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Influence of rolling resistance on the shear curve of granular particles

Chuang Zhao [a], Chengbo Li [b,*]

[a] College of Science, Guizhou University, Guiyang, 550025, China

[b] School of Mathematics and Physics, Anyang Institute of Technology, Anyang, 455000, China

HIGHLIGHTS

- A feasible model of the rolling resistance cannot be obtained without considering the appropriate rolling deformation.
- The simulation not only meets force–displacement and contraction/dilatancy curves, but also meets the rate independent theory.
- The reasonable model should also satisfy the objectivity.

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ABSTRACT

The rotation of a single particle plays a very important role in the simulation of granular flow through the discrete element method (DEM). Many researchers have noted that the effect of rolling resistance at the contact points should be considered in DEM simulations. The rolling resistance between particles, which is mainly introduced from the force or rolling deformation (velocity) between particles, is indicated in different models. However, various models cause different results. Hence, the most feasible model should be determined. For this purpose, five models are adopted to simulate the simple shear flow by DEM in this work. Simulation indicates that the contraction/dilatancy and force–displacement curves at different volume fractions are in good agreement with the experimental findings. The curves of Models 1 to 3 computed by force and angular velocity separate at different shear speeds, but this result does not satisfy the rate independent theory. The curves of Models 4 and 5, which are calculated by the rolling deformation, are better in keeping with the rate independence than the three previous models. After increasing the particle-size distribution, Model 5 appears to be more reliable. The defects of the four other models are discussed from the physical mechanism perspective. The force–displacement curves of Model 5 at a difference of 20 times in shear speed coincide perfectly. Overall, the findings satisfy both the objectivity and the rate independent theory.

1. Introduction

The macroscopic behavior of a particle system exhibits extreme complexity, which depends on the microscopic interactions of individual particles. To understand this behavior, various experiments can be performed. Most of these experiments are (ideally homogeneous) macroscopic tests in which the stress and/or strain path can be controlled. Such experiments are important in studying and calibrating constitutive relations, but they provide little information on the microscopic origin

* Corresponding author.
E-mail address: lechbo@126.com (C. Li).

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of the bulk flow behavior. Alternatively, the discrete element method (DEM) can provide information about the microstructure characteristics, such as coordination number, particle orientation, fabric tensor and stiffness tensor beyond what is experimentally accessible [1].

Various contact force models are used in DEM, and these models play a key role to simulate particle systems. Linear models are the most intuitive and simple models [2,3]; a more complex and theoretically sound model, the Hertz–Mindlin–Deresiewicz model, has also been developed [4]. Considering the complications, various simplified models based on the Hertz–Mindlin–Deresiewicz theories are popular in the application of DEM, one of which is the partially latching spring force model in the normal direction [5]. To create a model for a more realistic unloading/reloading behavior, the adhesive, elasto-plastic contact model was adopted by Luding [6], and this model is also used in the current research.

In addition to the normal and tangential forces of particles, the interaction of rolling among particles is also considered. The rotation of particles plays a very important role in simulations of granular flow through DEM [7]. For a simple case such as a rolling ball on a plane, the rolling displacement increases linearly with time without considering the rolling resistance, but apparently, the result is unphysical [8]. Stable and repeatable results for the formation of a sandpile are also difficult to obtain [9]. Aside from the numerical stability, the rotation of the particles in the shear band significantly influences the shear strength [10,11], and this effect is critical to the gradient of particle rotation in the discrete simulation of arching phenomenon in discharging particles from a hopper, shear band [12,13]. Different rotational degrees of freedom are responsible for sliding, rolling and torsion. Tangential forces depend on sliding, and the relative spin along the normal direction activates torsion resistance when two particles are rotating anti-parallel with spins parallel to the normal direction. Torsion is also considered correctly in Ref. [6].

However, the method to model correctly the rolling resistance remains questionable [14]. Two ways can be adopted to formulate the rolling resistance; the first is from the perspective of forces imposed on the particles and their angular velocities, and the second is from the perspective of the relative rolling velocity [7,12,13,15,16]. Numerous articles have proposed different rolling resistance models, and even the same researchers used various models in different periods [4,9,17–21], as mentioned in Section 2.1.

On the one hand, the rolling resistance models from the first method are reasonable and also in line with certain experiments. The key problem is to determine the most feasible model, which is suitable for all types of particle systems (gas, flow, and solid). On the other hand, although the rolling resistance models from the second method [22–25] are objective [6,15], they contradict each other. It needs to be clarified that which is best and correct.

To obtain the right equation of the rolling resistance, it is necessary to investigate the influence of different rolling resistance models on the calculations. In this research, the discrete element simulation of simple shear flow is performed using five rolling resistance models. The force–displacement curves and the contraction/dilatancy curves of the five models accord well with the existing experiments, causing difficulty in determining the most feasible models and excluding the unsuitable ones. However, the rationale of the models can be verified by the property of rate independence. The two types of models from the perspective of the rolling deformation (velocity) are better than the three models from the perspective of force and angular velocity. After increasing the particle-size distribution, the only reasonable model is left. The question regarding whether the correct definition of the rolling velocity can lead to more accurate and reasonable results is answered [25].

2. Contact models of particles and simple shear flow

2.1. Contact models

In this study, the normal and tangential forces are calculated using the model in Ref. [6]. The rolling resistance of Model 1 is denoted by:

$$\overrightarrow{q}^{rolling} = -\mu_r R_i \left| \overrightarrow{F}_{ij}^{n} \right| \hat{\omega}_i \tag{1}$$

where μ_r is the rolling friction coefficient (dimensionless), R_i is the particle radius, $\overrightarrow{F}_{ij}^{n}$ represents the normal force (including elastic and damping forces) imposed on particle i by particle j, and $\hat{\omega}_i$ is the unit vector of angular velocity of the particle i and $\hat{\omega}_i = \overrightarrow{\omega}_i / \left| \overrightarrow{\omega}_i \right|$ [18,26]. The resistance of Model 2 is given by Eq. (2):

$$\overrightarrow{q}^{rolling} = -\mu_r' \left| \overrightarrow{F}_{ij}^{n} \right| \hat{\omega}_i \tag{2}$$

where μ_r' is the rolling friction coefficient with the dimension of length, $\overrightarrow{F}_{ij}^{n}$ is the normal elastic contact force imposed on particle i by particle j, and $\hat{\omega}_i$ is the unit vector of angular velocity of the particle i [9]. The resistance of Model 3 is expressed as

$$\overrightarrow{q}^{rolling} = -\mu_r' \left| \overrightarrow{F}_{ij}^{n} \right| \hat{\omega}_{ij}^{t} \tag{3}$$