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Assessment of rolling resistance models in discrete element simulations

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ABSTRACT

Particulate systems are of interest in many disciplines. They are often investigated using the discrete element method because of its capability to investigate particulate systems at the individual particle scale. To model the interaction between two particles and between a particle and a boundary, conventional discrete element models use springs and dampers in both the normal and tangential directions. The significance of particle rotation has been highlighted in both numerical studies and physical experiments. Several researchers have attempted to incorporate a rotational torque to account for the rolling resistance or rolling friction by developing different models. This paper presents a review of the commonly used models for rolling resistance and proposes a more general model. These models are classified into four categories according to their key characteristics. The robustness of these models in reproducing rolling resistance effects arising from different physical situations was assessed by using several benchmarking test cases. The proposed model can be seen to be more general and suitable for modelling problems involving both dynamic and pseudo-static regimes. An example simulation of the formation of a 2D sandpile is also shown. For simplicity, all formulations and examples are presented in 2D form, though the general conclusions are also applicable to 3D systems.

1. Introduction

Particulate systems are of interest in many disciplines such as applied mathematics, condensed matter physics, geotechnics, agriculture, chemical engineering and civil engineering [1]. These particulate systems have often been studied numerically using different approaches, but most often the finite element method (FEM) and the discrete element method (DEM) [2]. The DEM simulates the interactions between individual grains. It is of special interest because it is able to investigate particulate systems at particle scale in which the packing structure of a particle assembly is observable and the process of particle rearrangement can be traced through the time domain.

In a DEM model, a granular medium is usually treated as an assembly of 2D disks or 3D spheres [3,4], or else as clumps of these shapes made by rigidly connecting and overlapping multiple disks or spheres [5–7]. Based on a conventional discrete element formulation [3,8], the interactions between two particles and between a particle and a boundary consist of contact spring forces and damping forces in both the normal and tangential directions. Recently the significance of the rotational inertia and energy loss in rotation of particles has been highlighted in both numerical studies [e.g., 9–11] and physical experiments [12–16]. Consequently, many researchers have attempted to incorporate a rotational frictional torque into their DEM formulations to account for the rolling resistance using different models [e.g., 11,17]. This paper presents a review of the commonly used models for rolling friction and proposes a more general model. These models are classified into four categories according to their key characteristics. The robustness of these models in reproducing rolling resistance effects arising from different physical situations was assessed by using several benchmarking test cases. The proposed model can be seen to be more general and to have some advantages over other types in problems involving both dynamic and pseudo-static regimes. An example simulation of the formation of a 2D sandpile is also shown. For simplicity, all formulations and examples are presented in 2D form, though the general conclusions are also applicable to 3D systems.

2. Rolling friction and rolling resistance

A granular system can be in a pseudo-static state, a dynamic flow state or in a mixed condition where the two states coexist. When modelling a granular system involving a dynamic flow phase such as avalanching, discharging from a container, stockpile formation, rotating drum, pneumatic flow and screw auger transportation, the resistance to rolling is usually referred as “rolling friction”. Consequently, terms like “rolling friction model”, “coefficient of rolling friction” and “rolling friction torque” were introduced [e.g., 17–19].

The term “rolling resistance” is commonly used by researchers when modelling pseudo-static systems such as shear bands, confined compression and penetration. Corresponding terms such

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as "rolling resistance model", "coefficient of rolling resistance" and "rolling resistance torque" have been used [e.g., 11,20]. In modelling a pseudo-static system, rolling resistance is often introduced to represent the effects on rolling of particle shape (non-sphericity in 3D or non-circularity in 2D) and inter-particle bonds. These have led to the use of terms such as "shape parameter" and "bond area parameter" [e.g., 21].

Although the terms "rolling friction" and "rolling resistance" have been used by different researchers, both types of model can be described using the same framework because both can be expressed as a pair of torques at a contact. Although it can be argued that rolling resistance covers the concept of rolling friction, a precise definition of the terminology is beyond the scope of this paper. For convenience, all the models reviewed here are referred to as rolling resistance models with corresponding terms such as rolling resistance torque and coefficient of rolling resistance adopted in this paper.

"Free rolling" [22] is defined as motion in the absence of a resultant tangential force. Resistance to rolling is then manifested by a couple M_r which arises from the asymmetry of the contact pressure distribution: higher pressures develop on the front half of the contact than at the rear. The rolling resistance can arise from several sources at the contact between two particles or between a particle and surface. These may include:

a) Micro-slip and friction on the contact surface [22–27]
Micro-slip may occur at the interface when the rolling bodies have dissimilar elastic constants [22]. This resistance depends on both the difference between the elastic constants and the coefficient of slipping friction μ_s. For typical pairs of materials, the micro-slip rolling friction is very small. Micro-slip can also develop because the two bodies have different curvatures at the contact, but this is often negligible [22].
b) Plastic deformation around the contact [22,28–31]
Plastic deformation is a major source of energy dissipation during particle rolling contact, and is thus an important cause of rolling friction. Here the energy is not usually dissipated at the interface, but within the solid at the location of the maximum shear stress caused by the contact.
c) Viscous hysteresis [28,32–39]
Viscous hysteresis is a further important energy dissipation mechanism during rolling contact between viscoelastic particles. The energy lost during deformation can be considerable and can depend significantly on both the temperature and the deformation rate [33,38].
d) Surface adhesion [40–45]
When adhesion between particles is present at the interface contact, energy dissipates in breaking the adhesive bond at the separation point during the rolling motion. When adhesion is present, the resistance to motion can be significant even in the absence of externally imposed pressure [46,47]. This mechanism is often most important in contacts between (sub)micron particles, where adhesive aggregates often develop [42].
e) Shape effect [20,48]
Rolling resistance may also arise from the effect of a non-spherical or non-circular particle shape. This lack of circularity is present in all real particles, but it can also arise from large deformations of spheres or disks. Unlike the previous four sources, which have commonly been regarded as the traditional mechanisms of "rolling friction", the shape effect cannot strictly be classified as rolling friction, but it is certainly an important source of rolling resistance. It is of special importance in DEM modelling, when idealized circular or spherical particles are used.
It may be noted that further components of rolling resistance also arise from other factors such as air drag in a multiphase problem, which are not considered here. This paper deals only with rolling resistance arising at or around the contact points.

3. Previous studies of rolling resistance models

A significant number of researchers have developed or studied rolling resistance models. These are briefly summarised here.

Bardet and Huang [9] were probably the first to introduce rotational constraints into a DEM model, with the aim of simulating the micropolar effects in an idealized granular material. They found that the micropolar constants which relate the rotation gradient to the couple stress had to be selected outside of the range of values that could be found from theoretical considerations in order to match their numerical predictions based on a conventional DEM formulation [49]. They proposed that contact couples arising at the contact point [27,50], which are ignored in a conventional DEM formulation, might play an important role. They further demonstrated that the overall internal friction angle of a particle assembly that is predicted when the particle rotation is fixed is higher than that when the particles are free to rotate. In a similar but more general way, Morgan [51] introduced rotational damping of particles to reduce or prevent coordinated particle rolling in his simulation of granular fault gouge to achieve results that were close to laboratory estimates. However, these treatments did not represent contact couples, which must occur in matched pairs at each contact point.

Sakaguchi *et al.* [18] were probably the first to introduce the "rolling friction" concept into a DEM model, in their comparisons of experimental and numerical modelling of plugging of granular flow during silo discharge. A rolling frictional torque, found as the product of the coefficient of rolling friction and the normal contact force, was included in their DEM code. To determine the direction of the rolling frictional moment, a back and forth scheme was implemented in the calculation of rotational velocity. They reported that an arch formed by circular disks was not stable and could easily be broken in a conventional DEM model, but their modified code was particularly effective in forming the arches found in plugging phenomena seen in physical experiments. It may be noted that the applied torque in their treatment was particle–based, and not based on a contact pair.

Iwashita and Oda [11] noted that huge voids and high rotational gradients are observed in shear band experiments, but that these were never reproduced by conventional numerical methods. They recognised that rolling resistance causes an arching action at the contacts, permitting the easy formation of large voids in physical tests, but in conventional DEM analyses, rolling takes place without any resistance at the contacts. To narrow the gap between the numerical predictions and test results, they proposed a modified model of the conventional discrete element method (MDEM) which took the rolling resistance into account. The model treated the rolling resistance as an elastic rotational spring, a dash pot, a non-tension joint and a slider (Fig. 1). They indicated that the relative movement at a contact during incremental deformation can be decomposed into sliding and rolling components, and the rolling component leads to the relative rotation between two particles with a common contact point. The rolling resistance was taken as a pair of torque couples whose magnitude was found as the product of the relative particle rotation and the rolling stiffness, with a additional viscous damping component to give numerical stability. Using this model, they successfully predicted shear band behaviour that was similar to that seen in natural granular soils. The rolling stiffness was assumed to be proportional to the contact normal force in Iwashita and Oda [11], but was later modified to be proportional to both the contact normal force and the overlap width of the two contacting particles [52]. Oda and Iwashita [48] further indicated that the rotational resistance of particles can be one of the dominant components that determine the strength of granular media. They also noted that rotational resistance does not only arise from contact behaviour, but also from particle shape. Their MDEM has attracted wide interest and has been adopted in other studies. For example, Wang *et al.* [53] implemented it in an investigation of interfacial shear behaviour of particles and