Effects of Granular Soil Micro-Mechanics on the Pressure-Sinkage Relationship

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Abstract. The pressure-sinkage relationship is a common and important issue in terrain mechanics to explore the soil-vehicle interaction for the off-road vehicles. There are a number of empirical pressure-sinkage relationships available, which were established by curve fitting to experimental data. However, not much research has been performed to establish the link between the micro-mechanics of soil and the pressure-sinkage relationship, e.g. the effect of soil density, inter-particle friction, particle rolling resistance, and different gravity. In this paper, the effects of micro-mechanical parameters of soil on the pressure-sinkage relationship were investigated using the Discrete Element Method (DEM). The pressure-sinkage relationship from the DEM simulations matched the result from the experimental tests on coarse sand. It has been found that the sinkage is quite sensitive to the inter-particle friction (particle surface roughness), but is not particularly sensitive to the soil-vehicle friction, which indicates that the sinkage of vehicle is mainly controlled by the soil strength. It is also found that the sinkage was influenced significantly by the particle rolling resistance, which is related to irregular particle geometry. Gravity also has a big effect on the sinkage, which means that the experiment test results obtained on the Earth should be scaled properly to be used in the design of martian rover or lunar rover.

Keywords: Pressure-sinkage relationship, DEM, Micro-mechanics, Martian rover
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INTRODUCTION

The European Space Agency (ESA) ExoMars mission involves landing a Rover on Mars for search of life and collecting samples from surface and shallow subsurface. Such exploration mission put forward a high requirement of the locomotion capacities of ExoMars rover over a variety of martian surfaces. To ensure the success of the mission, the locomotion capacities of ExoMars rover should be tested and fully understood in the martian gravitational environment.

A study of the pressure-sinkage relationship is necessary to ensure a vehicle to stand on the surface rather than be submerged. The sinkage is also coupled with the drag force which affects the trafficability of a vehicle. Therefore, the pressure-sinkage relationship is a key issue in examining the locomotion of the off-road vehicles such as ExoMars rover. A pressure sinkage test, where a plate is penetrated into soil under pressures, should be performed to obtain the data of contact pressure, p, and sinkage, z. A number of empirical pressure-sinkage relationships have been established by curve fitting to the test data [1]. The widely used model is the one proposed by Bekker [2] as

$$p = \left(\frac{k_c}{b} + k_\varphi\right) z^n \tag{1}$$

where n is an exponent, b is either the width of a rectangular plate or the diameter of a round plate for testing, k_c and k_Φ are the cohesive modulus and the frictional modulus, respectively. To determine the parameters in Bekker's model, as proposed by Wong [3], two pressure sinkage tests with two plate sizes, b_1 and b_2, should be performed. Two lines best fit to the log-log plots of the pressure and sinkage data are then attained as illustrated in Figure 1. The exponent n is the average slope of the two lines. The remaining soil constants, k_c and k_Φ can be obtained by rearranging Equation (1) as:

$$k_c = \frac{a_1 - a_2}{b_2 - b_1} \cdot b_1 b_2 \tag{2}$$

and

$$k_\phi = \frac{a_2 b_2 - a_1 b_1}{b_2 - b_1} \tag{3}$$

The available empirical pressure-sinkage models, including Bekker's model, were established based on the macro-scale experimental data. Limited work has been carried out to establish the link between the micro-mechanics of soil and the pressure-sinkage relationship, e.g. the effect of soil density, inter-particle friction, particle rolling resistance, and different gravity. In the current study, parametric studies of the pressure sinkage test were carried out using the Discrete Element Modelling (DEM) for this purpose.

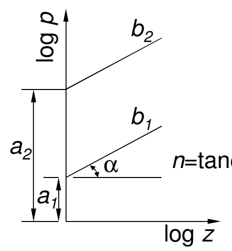

FIGURE 1. Illustration of determination of the soil constants in Bekker's model (after [3]).

DESCRIPTION OF DEM SIMULATIONS

The DEM simulations were performed using a code developed by O'Sullivan [4] and Cui [5] based on Ellipse3D [6]. To perform the DEM simulations of the pressure sinkage test, a virtual specimen containing about 13,500 spherical particles was firstly generated in a box of square cross-section (100 mm wide). These particles were assigned to one of the five radii, 2.20 mm, 1.93 mm, 1.65 mm, 1.38 mm, and 1.10 mm, with equal number of particles for each radius. The particles were settled under gravity into the box and the final height of the specimen was about 50 mm. To investigate the sensitivity of pressure-sinkage relationship to the specimen packing density, the specimen was then compressed by lowering and releasing a virtual boundary on the top of the specimen. Two denser specimens were obtained following the compression for the parametric study. The void ratios for the initial specimen and the two denser specimens are 0.673, 0.636, and 0.621, respectively (densities ρ=1584, 1620, and 1635 kg/m^3, respectively). A cylindrical rod was initially located on the surface of the specimen and then penetrated into the specimen at a speed of 0.1 mm/s until the sinkage reached around 20 mm. Two rods with diameters of 10 mm and 20 mm were tested to determine the soil constants in Bekker's model. The vertical force applied on the rod as a function of sinkage was monitored for the calculation of contact pressure. The coefficient of inter-particle friction, μ_{pp}, for the specimen was set to be 0.3 and the coefficient of friction between the particle and the boundary (including the rod), μ_{pb}, was set to be 0.1.

VALIDATION OF DEM SIMULATIONS

The soil constants in Bekker's model for the three specimens prepared using DEM were determined using the method proposed by Wong [3], as listed in Table 1. To validate the DEM simulations, the simulation results are compared with the experimental test results of coarse sub-rounded sand (ES-3) obtained by Brunskill et al [7], which are also listed in Table 1. A comparison of the pressure-sinkage relationship illustrated in Figure 2 shows more clearly that the DEM simulations for the two denser specimens, reproduced the experimental tests of ES-3 reasonably well.

PARAMETRIC STUDY USING DEM

Sensitivity to Coefficient of Friction

To investigate the sensitivity of the pressure-sinkage relationship to the coefficient of friction, the coefficient of inter-particle friction (μ_{pp}) for the specimen was changed to 0.5, and the coefficient of particle-boundary friction (μ_{pb}) was changed to 0.3 and 0.5. A comparison of pressure-sinkage relationship between various coefficients of friction is illustrated in Figure 3. As seen from Figure 3, the pressure-sinkage relationship is not sensitive to the coefficient of friction between particle and the penetrating rod, however, it is quite sensitive to the coefficient of inter-particle friction. These observations indicate that the surface roughness of rod does not influence its sinkage into the soil. The soil resistance to rod sinkage is mainly determined by the soil strength, which is controlled by the inter-particle friction. The particle displacements as the rod sinkage reached 10 mm are illustrated in Figure 4. It can be observed that the influence zone in the specimen due to the penetration of the rod is slightly wider with higher inter-particle friction.

TABLE 1. Soil constants in Bekker's model for DEM simulations and experimental tests performed by Brunskill et al [7]

	e	n	k_Φ	k_c
DEM 1	0.673	1.35	7106.48	3.46
DEM 2	0.636	1.03	2500.55	-5.64
DEM 3	0.621	0.94	2676.31	-14.81
Lab 1	0.646	0.92	1727.51	-14.12
Lab 2	0.615	0.87	1931.23	-16.41
Lab 3	0.503	0.76	2312.59	-30.10

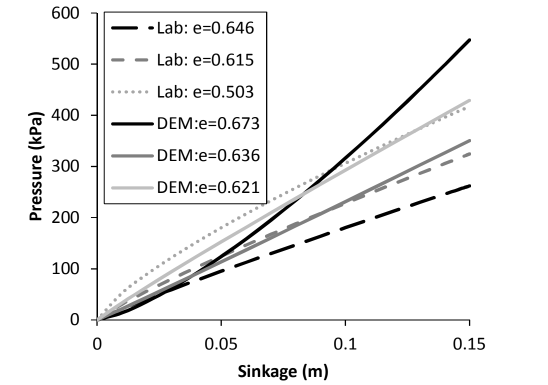

FIGURE 2. Bekker's model fit lines for DEM simulations and experimental tests performed by Brunskill et al [7].

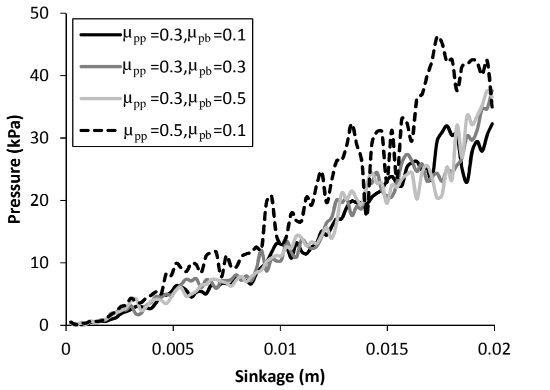

FIGURE 3. Comparison of pressure -sinkage relationships for various coefficients of friction.

Sensitivity to Rolling Resistance

In the current simulations, spherical particles were used in all DEM simulations. The real sand particle shapes are irregular and complex, resulting in higher rotational resistance on the particle contact interface. To perform a quick assess of the influence of the rotational resistance, the particle rotations were prohibited in one simulation. The pressure-sinkage relationship for the simulation with particle rotation prohibited is compared with that with rotations allowed as shown in Figure 5. The pressure required to reach the same sinkage increases significantly when the particle rotations are prohibited, indicating that soil containing angular particles is much stronger than that with rounded particles. The particle displacements shown in Figure 4 clearly illustrate that the influence zone due to the rod penetration is much deeper and wider when the rotations of particles are prohibited. It shows that higher rolling resistance causes a wider and deeper transmission of the soil disturbance, which requires a higher pressure on the rod.

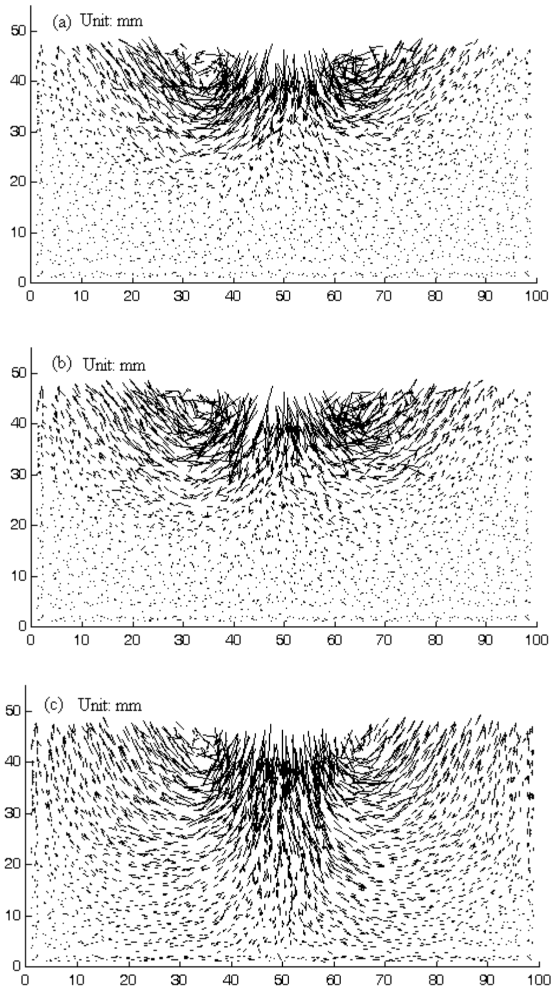

FIGURE 4. Particle displacements till the sinkage of 10 mm in the middle section of the specimen with a thickness of 20 mm. (a) μ_{pp}=0.3, μ_{pb}=0.1; (b) μ_{pp}=0.5, μ_{pb}=0.1; (c) rotation prohibited.

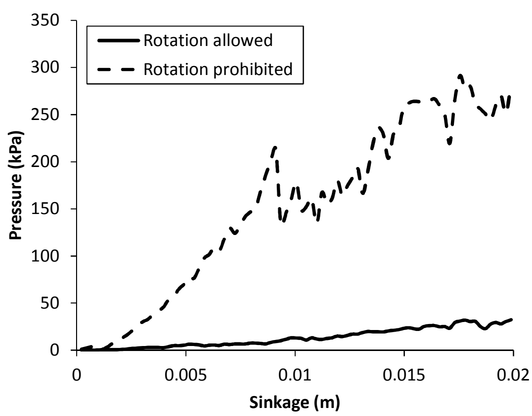

FIGURE 5. Comparison of pressure-sinkage relationship for different rolling resistance.

Sensitivity to Gravity

Another specimen was generated and a pressure sinkage simulation was performed under the martian gravity, i.e. g = 3.69 m/s^2. The initial void ratio of the specimen generated is 0.665 (ρ=1592 kg/m^3), similar to the void ratio of the specimen under the Earth gravity, i.e. g = 9.81 m/s^2. The pressure-sinkage relationships for both martian gravity and Earth gravity are compared in Figure 6. It is interesting to find that the pressure required to penetrate to the same sinkage on Mars is about 50% of that on Earth, although the gravity on Mars is about 40% of that on Earth. This example shows that the pressure-sinkage relationship on Mars cannot be determined directly from the pressure-sinkage relationship obtained on Earth following reduction by a ratio of two gravitational constants.

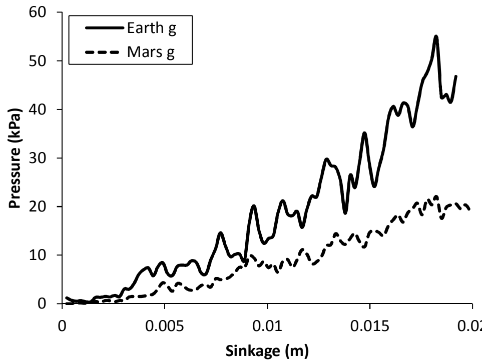

FIGURE 6. Comparison of pressure -sinkage relationships for different gravities.

Normalised Data

Three simulations were selected for normalised study: 1) ρ=1584 kg/m^3, b=20mm, g=9.81m/s^2; 2) ρ=1584 kg/m^3, b=10mm, g=9.81m/s^2; 3) ρ=1592 kg/m^3, b=10mm, g=3.69m/s^2. The pressure, p, is normalised by the density ρ, rod diameter b, and gravity g. The sinkage, z, is normalised by the rod diameter b. It can be found from the normalised pressure-sinkage relationship (Figure 7) that normalised pressure is independent on rod diameter, but is still dependent on gravity.

CONCLUSIONS

A parametric study of pressure-sinkage relationship was carried out using Discrete Element Modelling. The DEM simulations were validated by comparing with the experimental tests of coarse sand. It evidently shows that DEM is a feasible method to perform a parametric study for granular materials, such as sand.

The pressure-sinkage relationship is not influenced by the surface roughness of penetrating rod; however the required pressure for the same sinkage increases with the increasing inter-particle friction. The particle rolling resistance increases the required pressure for the same sinkage significantly. The pattern of the particle displacements indicates that higher rolling resistance or higher inter-particle friction assists the transmission of pressure/force, consequently causes wider and deeper soil disturbance. A wider and deeper soil disturbance then puts forward a higher requirement of the pressure applied on the rod to reach the same sinkage.

Simple reduction in the required pressure to reach the same sinkage in terrestrial soil by the ratio of gravity is not a proper method to obtain the pressure-sinkage relationship for martian soils. To attain an accurate pressure-sinkage relationship for Mars soil, pressure sinkage tests should be performed under martian gravity. A normalised study on the pressure-sinkage relationship is a better approach to figure out the independent parameters.

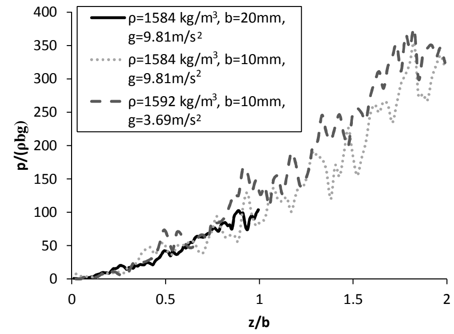

FIGURE 7. Normalised pressure-sinkage relationship.

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