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Microscopic contact model of lunar regolith for high efficiency discrete element analyses

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A B S T R A C T

The grains of lunar regolith are characterized with rough surfaces, angular shapes and mutual adhesions due to short-range interactions. These features control the macroscopic mechanical behavior of lunar regolith but have not been completely captured by contact models in previous Discrete Element Method (DEM) analyses. In this paper, a simplified two-dimensional microscopic contact model is proposed for high efficiency DEM analyses of lunar regolith. The model consists of three components in the normal, tangential and rolling directions respectively, plus two new parameters. A shape parameter is used to control the rolling resistance ability at the contact area between two particles to capture the features of grain shape and interlocking. The second parameter, micro-separation, which denotes the nominal minimum distance between the molecules of the two contacting particles, is introduced to account for van der Waals force as the major component of the short-range interactions that contribute to the adhesion of regolith grains in lunar environment conditions. The novel model has been implemented in a two-dimensional DEM code for numerical simulations of biaxial compression tests on lunar regolith. The effects of interparticle friction, grain shape, lunar environment conditions and void ratio on the strength of lunar regolith were numerically investigated. The results show that soils in the simulated lunar environment exhibit greater strength and more apparent strain-softening and shear dilatancy than on the Earth. The proposed model can capture the main features of the mechanical behavior of lunar regolith (apparent cohesion and high peak friction angle) and a wide range of strength indices can be obtained by the contact model.

1. Introduction

Lunar exploration has been one of the most challenging missions for humans since the early years of last century. The safe landing on the lunar surface, mobility of the exploring rovers and future construction of exploration bases require a good knowledge of the lunar surface, in particular, the mechanical behavior of lunar regolith. Lunar regolith is a kind of granular material widely distributed as the upmost layer of lunar ground and it can be classified as a silty sand with a mixture of coarse grains [1,2]. Table 1 presents the ranges of peak friction angle and cohesion of real lunar regolith [3] estimated by measurements made on the lunar surface through trench excavation, penetration, footprint, etc. This table, together with the existence of soil clumps on the lunar surface, indicates that lunar regolith is uniquely cohesive rather than cohesionless as similar dry materials on the Earth [1,4–8]. Besides, the peak friction angle is apparently larger than that of sands on the Earth. Such high strength of lunar regolith is attributed to the features of regolith grains and the environment conditions on the Moon.

Lunar regolith grains are featured with highly rough surfaces, angular shapes and a wide size distribution range. These factors significantly enhance the interlocking between grains and hence increase the strength of lunar regolith. The harsh lunar environment conditions including low-gravity field, ultrahigh vacuum, and high (low) temperature during the daytime (night-time) also play crucial roles in determining the mechanical behavior of lunar regolith. Experimental data obtained by Bromwell [9] and Nelson [10] under ultrahigh vacuum (10^{-7} Pa) and high temperature (394 K) indicated that the strength of lunar soil simulants can be higher by 13° in friction angle and 1.1 kPa in apparent cohesion than the strength obtained in a terrestrial environment. Increased cohesion of lunar soil simulant in high vacuum was also observed by Johnson et al. [11]. Reduced ultimate bearing capacity of lunar

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Table 1
Ranges of friction angle and cohesion of lunar regolith [3].

Depth (cm)	Cohesion (kPa)		Internal friction angle (°)	
	Average	Range	Average	Range
0–15	0.52	0.44–0.62	42	41–43
0–30	0.90	0.74–1.1	46	44–47
30–60	3.0	2.4–3.8	54	52–55
0–60	1.6	1.3–1.9	49	48–51

soil simulant [12] and aggravated mobility of a rigid wheel [13] were also observed under low gravity conditions.

Currently, the mechanical behavior of lunar regolith is either inferred from measurements by astronauts/robots on the lunar surface or investigated on the Earth by using real lunar soil or its simulants, such as FJS-1 [14], JSC-1A [15,16], GRC-1 [17], and TJ-1 [18,19]. These simulants are carefully prepared to capture the geometric features of real regolith grains, intending to reproduce the high interparticle interlocking of real regolith. However, any individual aspect of the lunar environment conditions (low gravity, high vacuum and extreme temperature) is difficult to maintain in common geo-laboratories, though some pioneering works have been reported [9–12]. Consequently, the present experimental data is still not enough to fully understand the mechanical behavior of regolith on the lunar surface.

Discrete Element Method (DEM) is a numerical technique which can play a very important role in granular material research and is complementary to the present physical tests on lunar regolith. Although the grains and particle–particle interactions are modeled in an idealized way, this numerical approach can still provide a useful insight into the mechanical behavior of granular system like lunar regolith starting from the micromechanics. Some DEM modeling trials of lunar regolith assemblies have been reported [12,14,20–27], although the features of regolith grains and the environment conditions on the Moon have not been fully taken into account. This unsatisfactory situation shows that an effective interparticle contact law is urgently required in DEM modeling to capture the major macro-mechanical behavior of lunar regolith, which must be able to distinguish the lunar soils from sands on the Earth. In addition, the contact law should also be as simple as possible for highly efficient simulations of boundary-value problems in a large domain. This composes the strong motivation in this paper.

In this paper, a novel contact model for high efficiency DEM analyses of lunar regolith incorporating interparticle rolling resistance and van der Waals interactions is introduced. The novel model has been implemented in a standard DEM code, by which numerical biaxial compression tests were carried out to check the performance of the model. Finally, the effects of interparticle friction, interlocking, van der Waals interactions representing lunar environment conditions and void ratio on the strength of lunar regolith were numerically investigated.

2. Grain-scale features of lunar regolith

2.1. Particle shape and interlocking

Lunar regolith grains are mainly composed of relatively smooth spherical glasses and angular/sub-angular agglutinates and breccias with rough surfaces [28], as shown in Fig. 1. As an assembly of grains is sheared, dilation is expected due to the particle interlocking with each other. In the discrete element approach, regolith grains are usually idealized as disks (2D) or spheres (3D) [12,20–23,25,27]. In this way, each individual grain can rotate freely without dilating adjacent grains, which is responsible for the low shear strength in DEM analyses. In contrast, grain shapes can be accounted for by generating particle clumps or using polyhedral particles with various geometries [14,26,29–31]. However, the employment of such irregular shapes faces several challenging problems. First, simulations with irregular particles require much more computational time for contact detection than spheres/disks, which will certainly make it difficult to apply DEM to large-scale boundary-value problems. Second, extreme efforts will be needed to experimentally obtain and numerically include information on particle shapes even in a small-size sample composed of millions of particles [14,30]. Third, particle angularities may evolve during loading in experiments, and tracking such morphological change becomes almost impossible in both experiments and numerical simulations on an assemblage of particles of sufficient number.

Fig. 1. Grains in lunar soil sample 10085 [28].

Alternatively, in order to capture the effects of particle shapes, rolling resistance was directly introduced into the contact law between disks or spheres [32,33]. This is because actually irregular grains are not always in contact at single points with neighboring grains but primarily over areas which can transfer interparticle moments. As a result, both terrestrial and lunar soils will demonstrate high strength. What specific to lunar materials is the highly angular to sub-angular particle shapes which greatly increase the ability to transmit moments at interparticle contacts and thus are responsible for the unusually high strength of lunar regolith. Therefore, in this study, lunar regolith grains are modeled by an assembly of spheres/disks with normal force, tangential force and moment exchanged at the contacts. This approach sacrifices details at the particle scale such as the shapes, but it is particularly suitable for prototype-scale simulations where the overall bulk behaviors of the medium are the top feature to capture as a react of the actual particle characteristics.

Note that dilation can be partially obtained with disk particles or spherical particles in comparison to real geo-materials. Plastic dilation stems from both relative displacements/rotations of particles at contacts and the change of fabric, especially the fabric describing particle orientation. This necessitates the incorporation of rolling resistance in contact model, which can reduce excess particle rotation and lead to more realistic fabric.

We model the interparticle contact behavior through two opposite circular flat contact areas for spheres (3D) or rectangular flat contact areas for disks with unit length orthogonal to the deformation plane (2D), as shown in Fig. 2. The contact size B (diameter of the circular flat area for spheres or width of the rectangular flat area for disks) can be defined by the particle size as

$$B = \beta r \tag{1}$$

where r is the common radius of two spheres/disks in contact, $r = 2r_1r_2/(r_1 + r_2)$; β is a dimensionless parameter introduced here