed of 6.5 rpm, advancing speed of 10 mm/min, covering depth of 600 mm, \(C/D = 1.5\), and water table \(H_w = 2D\). The soil parameters are listed in Table 5.

Table 4 Soil parameters in the model test

| wet density \(\text{kg/m}^3\) | cohesion/kPa | Angle of friction\(^\circ\) | Compression modulus/MPa |
|--------------------------|-------------|------------------------|--------------------------|
| 1860                     | 0.4         | 26.14                  | 0.22                     |

Figure 4 shows the time-varying vertical displacement of the numerical and experimental models at the same position on the ground surface during excavation. The horizontal distance between the monitoring point and starting position in the tunnel is \(0.5D\) (200 mm).

Figure 4 Time-history curve of the vertical displacement of the monitoring point
Figure 4 shows that the settlement of the monitoring point gradually increases with time. The settlement result of the numerical simulation is larger than that of the model test, which may have been caused by the difference in the support pressure and propulsion speed. In fact, maintaining a constant advancing speed and support pressure in the model test is difficult, whereas these two parameters can be ideally maintained in the FE simulations. However, they are close in terms of the change trend, which indicates that the FE model can well capture the trend of stratum displacement subjected to slurry shield tunneling and can be used to analyze other related parameters.

3.3 Ground displacement in the z direction along the tunnel axis

The displacement curves at different excavation instances are shown in Fig. 5. The x axis represents the horizontal distance from the model boundary on the launch side of the shield machine, and the y axis represents the surface displacement. A positive displacement indicates surface upheaval while a negative displacement indicates surface subsidence.

![Figure 5 Ground displacement along the tunnel axis at different instances of excavation](image)

Figure 5 shows that the shield tunneling obviously influences the surface displacement. When the advancing speed is 0.016 mm/s, the rotating speed of the cutterhead is 5 rpm, and the mud support pressure is equal to the hydrostatic pressure. The influence of shield tunneling on the ground surface is reflected as uplift, and the influence range is approximately from 700 to 1200 mm, which is slightly larger than the diameter of the cutterhead 400 mm (1D).

3.4 Reaction force and moment of cutterhead

Figures 6 and 7 show the plots of the variations in the reaction force and moment of the cutterhead with time, respectively. At the start of the shield advancement, the cutterhead panel is not in close contact with the soil at its front. Therefore, a certain idling phenomenon exists, which shows that the reaction force and moment are small. As the shield continues to advance, the reaction force and moment fluctuate around a certain mean value, which is caused by the cutterhead opening. The cutterhead periodically returns to its original position, which results in an approximately periodic fluctuation of the torque.
4. Discussion

The disturbance due to the tunneling process on the surrounding ground can be affected by many factors. This study investigates the influences of some key operating parameters on the tunneling-induced ground response through a series of parametric studies, including the advancing speed, rotation speed of the cutterhead, and magnitude of the support pressure with respect to the hydrostatic pressure at the workface. The simulation details are listed in Table 6.

| Case number | Advancing speed (mm/s) | Rotate speed/rpm | Supporting pressure coefficient |
|-------------|------------------------|------------------|--------------------------------|
| case1       | 0.008                  | 5                | 1                              |
| case2       | 0.016                  | 5                | 1                              |
| case3       | 0.024                  | 5                | 1                              |
| case4       | 0.032                  | 5                | 1                              |
| case5       | 0.016                  | 4                | 1                              |
| case6       | 0.016                  | 3                | 1                              |
| case7       | 0.016                  | 2                | 1                              |
| case8       | 0.016                  | 5                | 0.9                            |
| case9       | 0.016                  | 5                | 1.1                            |

*The support-pressure coefficient represents the ratio of the slurry pressure to the hydrostatic pressure.

**rpm: round per minute

4.1 Advancing speed

The ground deformations along the tunnel axis in cases 1, 3, and 4 are shown in Figure 8, whereas that in case 2 is shown in Figure 4. By comparing cases 1–4, the influence of the tunneling rate on the stratum displacement can be analyzed. When the advancing rate is 0.008 mm/s, the support force provided by the cutterhead panel is small, and the sum of the cutterhead panel and mud pressure is insufficient to support the soil in front of the excavation face. Therefore, a larger ground settlement is induced. When the driving speed increases, the surface gradually changes from settlement to upheaval. In this model, the advancing speed should be controlled between 0.008 and 0.016 mm/s to reduce the surface displacement as much as possible, and neither obvious settlement nor upheaval should occur.
4.2 Cutterhead rotation speed

The ground deformations along the tunnel axis under different rotation speeds are shown in Figure 9. By comparing cases 2, 5, 6, and 7, we can conclude that the more slowly the cutterhead rotates, the smaller is the surface upheaval in the disturbance area. The fluctuation amplitude of the surface displacement gradually decreases with time, which is also due to the periodic change in the cutterhead rotation. When the rotation speed of the cutterhead is slow, the rotation period of the cutterhead becomes longer, and thus, the corresponding fluctuation frequency of the formation displacement is reduced. To control the cutterhead rotation speed, it should be appropriately reduced to ensure the cutting soil efficiency and reduce the frequency of disturbance on the surface displacement, which is more favorable in maintaining stability.
4.3 Support pressure

Figure 10 shows the ground deformations at different support-pressure values. By comparing cases 2, 8, and 9, we can conclude that the change in the support pressure exerts a certain influence on the ground displacement. However, when the support pressure is in the range of 0.9–1.1 times that of the hydrostatic pressure, the effect is not obvious. Furthermore, the results show that the ground can resist the fluctuation of the support pressure and basically maintain stability before the breaking of the excavation face. This result can provide useful guidance in actual construction for the stability of a slurry-shield system. The support pressure is allowed to fluctuate to ensure stability of the excavation surface; however, the fluctuation should not be very large to avoid splitting.
5. Conclusion

This paper has presented a new simulation method of continuous shield tunneling based on element-deletion technology. The excavation operating condition and dynamic soil–shield and soil–cutterhead interactions can be appropriately simulated. The ground response during continuous shield tunneling is presented, and the influence of some key operating parameters on the ground responses is explored.

The results show that the shield advancement influences the displacement of ground surface within a certain range. When the burial depth is $1.5D$, the range is approximately $1D$. The reaction moment of the shield shows a periodic fluctuation within a certain range with the rotation of the cutterhead.

Through analysis of the excavation parameters, conclusions can be drawn that the increase in the driving speed can lead to a decrease in the land settlement and even upheaval of the ground. The cutterhead rotation causes periodic fluctuation of the formation displacement within a certain range, and the decrease in the rotation speed reduces its period. In addition, the influence of the support pressure in a small range on the surface displacement is limited.

We need to note that the proposed model still suffers from some disadvantages. For example, the coupling effect between the seepage and stress fields is not considered in the model, which is very important in the formation of good permeability. In addition to the constant-speed control, the working mode of the constant thrust and constant torque should be considered. These factors will be further investigated in the future.

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