Research on concrete slump based on discrete element method

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Abstract. The whole process of concrete slump experiment was simulated with Particle Flow Code 3 Dimensions (PFC3D) software based on discrete element simulation. The simulation results are in good agreement with the macroscopic results obtained from field experiments, indicating that the use of PFC software for concrete had the feasibility of slump experiment simulation. The software simulation results have a good observation on the speed and direction of the particles in the process of concrete slump.

Keywords: discrete element, concrete, slump.

1. Introduction
Nowadays, with the progress of the economy and society in China, all walks of life are developing very rapidly. Concrete is one of the most widely used materials which can be used in construction, tunnel support, and other fields. The connection between concrete and machinery is getting closer, and the demand for concrete is getting higher and higher [1]. The quality of concrete is related to aggregate size and water-cement ratio and its rheological properties after mixing. The concrete’s rheological properties can considerably assist the improvement of concrete construction and hardening performance after construction through accurate measurement. This article aims to study the rheological properties of concrete in microscopic aspects through discrete element simulation. Numerical simulation is a research method that is more realistic to study the rheology of concrete compared with theoretical research and experimental research. The discrete element method can be used to study the overall concrete condition of a single particle.

2. Establishment of Discrete Element Model
2.1. Discrete element background
The discrete element method is a numerical simulation research method commonly used to solve the environmental problems of the discontinuous working medium. The discrete element method was first proposed by Cundall in "A discrete numerical model for granular assemblies" in the 1970s, and since then, it has received great attention from scholars and developed a long way. In 1986, Wang Yongjia introduced the basic principles and application examples of the discrete element method to the field of
engineering and rock mechanics in China at the first National Symposium on Numerical Calculation and Model Testing of Rock Mechanics. Though starting late, the application of the discrete element method in China develops rapidly.

2.2. Introduction to Particle Flow (PFC)
The PFC2D and the PFC3D are discrete element programs based on a two-dimensional disc structure unit and a three-dimensional spherical element, respectively. PFC is mainly used to simulate the overall flow of particles and the mixing of materials under non-linear interaction [2]. The discrete element method simulates the movement and interaction of a circular granular medium. The motion control equation is carried out by the translation and rotation in the plane to determine the location and velocity of the particles at each moment. This approach can be applied to research the characteristics of granular media. Numerical simulation is used to divide the object into hundreds of representative granular units [3]. The PFC2D simulates the movement in a two-dimensional plane. The simple syntax cannot reflect the three-dimensional effect. For some experiments that are hard to observe from a two-dimensional perspective, only PFC3D can meet the requirements.

The PFC3D has a wide range of applications and has attracted much attention at home and abroad. Cao Guodong uses PFC3D to study the rheology and thixotropy of concrete, divides the concrete into two phases, coarse aggregate and cement mortar, and then uses two types of particles with different material properties to represent. Liu Xiaowen and Cha Chonglun simulated the unsaturated soil shear experiment with PFC3D. In his article, the particle bond strength is used as a bridge to establish a PFC3D direct shear numerical model of unsaturated soil to simulate the mechanical properties of unsaturated red soil under different consolidation stresses and matrix suction, get the relationship between shear stress and shear displacement. At present, there are not many domestic experiments using PFC3D to simulate concrete, but there are not many in-depth explorations of concrete slump experiments with software.

2.3. Build a discrete element model
Concrete is a multi-component mixture composed of cement as the main cementing material, fused with sand (fine aggregate), pebbles (coarse aggregate), water and other additives [4], as shown in Figure 1(a). There is no considerable fluid in the discrete element simulation. Therefore, in order to simplify the model, the concrete can be regarded as composed of only coarse aggregate and mortar and the coarse aggregate is represented by large particles and the mortar is represented by small particles, as shown in Figure 1 (b). At the same time, the number of cement particles should not be too much, considering the performance of the computer, calculation time, etc.

![Figure 1. Concrete object and simplified diagram](image)

The contact model of concrete uses a linear parallel bond model. Parallel bonding provides the mechanical properties of a piece of cement-like material of limited size deposited between two contact pieces (similar to epoxy resin bonded glass beads, as shown in Figure 2. The left side of the figure is between the particles and the particles. The contact between the particles and the wall on the right). The
parallel bonding component acts in parallel with the linear component and establishes an elastic interaction between the two pieces. Parallel bonding can transfer forces and moments between parts [5]. Parallel bonding is a set of elastic springs with constant normal stiffness and shear stiffness. The elastic springs are evenly distributed on the 3D cross-sectional contact plane and centered on the contact point. These springs act in parallel with the springs of the linear components. After creating a parallel bond, the relative movement that occurs at the contact will cause forces and moments to be generated in the bond material. The force and moment act on the two contact parts, and may be connected to the maximum normal stress and shear stress at the bonding periphery acting on the bonding material. If any of these maximum stresses exceeds its corresponding bond strength, the parallel bond will break, and the bond material and its accompanying forces, moments and stiffness will be removed from the model [6].

![Figure 2. Conceptual surface of limited dimensions (green and red) and the parallel bonding surface gap at the contact of the parallel bonding ball (left) and the spherical surface (right). (Photo of glass beads from [Holt2005])](image)

Concrete viscosity is reflected by damping $F^d$. Figure 3 shows the force between particles when linear parallel bonding is used, where $F^l$: linear force, $F^p$: parallel bonding force, $M^p$: parallel bonding moment, $g$: reference gap, $\sigma$: tensile strength, $k_n$: normal phase stiffness, $k_s$: tangential stiffness, $c$: viscous force, $\phi$: friction angle, $\mu$: coefficient of friction.

![Figure 3. The behavior and flow of the linear parallel bonding model with inactive dampers (picture from PFC3D tutorial file)](image)
If the linear parallel bonding model is bonded, or if the surface gap is less than or equal to zero, the contact with the linear parallel bonding model is active. For inactive contacts, skip the force-displacement law. When the reference gap is zero, the theoretical surface of the first interface coincides with the surface of the work-piece. The theoretical surface of the second interface is shown in Figure 2.

The force-displacement law of the linear parallel bond model produces contact-forces and moments.

\[ F_c = F^1 + F^d + \vec{F}, M_c = \vec{M} \]  

(1)

Parallel bonding force is decomposed into normal force and shear force, and parallel bonding moment is decomposed into torsion moment and bending moment:

\[ \vec{F} = -F_n \hat{n} + \vec{F}_s \]  

(2)

\[ \vec{M} = M_t \hat{n} + \vec{M}_b \]  

(3)

Where \( F_n > 0 \) is the tension, and the parallel bonding shear force and bending moment are located on the contact surface and are expressed in the contact surface coordinate system:

\[ \vec{F}_s = F_{ss} \hat{s} + F_{st} \hat{t} \]  

(4)

\[ \vec{M}_b = M_{bs} \hat{s} + M_{bt} \hat{t} \]  

(5)

When the bonding method is used to establish parallel bonding, an interface is established between two conceptual surfaces, and the parallel bonding force and moment are returned to zero. Parallel bonding provides elastic interaction between these two theoretical surfaces, and this interaction is eliminated when the bond breaks.

\[ \bar{R} = \lambda \begin{cases} \min(R^{(1)}, R^{(2)}), \text{ball} - \text{ball} \\ R^{(1)}, \text{ball} - \text{facet} \end{cases} \]  

(6)

\[ \bar{A} = \pi \bar{R}^2 \]  

(7)

\[ \bar{I} = \frac{1}{4} \pi \bar{R}^4 \]  

(8)

\[ \bar{J} = \frac{1}{2} \pi \bar{R}^4 \]  

(9)

Where \( \bar{R} \) is the contact radius, \( \bar{A} \) is the cross-sectional area, \( \bar{I} \) is the moment of inertia of the parallel bond cross section, \( \bar{J} \) is the polar moment of inertia of the parallel bond cross section, and the bond cross section is circular.

3. Slump test

3.1. Influencing factors of concrete slump

Concrete slump refers to the capability and plasticization performance of concrete, which is mainly expressed in the workability of concrete, that is, the characteristics of fluidity, water retention and viscosity of concrete during the construction process. There are many factors that affect the size of the concrete slump, mainly including gradation changes, water content, weighing deviation of the weighing instrument, the number of admixtures, and the temperature of the cement that is easily overlooked [7].
The quality of the concrete raw materials, the mixing time after mixing, and the concrete transportation time will all affect the slump of the concrete.

3.2. Slump test
The slump is widely used because of the time required and the amount of concrete is relatively small, the operation is simple and the experimental structure is easy to obtain. The equipment required for the experiment is: ① A round truncated funnel with a top diameter of 100 mm, a bottom diameter of 200 mm, and a height of 300 mm; ② A square iron plate with a side length of 1 m; ③ Prepare at least enough mixed concrete for four experiments; ④ A rod for tamping concrete (not too small); ⑤ Iron ruler for measuring height.

Experimental steps: First, water wet the square iron plate and the inner part of the slump bucket, place the slump bucket horizontally on the iron plate, keep it still, and then pour the mixed concrete into the bucket three times (after each installation, the concrete must be tamped with a stick). After it is filled, the concrete is smoothed against the top of the slump bucket [8], then the iron bucket is quickly lifted, and after the concrete stops flowing, the vertical height of the concrete is measured to obtain the slump of the concrete. For the drop value, the largest diameter in the horizontal direction is the concrete slump extension. As shown in Figure 4, H is the slump value and L is the slump extension value. Under normal circumstances, there are four types of concrete slump, as shown in Figure 5(a). This represents the slump of concrete under ideal conditions. At this time, the entire concrete only slumps to both sides for a certain amount, and the left and right sides symmetrical on both sides. Figure 5 (b) and (c) show that the concrete cannot be measured by the slump of its rheological properties at this time (d) shows that the experiment has failed, and the experiment needs to be repeated.

![Figure 4. Schematic diagram of slump cylinder](image)

![Figure 5. Four common collapse patterns](image)

When ordinary concrete and high-performance concrete have the same slump value but the two show different flow behaviors during the flow process, it indicates that the slump value at this time is only
connected to the yield strength of the concrete, and does not take into account the effect of stickiness. Some predecessors deduced the mathematical relationship between yield strength and slump on based on theoretical analysis and experimental research. The Kurokawa deduced equation is as follows [9]:

\[ \tau_0(S) = \frac{\rho g}{1200\sqrt{3}} (30 - S) \]  \hspace{1cm} (10)

\[ \tau_0(Sf) = \frac{\rho g v_c}{25\sqrt{3}nSf^2} \times 10^8 \]  \hspace{1cm} (11)

In the formula, \( S \) is the slump value, in mm; \( \rho \) is the density of concrete, in-unit kg/m\(^3\); \( g \) is the acceleration of gravity, in-unit m/s\(^2\); \( Sf \) is the slump fluidity, in mm; \( V_c \) is the volume of the slump bucket, in-unit m\(^3\). Figure 6 shows the final flow pattern of the concrete after the slump experiment. After many experiments, the slump value is about 221.3mm, and the slump extension value is about 365mm. To determine the microscopic parameters of the general discrete element model of concrete, the corresponding discrete element model of the slump experiment was established, as shown in Fig. 6(a), and Fig. 6(b) shows the final shape after the collapse.

\[ \begin{array}{c}
\text{(a) Before collapse} \\
\text{(b) After collapse}
\end{array} \]

\textbf{Figure 6. Discrete element simulation of slump experiment}

4. Conclusion

In the simulation, by continuously changing the random number, several numerical simulations were carried out on the slump experimental research. Finally, according to the calculation, the average value of the slump was about 226mm, and the relative error with the physical experimental data was 2.1%. The physical results and the experimental simulation results are close, indicating that the discrete element model established by the PFC3D software can simulate the flow behavior of concrete under its own gravity.

At the same time, some data that cannot be obtained in the experiment can be observed when using the software to simulate the concrete flow. Fig.7 shows the distribution of the velocity of the particles during the slump process. It can be seen from the figure that the slump cylinder goes from bottom to top to lift up, so the particles below move first, so the speed is the highest at this time. After a period of time, the particles in the upper layer have a falling acceleration process, so the speed of the particles in the upper layer increases at this time, and finally the particle speed is close to zero, and the slump basically ends.
Discrete elements have great advantages over other numerical simulation methods in rock and concrete simulation. However, because the discrete element has high requirements for computer performance and the contact model between particles is ideal, it must be simplified when simulating concrete and approximate processing. With the deepening of concrete research and the development of computer technology, the use of discrete element methods to study the rheological properties of concrete will contribute to the development of concrete.

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