Study on the Influence of Micro Parameters of Numeric Model Using Particle Flow Code on Macroscopic Mechanical Properties in Cobble Stratum

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Abstract: The widely distributed cobble in the subsurface brings about lots of technical problems to underground projects. Based on the physical and mechanical characteristics of the pebble layer, PFC particle flow software was used to establish a triaxial numerical test model. Considering multifarious situations, triaxial numerical tests were carried out with different mesoscopic parameters, and the influence of mesoscopic parameters of different types of sand pebbles on macroscopic mechanical properties was analyzed. Studying the influence of both contact stiffness and friction coefficient on the macroscopic response of pebble, the conclusions could provide references for the numerical simulation of cobble tunnel excavation.

1. Introduction
In loose ground consisting of cobble and sandy soil, medium particles are in point-to-point contact with each other, with acting forces transferred through the contact points. Therefore, when the ground is disturbed by excavation particles will move independently from each other. Furthermore, such ground is unstable due to the big gap between particles, small contact area, weak cohesion and high mobility of particles. During tunnel excavation in such ground, soil mass at the working face is difficult to stabilize and prone to instability if not controlled properly.

The inter-particle characteristics for sandy cobble strata result in discreteness of surrounding medium during excavation-induced loading and unloading. Traditional numerical methods for continuous medium such as finite element method (FEM) and finite difference method (FLAC) can be used to roughly calculate particle displacement but cannot accurately simulate particle movement process and characteristics. The discrete element method (DEM) [1] is intended for modeling each particle with a single-node element that has an independent motion equation. This basic idea matches the motion characteristic of cobble soil, therefore it is numerically simulated using Particle Flow Code (PFC) [2].
From a micro perspective, T. Funatsu [3] deduced average stress in material from stress in each particle and assuming displacement along each sliding surface 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.

Based on DEM scholars [4]-[7] worldwide conducted extensive research in geotechnical and underground engineering. To study deformations of discrete element ground, Williams numerically performed 2D biaxial compression test on soil grains in square, oval and round shapes and found particle geometry has a big influence on deformation. Using discrete element model (PFC2D) Chen Xiaoting [8] et al. studied surface settlement when the tunnel of Chengdu Metro Line 1 was advanced in sandy cobbles strata, the distance between centers of tracks in the double-track tunnel and the influence of excavation depth on surface settlement. From the perspective of micro mechanics, Ma Teng [9] studied technical issues encountered in TBM tunneling in sandy cobbled stratums, analyzed mechanical properties of different graded sandy cobbles and simulated the impact of different graded sandy cobbles on TBM tunneling. Using particle DEM, Tao Lianjin [10] investigated mechanical properties of soft rock during excavation and numerically simulated excavation of roadway in soft rock. From the micro perspective of discrete material, Wei Longhai [11] 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.

In this paper we use particle flow code to build a triaxial numerical model for analysis of cobbled material, investigate the influence of different micro parameters on its macroscopic mechanical property and establish the correlation between micro parameters of cobbled stratum model using particle flow code and its macroscopic mechanical property.

2. Project Overview
The tunnel site is in the Urumqi River basin. According to field test, the strata on the site consist of an upper layer of miscellaneous fill and a lower layer of medium dense cobbled. The miscellaneous fill is 0.5-10m thick. The cobbled stratum is 10-35m thick and consists of sandstone and limestone. The cobbled particle is roundish with good grind. During tunnel construction, the impact of groundwater is negligible.

3. Analysis of Influence of Micro Parameters for PFC Model
In principle, we can create any physical and mechanical property model by assigning particles mechanical parameters. Fore example we can build deformation and strength models by assigning particles deformation and strength parameters. If macroscopic and micro parameters of particle structure can be correlated by a model, then the model will be sufficiently accurate. However, establishing this correction is a complex process because there is a nonlinear and interactive relationship between actual material and PFC model. Micro parameters of material strength, for instance, include contact modulus between particles, parallel cohesion modulus, normal parallel bonding strength and tangential parallel bonding strength. Increased variables make it more complicated to control its overall change. By building a model to solve the correlation between mechanical properties and a series of material parameters, we make the overall pattern consistent and the model adequately accurate.

The essential difference between PFC model and continuous medium model in solving parameters is as follows: In continuous medium model the macroscopic mechanical properties of the material are generally obtained from survey and can be directly correlated to required parameters whereas in PFC model the required mechanical micro parameters between particles cannot be directly correlated to known continuous medium mechanical parameters. Under a given particle combination, this paper discusses changes in macroscopic mechanical properties of the structure and the influence of micro parameters on macroscopic mechanical behavior by adjusting contact stiffness, friction coefficient and other parameters in triaxial numerical model tests.
3.1 Triaxial numerical model test
Using PFC3D software we built a cylindrical triaxial numerical model as shown in Fig 1. The model is composed of wall elements and ball elements. The cylinder is simulated with ball elements while the boundaries are simulated with wall elements. Throughout the application of load to the specimen, the loading can be simulated by controlling the moving speed of upper and lower walls, with side wall of the cylinder simulating rubber membrane. Only upper and lower walls are moved through servo mechanism to keep confining pressure constant during the test.

![Fig 1. Triaxial test numerical model](image)

The test model has a cylindrical structure: the cylinder has a 5cm radius and 20cm height; maximum and minimum radii of ball elements are 10mm and 7.5mm respectively; a total of 2819 ball elements are generated in the numerical model.

During the test, loading and volume of the specimen keep changing. To control the moving speed of upper and lower walls and keep confining pressure constant, the stress and strain in the specimen need to be calculated on each time step during loading. The stress is calculated based on total contact force acting within the zone while the strain \( \varepsilon \) is calculated using the following equation:

\[
\varepsilon = \frac{L - L_0}{0.5 \times (L + L_0)}
\]  

where

- \( L \) — current radius or length of the specimen;
- \( L_0 \) — original radius or length of the specimen.

After generation of the specimen and during its loading, contact stresses in all ball elements in contact with wall elements are calculated from:

\[
\sigma_w = \frac{\sum_{N_c} F_w}{A}
\]  

where

- \( F_w \) — contact force acting on individual ball elements on wall elements;
- \( N_c \) — the number of ball elements acting on ball elements;
- \( A \) — the area of wall in contact with particles.

After generation of the specimen and during its loading, the moving speed of upper and lower walls is adjusted through servo mechanism and the stress in the upper wall element is maintained at around target stress \( \sigma_t \); the speed \( \nu^{(w)} \) of wall elements satisfies the following equation:

\[
\nu^{(w)} = G \cdot (\sigma_w - \sigma_t) = G \cdot \Delta \sigma
\]  

where \( G \) — control parameter which is calculated as described below.

When upper and lower walls have not yet contacted particles, the contact stress in wall elements
$\sigma_w = 0$, the servo mechanism has not started and the moving speed of the wall is initial value. Thereafter, when the wall comes into contact with particles the servo mechanism is put into effect to start loading. First of all, the contact force $\Delta F^{(w)}$ between particles and wall on each time step $\Delta t$ resulting from movement of wall elements is calculated as follows:

$$\Delta F^{(w)} = k_n^{(w)} N_c \cdot \nu^{(w)} \Delta t$$  \hspace{1cm} (4)

where $k_n^{(w)}$ —— average stiffness of all contact elements.

Thus from stress calculation formula the average stress $\Delta \sigma^{(w)}$ in wall elements is:

$$\Delta \sigma^{(w)} = \frac{k_n^{(w)} N_c \cdot \nu^{(w)} \Delta t}{A}$$  \hspace{1cm} (5)

In actual calculation, a stress relief factor $\alpha$ (typically 0.5 in default) is often introduced. The absolute value of average stress change in wall element must be less than that of the difference between calculated stress and target stress. Under this condition the system stability condition changes as follows:

$$|\Delta \sigma^{(w)}| < \alpha |\Delta \sigma|$$  \hspace{1cm} (6)

Put Eq. (3) and (5) into (6) to derive:

$$\frac{k_n^{(w)} N_c \cdot G|\Delta \sigma| \Delta t}{A} < \alpha |\Delta \sigma|$$  \hspace{1cm} (7)

Thus from Formula (7) we can obtain $G$ that meets system stability condition as follows:

$$G < \frac{\alpha A}{k_n^{(w)} N_c \Delta t}$$  \hspace{1cm} (8)

In any cyclic loading process the proposed wall element speed $\nu^{(w)}$ and the system stability control parameter $G$ are required to satisfy Formulae (3) and (8) respectively.

3.2 Influence of micro parameters on macroscopic mechanical properties

By adjusting inter-particle micro parameters in triaxial numerical model test we can derive the macroscopic mechanical property curves of the soil mass and examine how its macroscopic mechanical properties are affected by changes in micro parameters. On this basis we keep adjusting inter-particle micro parameters, contact stiffness and friction coefficient, to establish the correlation between PFC micro parameters and macroscopic mechanical behavior.

(1) Influence of contact stiffness on macroscopic properties
Fig 2. Change of stress-strain curve with different contact stiffness

Under the condition of confining pressure at 400kPa, porosity of 0.1 and friction coefficient of 0.8, we adjust inter-particle contact stiffness to derive macroscopic stress-strain curves as shown in Fig 2 and the stiffness vs. deformation modulus curve as shown in Fig 3. As shown in Fig 2, prior to shear failure, the macroscopic initial tangential modulus of the material increases with contact stiffness, the failure strain decreases as stiffness increases but the stress increases; after shear failure, the axial stress of material drops about 10% from the peak value with no noticeable difference in the falling rate between different contact stiffnesses and the strain will continue rising. As shown in Fig 3, the deformation modulus is proportional to contact stiffness; as contact stiffness rises by 5 folds, the deformation modulus increases by 2 folds; the deformation modulus increases slower than contact stiffness; increasing contact stiffness will cause linear increase of deformation modulus.

Fig 3. The relation between contact stiffness and deformation modulus

Under the same conditions, we establish the volumetric strain vs. axial strain curves with different stiffnesses as shown in Fig 4 and the Poisson's ratio vs. contact stiffness curve as shown in Fig 5. As shown in Fig 4, in the initial phase of soil particle deformation under stress, the shear resistance effect of the soil particles will come into play, compressing particles and reducing porosity. This is expressed as shear shrinkage on macroscopic curves. When inter-particle shear strength has played its full role, the shear effect weakens, lateral slide occurs between soil masses, inter-particle porosity increases, soil mass volume expands and dilatancy effect is observed. When contact stiffness increases, the slopes of volumetric strain curves in dilatancy phase are roughly in parallel and the shear shrinkage deformation phase gradually narrows. As shown in Fig 5, as contact stiffness increases, the Poisson's ratio also increases though tending to slow; the contact stiffness between particles has a noticeable influence on Poisson's ratio.
(2) Influence of friction coefficient on macroscopic properties

In the triaxial numerical analysis of specimen the shear friction effect of the soil specimen is represented by introducing friction coefficient. In the discrete element model, friction coefficient is used to represent the contact state on particle surfaces. Macroscopic physical and mechanical parameters of soil mass such as internal friction angle, cohesion and Poisson's ratio are all related to friction coefficient. The friction coefficient is strongly correlated to friction angle of soil mass. Since inter-particle cohesion is weak in cobble stratum, the influence of cohesion is not analyzed in the triaxial test.

Fig 4. Change of volume deformation curve with different contact stiffness

![Fig 4. Change of volume deformation curve with different contact stiffness](image1)

Fig 5. The relation between Poisson's ratio and contact stiffness

![Fig 5. The relation between Poisson's ratio and contact stiffness](image2)

Fig 6. Change of the stress-strain curve with different friction coefficient

![Fig 6. Change of the stress-strain curve with different friction coefficient](image3)

Under the condition of confining pressure at 400kPa, porosity of 0.1 and contact stiffness of 1e8N/m, we performed triaxial compression tests with different friction coefficients to derive macroscopic property curves of soil mass with different friction coefficients between soil particles. Fig 6 gives the stress-strain curves with different friction coefficients. Fig 7 gives the internal friction
angle vs. friction coefficient curve. As shown in Fig 6, initial deformation moduli vary little with
different friction coefficients but peak stress decreases markedly with decreasing friction coefficient.
Peak stress drops by 43% as friction coefficient falls by 65%. The curve softening characteristic varies
with friction coefficient. When friction coefficient is 0.7 the post-peak stress falls by 15% from its
peak while when friction coefficient is 0.25 the curve softening characteristic is not noticeable. As
shown in Fig 7, internal friction angle increases with friction coefficient. When friction coefficient
rises by 25% from 0.4 to 0.5, the internal friction angle increases from 24° to 26° by 9%, a rate lower
than that of friction coefficient.

Fig 7. The relation between friction coefficient and internal friction angle

Fig 8 gives volumetric strain-axial strain curves with different friction coefficients. Fig 9 gives the
Poisson's ratio vs. friction coefficient curve. As shown in Fig 8, axial stress values vary little at around
5% from shear shrinkage effect to dilatancy effect with different friction coefficients. As friction
coefficient increases the peak shrinkage strain slightly rises while the dilatancy effect changes faster.
As with the internal friction angle of soil specimen, its Poisson's ratio increases linearly with friction
coefficient though by a much lower rate. When friction coefficient rises by 25% from 0.4 to 0.5,
Poisson's ratio increases by about 3% or 0.02.

Fig 8. Change of volume deformation curve with different friction coefficient

Fig 9. The relation between friction coefficient and Poisson's ratio
4. Conclusions

(1) Based on DEM we have built a triaxial numerical model for cobble material to analyze the stress-strain curves and volumetric strain curves of cobble material with different micro parameters.

(2) As contact stiffness and friction coefficient increase, the stress-strain curves of cobble material shift from stress hardening to strain softening; and both contact stiffness and friction coefficient are positively correlated to peak value of deviatoric stress.

(3) The friction coefficient and contact stiffness are proportional to deformation modulus, and the increase effect of contact stiffness is greater than the latter. Volumetric strain undergoes two phases: shear shrinkage and dilatancy. Increased friction coefficient enhances both phases whereas increased contact stiffness enhances the shrinkage phase and weakens the dilatancy phase.

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