Numerical Modeling of the Strata Deformation During Tunnel Excavation Based on Discrete Element Method

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Abstract: The construction of transportation infrastructure is transferring from ground to underground, which could evacuate the urban traffic and is also the future trend of the expansion of our cities. The cobble stratum brings about many technical problems in the underground engineering. Based on the calibration test and macroscopic mechanical characteristic curve, the microscopic calculation parameters of particle flow code simulation used for cobble strata in Urumchi were determined. According to establishing the numerical model of pebble tunnels using double-side-drift method, both the ground deformation and force chain evolution were analyzed for the tunnels using subsurface excavation method. This manuscript presented the differentiation of influence on ground deformation in cobble stratum under different excavation stages, the influence extent was ranked as follows, upper bench > double-side-drift > lower bench; the result of numerical simulation test was compared with the field monitoring data, proving that it is reasonable to adopt the particle flow code to simulate the excavation of pebble tunnels, and the research result could be provided for reference for the similar engineering.

1. Introduction

In research on tunnel excavation, disturbance to the soil mass in which the tunnel is advanced governs structural stability and support structure and the soil mass is affected by a combination of depth, groundwater level, advance rate and span width. Consequently, deformations induced by disturbance to the soil mass in which the tunnel is advanced have been the focus of many scholars' work [1-3]. Due to its non-homogeneous distribution, high discreteness and low cohesion, cobble strata when disturbed during construction cause more complex ground deformations. Discrete element method (DEM) is a numerical method originally developed by American Cundall [4-5] based on Newton's second theorem to solve rock slope problems. DEM is intended to analyze deformations of joints and fissures or blocky rock under quasi static or dynamic conditions. As a branch of DEM, particle flow code may be used to study nonlinear constitutive interaction between particles. Based on DEM Zhou Jian [6] performed numerical simulation of biaxial test on sandy soil and presented the macroscopic mechanical behavior of...
sandy soil samples with different micro parameters. From a micro perspective, T. Funatsu [7] established the relationship between displacement vector and contact force vector of discrete material, developed its micro sliding theory and established linear relationship between particles of discrete material. From the micro perspective of discrete material, Wei Longhai [8-10] found from conventional lab triaxial test results that its mechanical properties are affected by inter-particle friction coefficient and particle composition and obtained the constitutive relationship between particles of discrete material. Using discrete element model (PFC2D) Chen Xiaoting [11] et al. studied surface settlement when the tunnel of Chengdu Metro Line 1 was advanced in sandy cobble strata, the distance between centers of tracks in the double-track tunnel and the influence of excavation depth on surface settlement. Potyond D.O [12] compared DEM data with field test data from the TBM-constructed subway in Madrid and found little disparity demonstrating the effectiveness of DEM. Based on DEM, T.Hoshino [13] modeled the effect of different support measures in different strata and obtained the support structure suitable for cobble strata. Based on DEM, Wang Mingnian [14] modeled construction of Chengdu Metro Lines 1 and 2, studied the characteristics and failure of active tunnel face and concluded the support effect of support structures during tunneling undergoes three stages. Using particle DEM, Tao Lianjin [15] investigated mechanical properties of soft rock during excavation. Based on DEM this paper covers research on ground deformation and settlement caused by constructing a subway in cobble strata in Xinjiang, discussions about deformations of mined tunnel in cobble strata and comparison between ground deformation from numerical modeling and field measurements. The findings can provide useful reference for similar projects.

2. Parameter Calibration

This study is conducted in the context of a tunnel of Urumchi Metro Line 1 in Xinjiang. This tunnel is in a cobble stratum in Urumchi. The construction site is on a generally flat terrain tilting toward north, at elevations of 650.7-668.9m above sea level. According to field test, the strata on the site consist of an upper layer of miscellaneous fill and a lower layer of Quaternary silt and cobble. Modeling tunnel excavation by DEM requires determination of micro parameters of the strata under consideration. The geological investigation report gives microscopical mechanical parameters however. Consequently, micro parameter calibration is required prior to modeling. In this study, we calibrate micro parameters through triaxial test. At three confining pressures of 50kPa, 200kPa and 400kPa we continue to adjust particle micro parameters in the numerical triaxial test model until the macroscopic characteristic curve in the numerical model is roughly consistent with lab test results, as shown in Fig1.

![Fig 1. The stress-strain curve of triaxial test of cobble stratum](image)

As shown, the stress-strain curves of cobble stratum from the numerical model test using these micro parameters in three different types of surrounding ground are beautifully fitted to lab test results,
thus establishing a relation between micro parameters of cobble stratum and its macroscopic mechanical property. Through calibration, DEM micro parameters corresponding to macroscopic mechanical parameters of miscellaneous fill and moderately dense cobble soil for the tunnel of Urumchi Metro Line 1 are obtained as shown in Table 1.

| Description               | $\rho (kg/m^3)$ | $R_{max}/R_{min}$ | $\mu$ | $K_n (KPa)$ |
|---------------------------|-----------------|-------------------|--------|-------------|
| Miscellaneous fill        | 2700            | 4.0               | 0.5    | 1800        |
| Moderately dense cobble   | 2610            | 6.0               | 0.9    | 3500        |

### 3. Creation of DEM Ground Model

We built a numerical model based on engineering geology on the site of the cobble stratum tunnel of the background metro project, tunnel profile and cross section designs. We set basic dimensions of the numerical model to be 60m transversely and 60m longitudinally considering the correctness of numerical calculation results, model boundary effect (Saint-Venant principle) and the operability of numerical model. The PFC model takes into account the effects of upper layer (miscellaneous fill) 0-10m below the ground surface and lower layer (moderately dense cobble) 10-60m below the ground surface. These two layers are modeled with particle elements of varying sizes, using 2-8cm diameter particles for the upper layer soil and 2-12cm diameter particles for the lower layer soil. A linear contact stiffness model is selected as material constitutive model. Table 1 shows the micro parameters selected for the two layers in the model.

In building the PFC2D model we simplified some conditions as follows:

1. The loading effect of surface structure is not considered, with gravity being the only initial load in the model;
2. Groundwater effect is not considered;
3. Lateral fixation restraint - lateral earth pressure on particles is provided by gravity.

The tunnel is in the lower cobble stratum. The boundary is simulated with wall elements. The constitutive model of stratum particles and the boundary is a linear model. Because the tunnel is at shallow depth in a loose stratum, the model only considers the effect gravity without considering geostatic stress. Within delineated stratum space, particle assembly is generated according to proposed particle size and assigned gravitational acceleration under the effect of which the stratum model accumulates. After the model reaches the ultimate equilibrium, particles outside the wall are removed; particles in the model are assigned mechanical parameters according to their spatial locations to simulate soil layers in different locations. A computational procedure for the model is generated with the stop condition set as minimum inter-particle unbalanced force less than $10^{-5}$. The model of the cobble stratum by using particle flow code is displayed in Fig. 2.
4. Tunnel Excavation Sequence

The tunnel under consideration is a single-tube two-track tunnel designed with a span width of 12m and at 15m depth. We analyze its excavation process from the micro perspective of particle flow code. In the numerical calculation software, we simulate the excavation process by deleting particles inside the excavation line in accordance with excavation sequence. The excavation method used is double-side-drift method. We simulate the temporary support measure following excavation using wall elements. The simulation steps are as follows: remove particles in double side drifts (Part I) → apply support elements for double side drifts → remove particles in upper bench (Part II) → apply support elements at the crown → remove particles in lower bench (Part III) → apply support elements at the bottom. Fig. 3 displays the excavation sequence. After excavation in the model, we apply inter-particle unbalanced force until the value is less than 10^{-5} triggering the stop of iterative operation in order to simulate particle location update and stress redistribution in the process of excavation unloading.

5. Analysis of Deformations of Cobble Stratum Induced by Excavation Unloading

(1) Excavation of double side drifts

Right after excavation of drifts on both sides we apply tunnel support with wall elements and perform iterative operation until the model converges. Vertical displacement following excavation is illustrated in Fig. 4. As shown, the first step of excavation disrupts the original stress state near the drifts leading to vertical displacement of about 15mm; the transfer of the unloading effect in the drifts to cross-section crown and bottom resulting in crown displacement of 10-12mm downward and
bottom displacement of 15-16mm upward, about 25% greater than the crown displacement. This suggests stresses in the ground are quickly relieved after excavation resulting in stress relaxation at the bottom whereas the stress increase rate at the top is less than the stress relaxation rate at the bottom because of the slow process of particle flow at the top. At this point, particle flow also occurs around the excavation line and has not reached the ground surface, so the ground surface will not experience settlement and noticeable deformation. As excavation progresses, particles above the tunnel roof begin moving vertically to a maximum of 15mm; particles near the excavation opening undergo greater vertical displacement representing greater disturbance. Subsequently, with increasing vertical displacement of particles over the tunnel, the deformation propagates to ground surface leading to surface settlement and creation of a 7m high "arch" zone of 45° with respect to sidewalls.

Fig 4. Vertical displacement of cobble stratum after excavating the heading

To further investigate the effect of drift excavation on stresses in cobble stratum, we present the distribution of the force chain between particles during excavation as shown in Fig. 5. Prior to excavation of side drifts the force chain between particles in the ground is distributed uniformly and stable. After excavation of double side drifts (Step 100) the force chain in surrounding ground is intact since ground stress is yet to be relieved. As excavation progresses (Step 5000), local stress relief occurs, forming a triangle-like zone both above and under the tunnel due to ground loss and under the effect of upper particle gravity and particle displacement redistribution; in the meantime, radial expansion of stresses on both sides results in the formation of loosened zones. Discontinuous and broken force chains exist between particles. This suggests ground uplifting or settlement during tunnel excavation leads to particle element flow and hence the breaking of effective force chains. As excavation comes to an end, force chains between particles near the surface are broken to some degree because particle loosening above the tunnel resulting from excavation extends upward while effective force chains are formed between lower particles. After surface settlement has ceased, particles are rearranged in close contact; the force chains between particles are sparse within 5m in vertical direction of the tunnel and effective beyond with good bearing capacity though more sparse than in the original ground.
Fig 5. Distribution of the force chain between particles during excavation of the heading

(2) Excavation of upper bench (Part II)

The same excavation method is used. We simulate the support structure with wall elements until convergence. Fig. 6 displays the vertical displacement after excavation. As shown, the excavation of upper bench results in vertical displacement up to 35mm of particles 10m above and 12m below the tunnel; the amount of particle displacement is 2~3cm. On top of the surrounding ground deformation induced by drift excavation, the affected zone expands by 20% from 10m to 12m; maximum amount of displacement increases by 2.5 folds from 10mm to 35mm. Fig. 7 displays the distribution of force chain between particles after the excavation of upper bench. As shown, excavation of Part II redistributes force chains in the model; as the model calculation converges, force chains between particles are gradually stabilized, forming effective force chains around the tunnel circumference.

(3) Excavation of lower bench (Part III)

In modeling excavation of lower bench (Part III) we simulate the support structure with wall elements until convergence. Fig. 8 displays the vertical displacement after excavation. As shown, no noticeable changes occur to vertical displacement induced deformation zones after this excavation because the soil masses above and beside the cross section have stabilized after unloading in previous excavation. However, loosened zones above and below the tunnel opening have decreased to 6-7m. Maximum displacement of particles above and below the tunnel increases by 25% to 44mm. This suggests relatively small disturbances of this excavation to the ground and that ground displacement comes mainly from ground rebalance. Fig. 9 gives the distribution of force chains between particles after the excavation of lower bench. The distribution of force chains between particles has a similar pattern: in the early stage of the excavation, force chains between particles 3-4m below the tunnel bottom become sparse and discontinuous. As excavation progresses, force chains between particles become less discontinuous and particles are rebonded during flow; force chains between upper particles weaken until excavation of the lower bench comes to an end when particles are rearranged tightly forming effective force chains between them.
6. Analysis of Cobble Tunnel Excavation Unloading Result

To further examine different disturbances to the surrounding ground from different excavation steps for the cobble tunnel and compare simulation results with field measurements, Fig. 10 illustrates additional surface settlement in each excavation step. As shown, the curve of surface settlement caused by excavating the double side drifts is overall in normal distribution and matches the settlement curve developed by Peck. In terms of settlement values, they increase up to a maximum of 6.5mm as the distance to the tunnel centerline decreases; the displacement of particles at a distance of 25m from the tunnel centerline on both sides is about 1mm, 85% less than the maximum value. Excavation of Part II results in additional surface settlement to a maximum of 11.5mm at the tunnel centerline, 77% greater than that caused by excavation of side drifts. Ground stress 1m above the crown decreases markedly by 25% at the crown and by 12% within 15m on either side and then tends to stabilize. Excavation of Part III causes mild additional surface settlement of 2mm maximum.

Comparison of final surface settlement curves shows it is suitable to model tunnel excavation in cobble strata in Urumchi by DEM on the basis of accurate calibration of particle flow code parameters corresponding to the cobble strata.
6. Conclusions

(1) The triaxial numerical model of the cobble stratum by using particle flow code has produced results that are well fitted to lab test results. This enables us to establish micro parameters for the cobble tunnel model using particle flow code;

(2) During cobble tunnel excavation by double-side-drift method, excavation of the upper bench has the biggest influence on ground displacement accompanied by the greatest surface settlement; excavation of side drifts has less disturbance to the ground; excavation of the lower bench has the least effect on the surrounding ground;

(3) Stress redistribution in the cobble stratum caused by tunnel excavation at particle level; the contact between particles is broken and then reestablished, a process that moves outward progressively;

(4) Tunnel excavation causes noticeable stress relief in the surrounding ground within 0.4D from the tunnel circumference. Beyond 0.4D, the force chains attain enough strength to carry ground load though less strong than in the original state of ground stress;
(5) From the comparison of numerical analysis and field monitoring results we conclude the particle flow code model for cobble tunnel excavation is suitable and that the modeling results can provide some reference for similar projects.

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