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Research Article

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Discrete element simulation on mechanical properties of modified sandy gravel

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ABSTRACT

Through the laboratory experiments, the mechanical properties of sandy gravel are obtained. Then, based on the slump tests, a modified sandy gravel model is developed by PFC^{3D} (particle flow code of three dimensions), to which relevant microscopic parameters are assigned to numerically simulate the laboratory experiments. The laboratory test results are compared with that of the numerical simulation by PFC^{3D}, which shows their perfect agreement. Thus the particle flow method is able to better simulate the process of the laboratory experiments of sandy gravel. A new approach for the study of the physical and mechanical properties of modified sandy gravel is proposed in the research to overcome the limitations of conventional tests.

Key words: discrete element simulation; modified sandy gravel; triaxial test; mortar model

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INTRODUCTION

In sand gravel layer, the stratum structure is loose and not cemented, and has poor self-stability, besides, the content of gravel in the layer is high and the particle size is uneven. The sand gravel layer is a typical unstable layer with high sensitivity[1]. It is very hard to arch the soil formations in the shield construction process. When the cutter is rotating, it is easy to destroy the original stability of the formations, causing collapse and large disturbance of surrounding rocks. Thus, there are a lot of technical problems in the shield construction process with earth pressure balance, such as instability of excavation face, promoting resistance, serious cutter wear, occlusion of pressure positions, caking and spewing, even surface collapse[2].

Distinct Element Method is proposed by Cundall P.A[3]. It is a discrete body of a particulate material analysis method, it is based on the principle of molecular dynamics and it is first used in rock mechanics. On this basis, Cundall and Strack put forward the rigid disc granular model in 1978 and put the model into application in soil mechanics, the results are consistent with photoelastic experiment results proposed by Drescher[4-5]. In the process of shield construction, the cohesive force of soil c and internal friction angle φ are two critical control parameters, the rationality of the value and the veracity of the value play decisive roles to the determination of excavation face support pressure and the stability of the excavation face. Soil particles in sandy gravel are independent from each other. Complex attributes displayed in the course of the force, which has yet to establish appropriate constitutive models. Development and validation of constitutive relationship require a lot of physical experimental data as a basis for research, however the large diameter triaxial tests the high cost, complicated operation, Additionally, the large discreteness of test results caused by the complexity and uncertainty of the microscopic structure of sandy gravel soil is also the problem in accurate description of its mechanical behavior. Therefore, this paper from the view of microcosmic, taking PFC^{3D} as the tool, according to the sandy gravel gradation curve construction site has self-programming to obtain the numerical model, laid the foundation for the study of the mechanical properties of sandy gravel. Through the laboratory experiments, the mechanical properties of sandy gravel under different stress levels are obtained. A modified sandy gravel model based on the slump tests is established to explore the basic mechanical properties of modified sandy gravel, laying a solid foundation for the study of soil improvement and numerical model tests.

BASIC THEORY

CALCULATION CYCLE OF PFC

The calculation cycle in PFC^{3D} is a timestepping algorithm that requires the repeated application of the law of motion to each particle, a force-displacement law to each contact, and a constant updating of wall positions. Contacts, which may exist between two balls, or between a ball and a wall, are formed and broken automatically during the course of a simulation. The calculation cycle is illustrated in Fig 1. At the start of each timestep, the set of contacts is updated from the known particle and wall positions. The force-displacement law is then applied to each contact to update the contact forces based on the relative motion between the two entities at the contact and the contact constitutive model. Next, the law of motion is applied to each particle to update its velocity and position based on the resultant force and moment arising from the contact forces and any body forces acting on the particle. Also, the wall positions are updated based on the specified wall velocities. The calculations performed in each of the two boxes of Fig 1 can be done effectively in parallel[6].

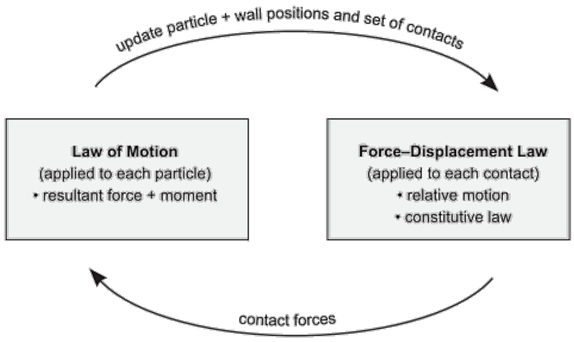


Fig. 1: Calculation cycle in PFC^{3D}

FORCE DISPLACEMENT LAW

The particle flow method which is based on the discrete element method is to simulate the movement and interaction of rigid spheres. PFC^{3D} is one of discrete element programs, the basic unit is a pure spherical particle. The force-displacement law relates the relative displacement between two entities at a contact to the contact force acting on the entities. For both ball-ball and ball-wall contacts, this contact force arises from contact occurring at a point. For ball-ball contact, an additional force and moment arising from the deformation of the cementations material represented by a parallel bond can also act on each particle[6].

(1)Contact model

The normal contact force and the relative displacement between the two spheres in contact with each other is calculated by:

$$F_i^n = K^n U^n n_i \tag{1}$$

Where K^n is the normal stiffness, U^n is the overlap in the normal direction, n_i is the unit normal.

The shear elastic force-increment vector is calculated by:

$$\Delta F_i^s = -K^s \Delta U^s \tag{2}$$

K^s is the shear stiffness at the contact.

(2)Sliding friction model

During the loading process, there is friction between sandy gravel particles, therefore the sliding friction model introduced to simulate the sliding behavior between particles allows particles to slid within the scope of the shear strength. The contact is checked for slip conditions by calculating the maximum allowable shear contact force:

$$F_{max}^{s} = \mu \left| F_i^n \right| \tag{3}$$

Where μ the friction coefficient, F_i^n is normal contact force.

If $\left| F_i^s \right| > F_{max}^s$, then slip is allowed to occur, and $F_i^s = F_{max}^s$

LABORATORY EXPERIMENTS

TRIAXIAL TEST

The test instrument is the large-scale triaxial apparatus. Its operating principle is that acting an axial force on samples through axial system and acting a circular force on samples through pressure cell to simulate the sample failure under three dimension pressures, from which the stress-strain curves of the tests are obtained. The triaxial apparatus parameters are as follows.

Table 1 Triaxial apparatus parameters

Sample size	Φ300mm×600mm
Maximum axial compression	2000kN
Axial displacement	0～300mm
Maximum confining pressure	10MPa
Maximum pore water pressure	10MPa

The sandy gravel sampled from the Beijing subway construction site is used to prepare the specimen. The standard
The sandy gravels taken from the Beijing subway construction site are used to prepare the specimen. The standard screens which has six kind of apertures(6cm、4cm、2cm、1cm、0.5cm、0.2cm)are used to screen the fully dry sandy gravel .Repeat screening 4 times then calculate the average, the distribution of the sandy gravel particle size range is shown in table 2.

Table2 Sandy gravel particle size distribution

Particle diameter (mm)	40~20	20~10	10~5	5~2	0.2
Mass percentage (%)	29	22.2	9	7	32.8

According to table 2, the sandy gravels of different particle size are weighed and mixed, then put in the steel cylinder in which the samples are divided into 5 layers in order to ensure the compactness. Isotropic consolidation drained shear (CD) test method is used, with a shear rate of 2mm/min. The specimen fails when its displacement reaches 15% height of the specimen. In order to study the strength and deformation properties of sandy gravel, tests with 3 confining pressures (0.1MPa, 0.2 MPa and 0.3MPa) are conducted during which the stress and strain data are recorded.

SLUMP TEST

The slump test is a commonly used for the test method for measuring the workability of fresh concrete. Through modification of the content of different mud of modified sandy gravel slump test, the relationship between dosage of mud and the liquidity of modified sandy gravel has been established. The basic data to determine the model of rheological parameters of mortar is obtained. The standard slump cone as shown in Fig 4:

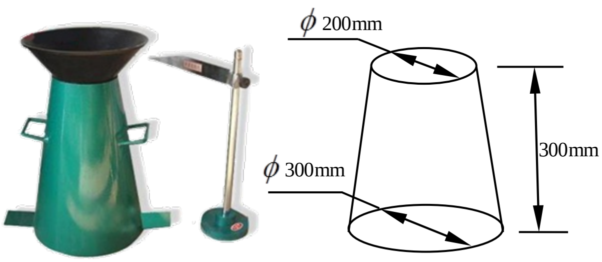


Fig 4: The standard slump cone

Before the slump test, the modified sandy gravel should be prepared at first. The modified sandy gravel is mainly composed of sandy gravel, mud and water. Sandy gravel soils in accordance with table 2, which is needed 40 kg (approximately 15 L) according to the volume of the mixing drum. The additive amount of mud every time is 200ml, The slump tests are carried out in accordance with the standard test method after mixing evenly, until the plastic flow of the soil was too large so far[7].

NUMERICAL SIMULATION TEST

NUMERICAL SAMPLE OF TRIAXIAL TEST

The cylindrical specimen of the triaxial test numerical model is 60cm in height and 30cm in diameter. The upper and lower planes are both loading board whose stiffness is slightly larger than the normal stiffness of the particle. The cylinder wall is subjected to flexible constraints and its normal stiffness is smaller than that of the particles. According to the grading curve, the Fish language embedded in $PFC^{3D}$is used to establish the numerical model. In order to ensure computational efficiency, the minimum size of particles is controlled to 10 mm. The distribution of the particle size range of numerical samples is shown in table 3, and the numerical sample is shown in Fig 3.

Table 3 Particle size distribution table

Particle diameter (mm)	40~20	20~10	10
Mass percentage (%)	29	22.2	48.8

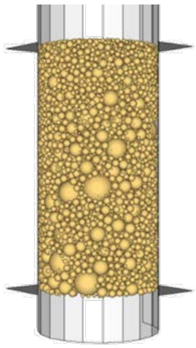


Fig3: Numerical sample

The generation process is divided into the following steps, taking group 1 (40~20mm) for example:
(1) First the total volume of the particle aggregate is calculated by the equation below:

$$V_s = nV = n\pi H\left(\frac{D}{2}\right)^2 \tag{4}$$

Where n is the porosity of the sample, V is the total volume of the sample, H is the sample height and D is the sample diameter.

(2) N particles are generated within a range of the particle radius (40~20mm), the radius compliance with Gaussian distribution.

(3)The total volume of all the particles of this group can be calculated as follows:

$$V_{s1} = \frac{4}{3}\pi\sum_{i=1}^{N_1}\left(\frac{d_i}{2}\right)^3 \tag{5}$$

Where d_i is the diameter of the particles.

(4) When $\left|\frac{V_{s1}/V_s - P_1}{P_1}\right| > \varepsilon$, all particles in the grain group are deleted.

Where $P_1$is mass percentage of this group, and ε is the control precision, ε=0.01.

(5) N_1=N_1+1, repeat steps (2)~(4)

(6) Repeated steps (1)~(5), until the condition is satisfied requirements:

$$\left| \frac{V_{s1}/V_s - P_1}{P_1} \right| \le \varepsilon \quad (6)$$

Then the particles are generated next group. The particle number of each group is shown in table 4.

Table 4 Particle number of each group

Particle diameter (mm)	40~20	20~10	10
Particle number	75	451	3669

NUMERICAL SAMPLE OF SLUMP TEST

Three groups of the slump test of modified sandy gravel was executed, the additive amount of mud is 5%, 10% and 15% respectively. According to the results of triaxial test, the model parameters is determined the numerical model of slump test is shown in Fig 5. The mortar in this model is replaced with a diameter of 5mm particle, the model parameters of sandy gravel particles and the mortar particles are evaluated separately.

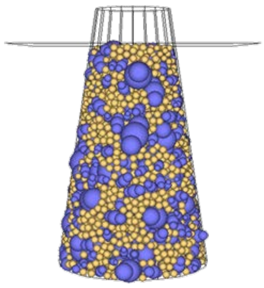


Fig 5: The numerical model of the slump test

RESULTS AND DISCUSSION

The data under a confining pressure of 0.1Mpa of the numerical test are compared with that of the laboratory test. After repeated adjustments, a set of perfect value of the simulation parameters is obtained as shown in table 5, which are then used for the numerical simulation test with confining pressures of 0.2Mpa and 0.3Mpa.The stress-strain curves of numerical simulation and laboratory test are compared as shown in Fig6.

Table 5 Values of micro parameters

k_n (N/m)	k_n / k_s	k_n^p (N/m)	k_n^c (N/m)	μ	v (m/s)	ρ (kg/m^3)
1.5e7	2.0	1e8	5e6	1.5	0.01	2680

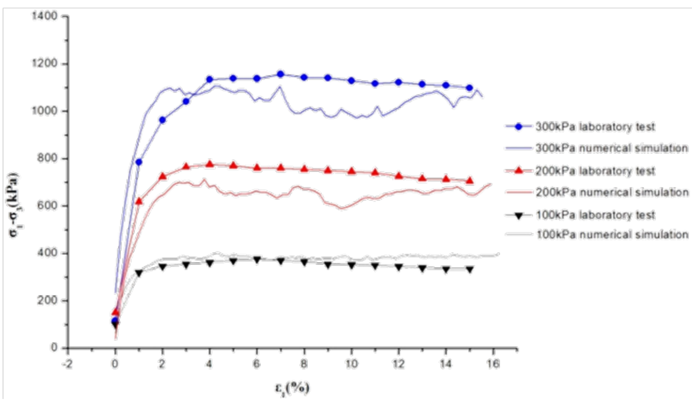


Fig 6: Stress-strain curves of numerical simulation and laboratory test

The Fig6 shows that the laboratory test results and the numerical simulation by PFC^{3D} are perfect agreement. As the increase of confining pressure, the peak strengths of numerical test raise. There are a few deviations between the stress strain relation under different confining pressures from numerical simulation and laboratory test, whereas the basic trend is consistent. When axial pressure is large, the slide may occur and the arrangement of the inner particles of the numerical model is not compacted as that of the real sandy gravel, thus the decreased interlocking causes the deviation.

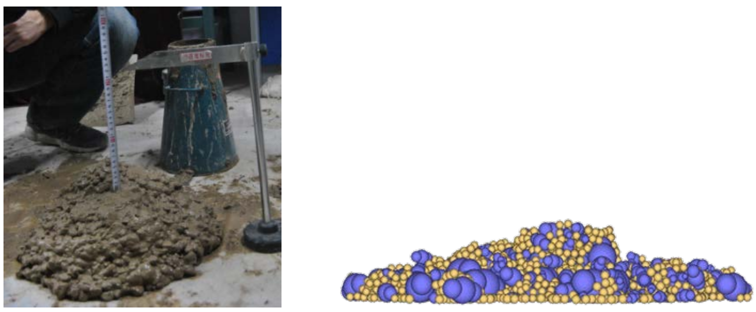
The numerical simulation and the actual results of slump tests are shown in table 6. The final state of tests is shown in Fig7.

Table 6 Comparison of results between the numerical simulation and the actual slump test

No.	Mud content /%	Actual slump /cm	Simulation slump /cm	Errors /%
1	5	6.8	7.6	11.8
2	10	13.6	15.2	10.5
3	15	21.8	22.6	3.7

(a) The slump of 5% mud content

(b) The slump of 10% mud content



(c) The slump of 15% mud content

Fig 7: The final state of slump tests

The Fig7 shows that three group errors of the numerical simulation and the actual slump test results are small. The numerical simulation reproduced the whole process of the slump test. Because the model of the mud particles are 5mm diameter balls, the bite force between particles are relatively low, particles are more prone to movement, the results of numerical simulation is larger than the actual.

CONCLUSION

Sandy gravel is a particle aggregate that consists of particles of different sizes. Base on the laboratory triaxial tests and the slump tests, the numerical models of triaxial tests and slump tests based on the graduation of the sandy gravel materials in construction site is established by PFC^{3D} from microscopic perspectives in the paper, and the conclusion is made as follows by comparing two test results.

(1)The triaxial tests of sandy gravel are completed and the stress-strain curves of sandy gravel under different confining pressures are obtained.
(2)The modified sandy gravel model is developed, which is composed of gravel particles and mortar particles. The slump test results of the numerical model are in agreement with actual test.
(3)The triaxial model and the modified sandy gravel model established herein are able to simulate the physical and mechanical properties of sandy gravel accurately, which overcome the limitation of laboratory tests and the discreteness of the test results.

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