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Research on rotational resistance in particle motion simulation based on discrete element method

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Abstract: In this paper, the effect of rotational resistance on particle motion in discrete element method is studied. In the discrete element method, the interaction between particles is simulated by point contact, and the mechanical constitutive model of contact action is established by a set of normal and tangential springs and dampers for each contact point. However, in the process of contact between particles, there are not only the normal and tangential forces that affect the relative translation of particles, but also the torque effect that affects the mutual rotation of particles. In this paper, the effect of rotating resistance on particle motion is studied by adding rotating spring and rotating damper to the contact point model. The rolling process of a single sphere and the formation process of a three-dimensional particle pile under certain conditions are simulated, and some results are obtained which are different from those without considering the rotation resistance. These results have some guiding significance for the motion behavior of granular materials in nature and engineering.

1. Introduction

Particle materials are widely used in nature and engineering fields, and it is of great significance to study their motion behavior. Discrete element method is a commonly used method to simulate particle motion. By modeling the interaction between particles, the mechanical behavior of particle materials can be simulated.

This method is based on a continuum model of granular matter and the Eulerian Finite Element Method (FEM) which can efficiently simulate the discharging process and predict the MDR. (Huang et. al., 2020) study shape optimization of conical hoppers to increase mass discharging rate. With the focus on conical hoppers, the widths of silo and hopper outlet as well as the vertical height of hopper are fixed. The Discrete Element Method (DEM) is a valuable tool for simulating the bulk behavior of granular materials that has rarely been used for biomass feedstocks. (Pachón-Morales et. al., 2020) focus on the numerical investigation of the flow of raw and torrefied biomass particles in a loose and dynamic conditioning using a rotating drum. Discrete Element Method (DEM) is a well-established and validated tool for the simulation of bulk materials. (Ajmal et. al., 2020) present a calibration approach using the draw down test. (Guzman et. al., 2020) study discrete element modeling of seed metering as affected by roller speed and damping coefficient. The discrete element method (DEM) was used to simulate metering of seeds with a fluted roller meter. Angle of repose experimental tests and simulations were performed to calibrate the rolling friction coefficient for peas. One of the key challenges in the implementation of discrete element method (DEM) to model powder's flow is the appropriate selection of material parameters, where empirical approaches are mostly applied. The purpose of (El-Kassem et. al., 2020) is to develop an alternative systematic numerical approach that can efficiently and accurately predict the influence of different DEM parameters on various sought macroscopic responses, where, accordingly, model validation based on experimental data is applied. The computation time of Discrete Element Method (DEM) simulations increases exponentially when particle size is reduced or the number of particles increased. (Mohajeri et. al., 2020) develop a hybrid particle-geometric scaling approach with a focus on Elasto-Plastic Adhesive contact models. Three rolling resistance models, with varying coefficient of rolling friction, are considered for spherical particles. (Soltanbeigi et. al., 2021) present extensive quantitative results showing how the various ways used to represent shape affect the bulk response, allowing comparisons between different approaches. (Wu et. al., 2021) present a novel three-dimensional characterisation of the wear effects of a roll surface on the texture transfer in skin-pass rolling. It is expected that the method established can be used to control the surface texture transfer in skin-pass rolling under the continuous wear of roll surfaces. The rotary drum is chosen as simple equipment to calibrate particle–particle and particle–material interaction properties, as there is a lack of research on whether the rotary drum is adequate equipment to calibrate particle–material interaction properties (Sugirbay et. al., 2022). The particle–particle static and rolling friction coefficients were calibrated according to the angle of repose when the rotary drum is vertical. Other influential work includes (Coetzee, 2020).

In discrete element calculation, particle elements simulate the interaction between particles through point contact. However, in the contact process between particles, in addition to the normal and tangential forces, there is also a torque effect that affects the mutual rotation of particles. The effect of rotational resistance on particle motion is very important. However, there are relatively few researches on rotational resistance in discrete element simulation. Therefore, the purpose of this study is to study the effect of rotational resistance on particle motion by adding rotating spring and rotating damper to the contact point model. We will simulate the rolling process of a single sphere and the formation process of a three-dimensional particle pile under certain conditions, in order to obtain some results different from those without considering the rotation resistance. These research results will help to deeply understand the motion behavior of granular materials, and provide theoretical guidance and practical application value for related engineering and natural phenomena [1-4].

2. Improvement of discrete element method

In the traditional discrete element analysis, it is necessary to provide a contact point for the transmission of the contact force between particles. Each contact point is assumed to consist of a series of normal and tangential springs, dampers, tension-free hinges, and tangential sliders, which reflect the magnitude of the contact force. In general, the contact force is decomposed into the normal component Fn and the tangential component Ft. The schematic diagram of its contact model mechanism is as follows (Figure 1, Figure 2):

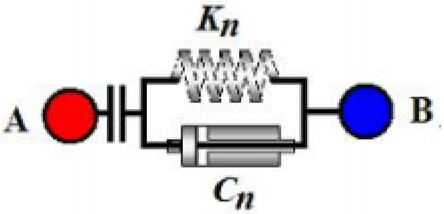

Figure 1: Normal contact model

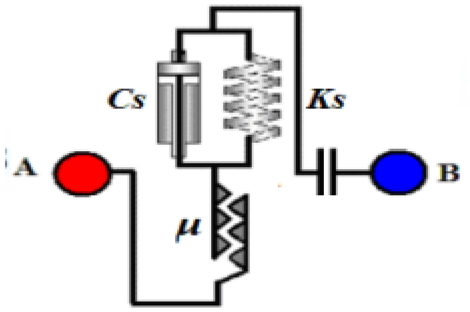

Figure 2: Tangential contact model

The normal and tangential components of the contact force are respectively calculated by the following formula:

$$F_n = K_n \Delta_n - C_n V_n$$

$$F_s = min(K_s \Delta_s - C_s V_s, \mu F_n)$$

K is the stiffness coefficient; C is the damping coefficient; Δ is the amount of deformation (the amount of overlap between particles in the elastic model); V is the velocity of particle movement; μ is the sliding friction coefficient. n and s represent the normal and tangential directions respectively.

In the traditional discrete element model, the contact force is transmitted through the contact points between particles. In fact, the contact between particles is a surface, not a point. If the stress distribution on the contact surface is unbalanced due to particle rolling, this imbalance can be characterized by the equivalent torque, which is the rolling impedance. Figure 3.

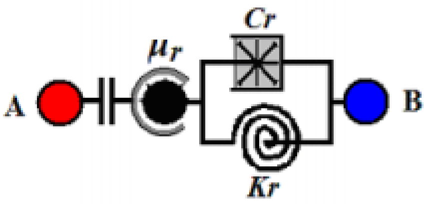

Figure 3: Contact mechanism of rolling impedance

The rolling impedance can be given by:

$$M = min(K_r \Delta_r - C_r \omega, \mu_r F_n)$$

Where, ω is the angular velocity; Kr is the rolling stiffness, which is related to the material properties and the size of the contact surface, and can be defined as:

$$K_r = \gamma K_n \cdot \Delta_n \cdot r$$

Where, γ is the rolling stiffness coefficient and γ is the overlap distance between objects. r is the radius of the particle. μr is the coefficient of rolling friction, which can be calculated as follows:

$$\mu_r = B \cdot \frac{\zeta_r}{2}$$

3. Example of a single sphere plane rolling

The example simulates the free rolling of a round ball on a flat plate, and its model is shown in Figure 4. The radius of the ball is R, the resultant force is 0, and the initial linear velocity V and angular velocity ω are given to make the particle roll on the plate. The influence of various parameters in the model on the change of velocity, acceleration, displacement and so on is analyzed. The material parameters are as follows: normal stiffness Kn=10822786.69, shear stiffness Ks=10822786.69, normal damping coefficient Cn=1637.58, tangential damping coefficient Cs=163.758, sliding friction coefficient μ=0.8.

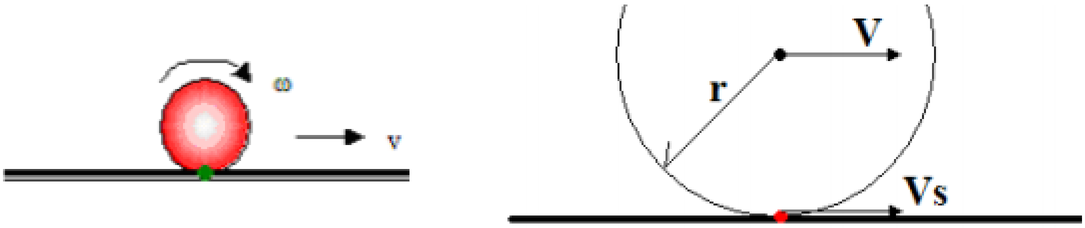

Figure 4: The ball rolling on the plate

A) Traditional discrete element simulation

In the horizontal direction, the initial velocity of shear deformation at the contact point is calculated as follows:

$$V_s = V - \omega \cdot r$$

If V is equal to $\omega \cdot r$, then the initial shear velocity Vs is zero. In time t, the shear deformation is $\Delta_s = V_s \cdot t = 0$. In this case, there is no sliding friction, and the ball particles will maintain a stable rolling state. In fact, due to the existence of sliding friction, the initial shear speed will not be zero, but the action of friction and damping forces will adjust V and ω, so that Vs gradually decreases to zero, and finally the particles reach a stable rolling state[5-8].

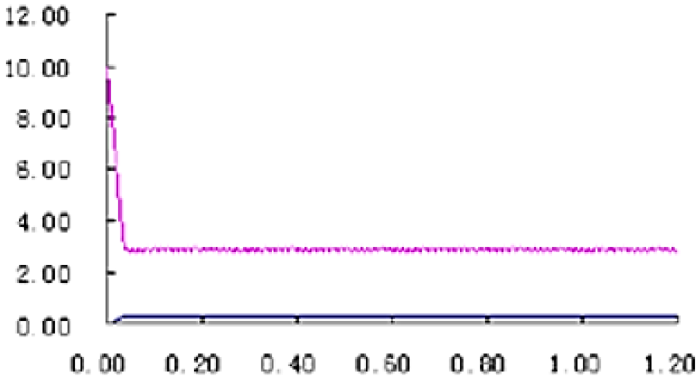

Figure 5: Changes in particle rolling velocity under the action of initial angular velocity (abscissa is time s, ordinate is velocity m/s or rad/s, blue curve is moving velocity, pink curve is angular velocity, the same below)

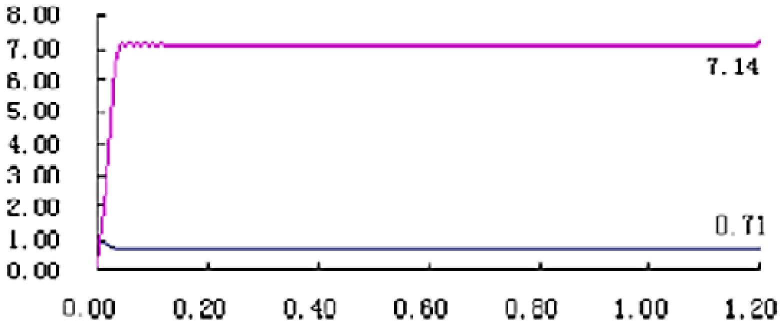

Figure 6: Changes of particle rolling velocity under the action of initial linear velocity

The numerical example is divided into two cases to verify the above analysis: (1) R=0.1, V=0, ω=10rad/s, and the simulation results are shown in Figure 5; (2) Take R=0.1, V=1, ω=0rad/s, and the results are shown in Figure 6. In Figure 5, when the particle linear velocity is 0.28m/s and the angular velocity is 2.8rad/s, it does not change. In Figure 6, the final linear velocity of the particle is 0.71m/s and the angular velocity is 7.1rad/s. As can be seen from the two figures, the final velocity of the contact point becomes zero, and since there is no action to prevent the particles from rolling, the ball will not stop rolling.

On the basis of example (2), the friction coefficient μ=0.2, Young's modulus is 6.89×106N/m3, and the density is 1946kg/m3, respectively. The results are shown in the figure below.

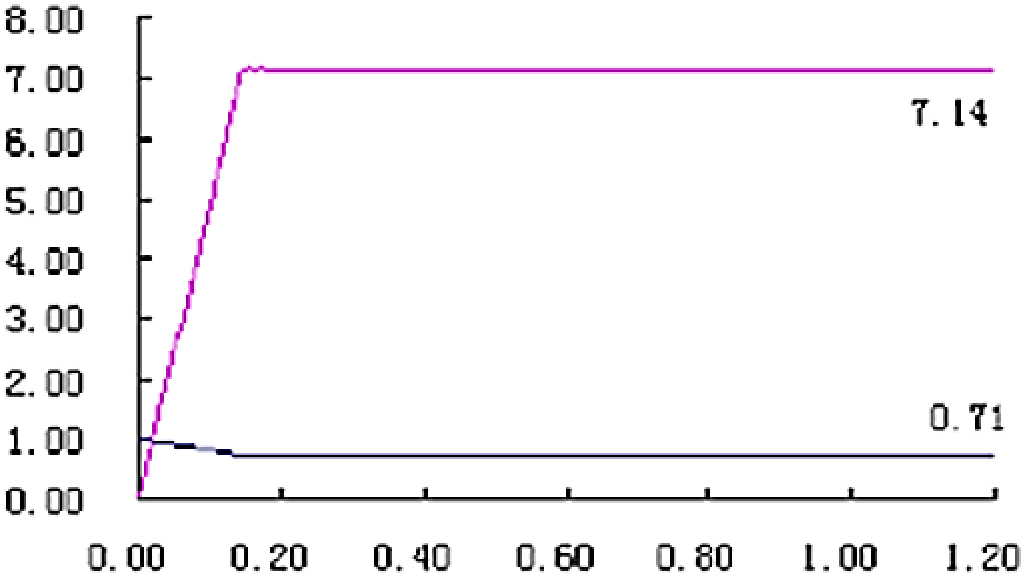

Figure 7: Particle rolling process when μ=0.2

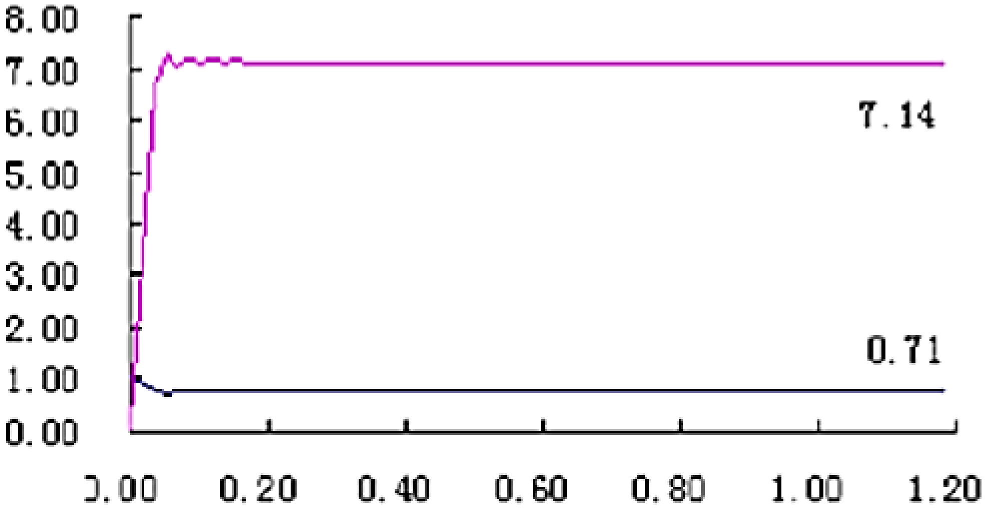

Figure 8: Particle rolling process when Young's modulus is 6.89×106N/m3

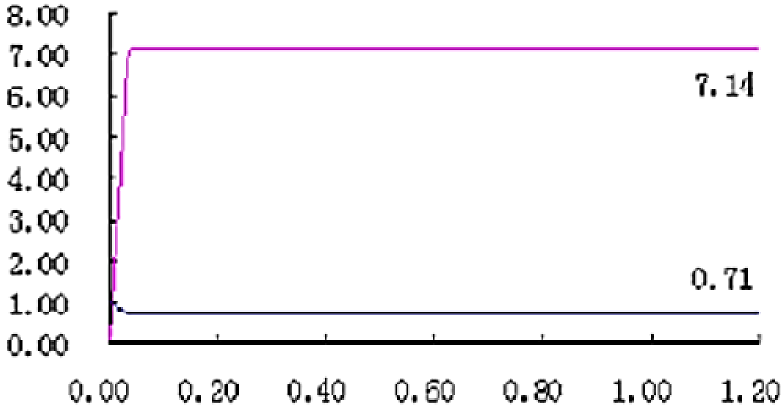

Figure 9: Particle rolling process at a density of 1946kg/m3

As can be seen from Figure 7, the sliding friction coefficient does not change the velocity of the particle after it is stabilized, but only the time to reach the stable velocity. It also indicates that there will be no sliding at the contact point after the particle is stabilized. By comparing FIG. 6 with FIG. 8 and FIG. 9, it can be seen that changes in Young's modulus and density also do not affect the final velocity of particles[9-11].

B) Improved discrete element simulation

The rolling of particles on a plate is simulated by the discrete element method with introduced rolling impedance. Given the initial linear velocity V=0.1, the initial angular velocity ω=1.0. The rolling damping coefficient Cr and sliding damping coefficient Cs are defined as zero, the rolling stiffness coefficient γ=0.1, and the rolling friction coefficient zeta r=3. The particle velocity and displacement results are shown in FIG. 10 and FIG. 11. It can be seen from FIG. 10 and FIG. 11 that under the action of only elastic impedance, the particle linear velocity and angular velocity both decrease to near zero, and the velocity and displacement eventually maintain small amplitude fluctuations.

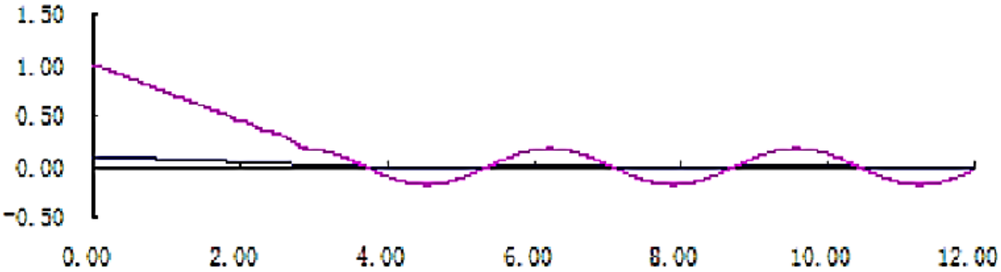

Figure 10: Particle velocity under elastic rolling impedance

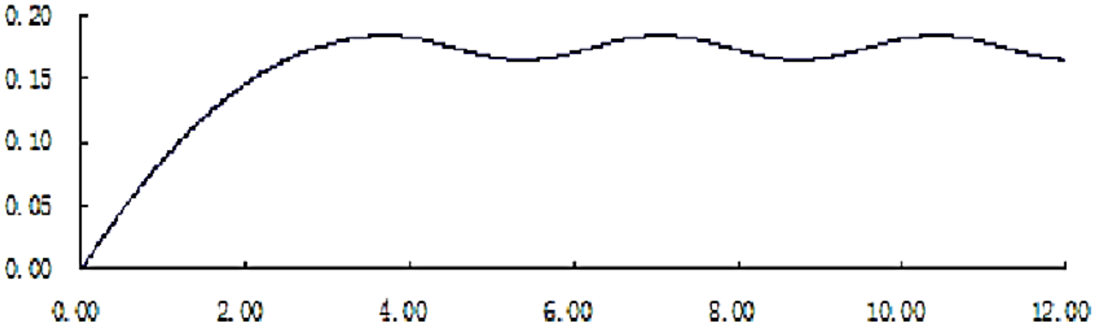

Figure 11: Particle displacement under elastic rolling impedance (horizontal coordinate is time s, vertical coordinate is speed m, the same below)

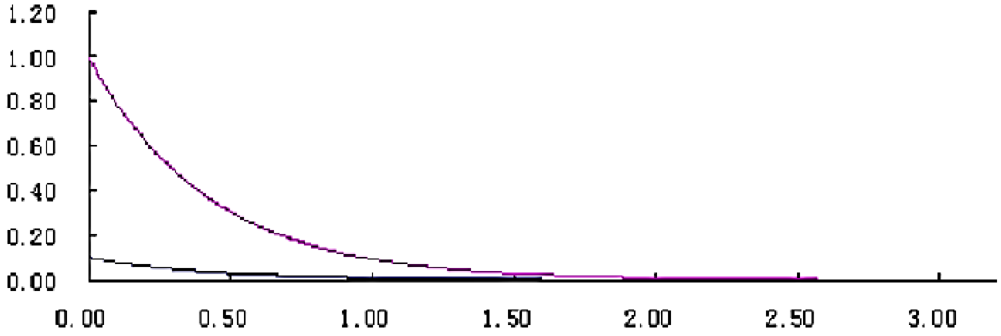

Figure 12: Particle velocity under viscous rolling impedance

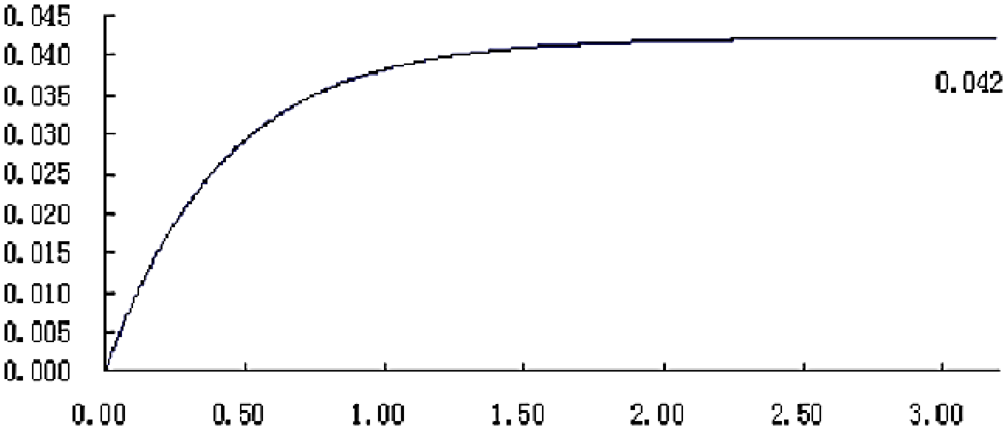

Figure 13: Particle displacement under viscous rolling impedance

Parameters Cr=107.77 and γ=0.0 were changed for simulation, and the results were shown in FIG. 12 and 13. The velocity quickly decreases to zero, the displacement simultaneously reaches a maximum, and the particles stop rolling. Obviously, the effect of rolling damping Cr causes the particles to stop rolling completely. Change the parameters, take Cs=136.758 for simulation, speed and displacement do not change. Therefore, the shear damping does not hinder the rolling of the particles. Parameters Cs=136.758, Cr=0.01, γ=0.1, ζr=3 were selected for numerical simulation. The results were shown in FIG. 14 and 15. The rolling direction of the particles changed, and eventually the rolling stopped gradually, the speed decreased to zero, and the maximum displacement was 0.016m. By changing the coefficient of rolling friction ζr=0.3 to re-simulate the calculation, it is found that the final displacement is 0.03m, which is larger than that when ζr=3, as shown in Figure 16.

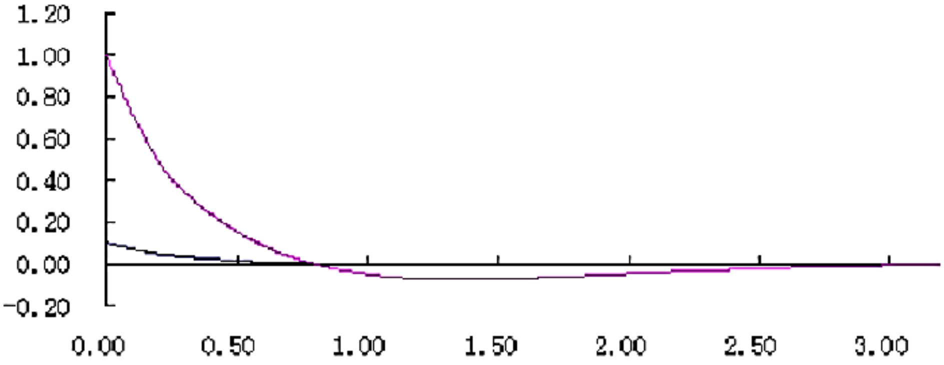

Figure 14: Particle velocity under full rolling impedance

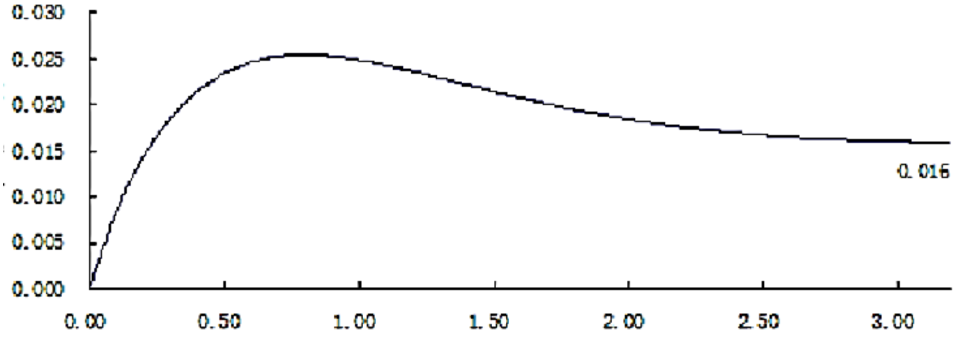

Figure 15: Particle displacement under full rolling impedance

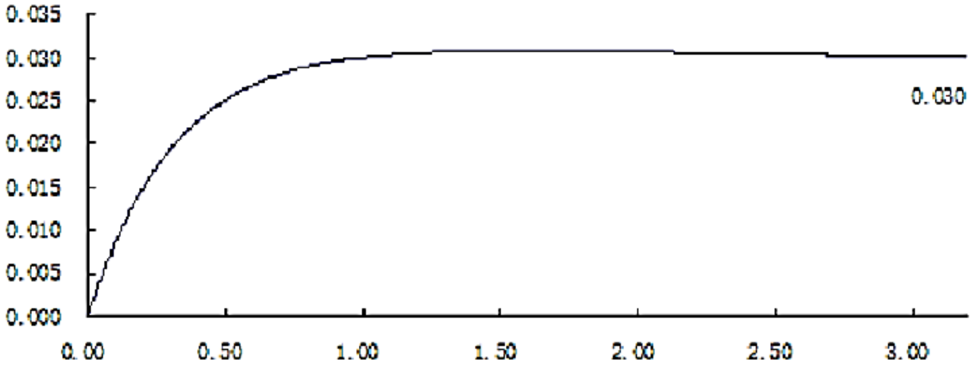

Figure 16: Particle displacement when rolling friction coefficient zeta r=0.3

4. Future development prospect

The study of rotational resistance in particle motion simulation based on discrete element method provides an important theoretical basis for the mechanical behavior of particle materials, but there are still many aspects that can be further explored and improved in future research. Firstly, the influence mechanism of rotational resistance on particle motion can be further studied, including the variation law of rotational resistance under different particle shapes, material properties and contact conditions, as well as the relationship between rotational resistance and particle interaction. This will contribute to a more comprehensive understanding of the motion behavior of granular materials, providing more accurate simulations and predictions of related engineering and natural phenomena. Secondly, the application of rotational resistance in different particle systems can be further explored, including particle accumulation, particle flow and other fields. Through the study of rotational resistance, the dynamic characteristics of particle system can be better understood, and more effective design and optimization schemes can be provided for engineering applications such as processing, conveying and stacking of particle materials. In addition, the model and parameters of rotational resistance in discrete element simulation can be verified by experimental studies to further improve the reliability and accuracy of simulation results. Through the combination of theoretical research and experimental verification, the mechanism of rotational resistance in the motion of granular materials can be better revealed, and more reliable theoretical support can be provided for engineering applications in related fields. In conclusion, the future research can further deepen the theoretical research and practical application of rotational resistance in the discrete element method, and provide a more comprehensive and in-depth understanding and solution for the mechanical behavior and engineering application of granular materials.

5. Conclusion

In summary, the rolling process of a spherical ball on a plate is simulated by discrete element method, and the effect of rolling impedance is studied. Firstly, the simulation results of the traditional discrete element method show that the particles will eventually reach a stable rolling state because the rolling impedance is not considered, and the rolling speed is related to the initial velocity and particle shape, but not to the material properties. Secondly, the modified simulation results after introducing rolling impedance show that the particles will gradually stop rolling, and the rolling direction may change before stopping, which is consistent with the actual situation, and verifies the rationality of the established rolling model. In addition, it is found that under given conditions, the change of particle size has limited influence on the change of resting Angle, and the increase of rolling resistance will lead to the formation of particle pile, and the resting Angle will also increase. Therefore, rolling impedance plays an important role in discrete element simulation and is of great significance for particle motion simulation. These research results provide new theoretical and practical guidance for the motion behavior of granular materials, and have certain application value for engineering and natural phenomena.

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