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3D DEM analysis of lunar soil excavation test under different gravity fields

Analyse 3D par MED de la résistance à la coupe de la lame lors d'un essai d'excavation de sol lunaire sous différents champs de gravité

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ABSTRACT: The harsh lunar environment features low gravity field, which plays an important role in predicting the excavation force of lunar soil. This paper presents a numerical study on blade cutting resistance in lunar soil excavation test with focus on the gravity effect by three-dimensional distinct element method (DEM). Firstly, a practicable three-dimensional (3D) contact model, which incorporates rolling and twisting resistances due to grain shape and Van der Waals force, was used to capture the mechanical behavior of lunar soil. After which, a series of lunar excavation tests was carried out under different gravity fields (1 / 6*g*, 1 / 2*g*, 1*g*, 2*g*, 5*g*, 10*g*). Finally, the gravity effect on the horizontal cutting resistance, vertical cutting resistance, and ratio of vertical cutting resistance to horizontal cutting resistance were investigated. The results show that the 3D contact model can well capture the mechanical behavior of lunar soil. Both the horizontal and vertical cutting resistances increase non-linearly with the increasing gravity level. In addition, the ratio of vertical cutting resistance to horizontal cutting resistance increases rapidly with the increasing gravity level at first, and then gradually approaches to the value of blade friction coefficient.

RÉSUMÉ : L'environnement lunaire difficile présente un champ de faible gravité, qui joue un rôle important dans la prédiction de la force d'excavation du sol lunaire. Cet article présente une étude numérique sur la résistance à la coupe de la lame dans le test d'excavation du sol lunaire en mettant l'accent sur l'effet de différents champs de gravité en utilisant la Méthode des Éléments Distincts (MED). Tout d'abord, un modèle de contact tridimensionnel (3D) réalisable, qui incorpore des résistances de roulement et de torsion dues à la forme du grain, a été utilisé pour capturer le comportement mécanique du sol lunaire. Deuxièmement, une série d'essais d'excavation lunaire sous différents champs de gravité (1 / 6*g*, 1 / 2*g*, 1*g*, 2*g*, 5*g*, 10*g*) ont été réalisés. Enfin, les effets de différents champs de gravité sur la résistance à la coupe horizontale, la résistance à la coupe verticale et le rapport entre la résistance à la coupe verticale et la résistance à la coupe horizontale ont été étudiés. Les résultats montrent que le modèle de contact 3D peut bien capturer le comportement mécanique du sol lunaire. Les résistances de coupe horizontale et verticale augmentent de manière non linéaire avec l'augmentation du niveau de gravité. De plus, le rapport de la résistance à la coupe verticale à la résistance à la coupe horizontale augmente rapidement avec le niveau de gravité croissant au début, puis se rapproche progressivement de la valeur du coefficient de frottement de la lame.

KEYWORDS: distinct element method, cutting resistance, lunar regolith, gravity field.

1 INTRODUCTION

In recent years, the lunar exploration and development has attracted increasing attention from government around the world. The lunar soil excavation are very common in many lunar exploration and exploitation activities, such as sampling on the lunar surface (Liu et al. 2014, Yang et al. 2016), In Situ Resource Utilization (Mueller & King 2008, Just et al. 2020), and lunar base construction (Kashanov et al. 2017, Bonneville 2018). Cutting resistance is one of the most important indicators to estimate the excavation performance of excavator (Sun & Li 2012), and increasing the weight of the excavator is one of the main methods to improve the cutting resistance. Nevertheless, the Moon has a low gravity level ($1/6^{th}$ that on Earth, g=9.81m/s^2), and the cost of launching and transporting equipment increases exponentially with the increasing mass of the equipment (Zacny et al. 2010). Consequently, it is unrealistic to increase the cutting resistance using the above method. Hence, it is important to take the gravity effect into consideration when studying the blade cutting resistance of excavator under extraterrestrial environment.

A number of research projects have dealt with excavation of lunar soil, for instance, many analytical techniques (Godwin & Spoor 1977, Patel & Prajapati 2011) have been developed to study lunar excavation on the Earth, and extensive experimental tests (Boles & Connolly 1996, Boles et al. 1997, Kobayashi et al. 2006) have been carried out with lunar soil simulant (Mckay et al. 1994, Jiang & Li, 2011) for analyzing the excavation performance. Boles and Connolly (1996) and Boles et al. (1997) investigated the effect of reduced gravity environment on the excavation forces by conducting tests on an aircraft. The results show that horizontal force for 1/6*g* condition is about 1/3 of the horizontal force for 1g condition. Nevertheless, there are some disadvantages to simulate the reduced gravity environment on experimental excavation test: (1) the reduced gravity environment cannot be steadily maintained for a long time. (2) the simulation of the reduced gravity environment costs too much. These disadvantages will affect the accuracy and repeatability of the experimental results.

Numerical simulation seems to be a useful method in studying the excavation test under different gravity fields. Some researchers employed the Finite Element Method to study the excavation tests (Abo-Elnor et al. 2003, Zhong et al. 2010). On the other hand, Distinct Element Method (DEM) proposed by Cundall and Strack (1979) has become a promising tool for the research of granular mechanics (Jiang et al. 2005, Thornton 2000), especially for the large deformation and failure problems. Nakashima et al. (2008) investigated the gravity effects (*μg*, 0.15*g*, 0.3*g*, 0.5*g* and 1*g*) on the rotational cutting tests of lunar soil simulant by using DEM, and compared the results with those of laboratory tests. But their used contact model is the linear contact model with constant spring stiffness. Bui et al. (2009) introduced an interlocking force to characterize the lunar soil properties to analyze the gravity effect (1/6*g* and 1*g*). But the focus was placed on the bearing capacity of lunar soil with different gravity field, instead of the analysis on the excavation test. In view of the contact model employed in DEM simulations of lunar soil excavation test that cannot capture the main characteristic of lunar soil, Jiang et al. (2013) developed a two-dimensional (2D) contact model for lunar soil, which takes the rolling resistance and van der Waals forces into consideration. This model can capture the mechanical behavior of lunar soil (high peak internal friction angle and apparent cohesion) and then was employed to study the soil-tool interaction under different gravity field (1/6*g*, 1/2*g*, 1*g*, 2*g* and 5*g*) (Jiang et al 2017). Nevertheless, the realistic representation of the soil grain and volumetric response have been limited by using the 2D simulations. Whereafter, Xi et al. (2021) uses the 3D complete contact model which considers the normal, tangential, rolling and twisting resistances (Jiang et al. 2015), to investigate the failure mechanisms from macro to micro and the influence of blade parameters of lunar soil simulant excavation. However, the effect of different gravity fields especially the low gravity levels have not been systematic studied with the above 3D simulations.

This paper aims to investigate the influence of gravity field on cutting resistance of blade in lunar soil excavation test by distinct element method. First, in order to characterize the mechanical behavior of high internal friction angle on lunar soil, a 3D contact model (Jiang et al. 2015) incorporating rolling and twisting resistances is used to simulate the characteristic of lunar soil. Then, a series of lunar excavation tests under different gravity fields (1/6*g*, 1/2*g*, 1*g*, 2*g*, 5*g*, 10*g*) are carried out. After which, the horizontal blade cutting resistance in this study is compared with the 2D simulation results (Jiang et al. 2017). Finally, the impact of different gravity field on horizontal cutting resistance, vertical cutting resistance, and ratio of vertical to horizontal cutting resistance are analyzed. The lunar environment includes low gravity field, ultra-high vacuum and large temperature difference (Heiken et al. 1991), in this paper, the ultra-high vacuum condition which cause the lunar soil has the mechanical behavior of slightly apparent cohesion has not been considered because of the limitation of computing power. It is our future work to carry out 3D simulation to study the lunar environment (low gravity level and ultra-high vacuum) impact in the excavation test by using the latest workstations.

2 METHOD

2.1 *Model selection and parameter calibration*

To represent the high internal friction angle of lunar regolith, a reasonable contact model is the key to simulate this mechanical property. These simulations use a complete 3D contact model incorporating rolling and twisting resistances (Jiang et al. 2015), which can characterize the mechanical properties of lunar soil accurately. Table 1 provides the material parameters of DEM specimens.

Table 1. The material parameters of DEM specimens

	Parameter Name	Symbol	numerical value
Particle	Friction coefficient	μ_b	0.2
	Ratio of Normal to Tangential stiffness		1.5
	Particle modulus (Mpa)	E^*	800
	Density (kg/m^3)	ρ	2720
	Viscous damping		0.8
	Anti-rotation coefficient	β	0.6
Wall	Friction coefficient	μ_w	1.0
	Anti-rotation coefficient	β_w	0.6

2.2 *Generation of DEM specimens and test procedures*

Figure 1 presents the particle size distributions used in the DEM simulations. The 15 different sizes of spherical particles were employed in the DEM simulations. The maximum and minimum diameter of DEM material is 2.0mm and 0.50mm respectively, with an average particle diameter d_{50}=1.27mm and uniformity coefficient C_u=2.46.

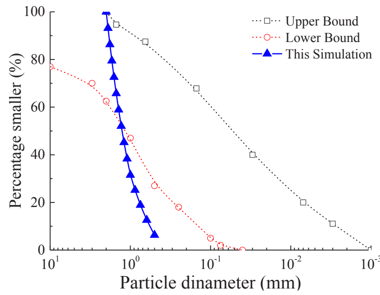


Figure 1. Particle size distribution in the DEM simulations of lunar soil excavation test (Bui et al. 2009, Jiang et al. 2012)

In order to capture the large void ratio (e=0.84) and homogeneity of ground specimen, the DEM specimen is prepared in two steps: (1) prepare loose and homogeneous specimen at the specific void ratio of 0.84, by using the multilayer under-compaction method (UCM) (Jiang et al. 2003); (2) after the homogeneity of specimen was generated, it was subjected to an amplified gravity level of 3.5 multiple was used, which principle similar to the centrifuge modeling. When the equilibrium of the entire system was achieved, the top wall is removed away to simulate a free top boundary of the ground, and the remaining walls are all kept as frictionless.

The configuration of excavation model is illustrated in Figure 2, the DEM specimen contains 750,000 spherical particles. The blade width and the cutting depth is 50mm and 100mm respectively.

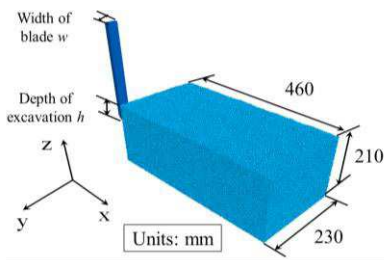


Figure 2. The numerical specimen for the DEM simulations

The lunar soil excavation test is simulated by two steps: (1) Generating the blade of specified size from the left boundary of the ground at the coordinate point of x=-0.1mm, y=0mm, z=0mm to ensure there is no contact between blade and the ground specimen, after the consolidation is finished. Then move the blade toward to the ground specimen with a very slow velocity, to ensure the blade and ground specimen contact with each other and the contact force is negligible. (2) When the equilibrium of DEM specimen is arrived, driving the blade along x positive direction at a constant rate of 27.2 mm/s, and measure the horizontal (x axis) and vertical (z axis) cutting resistance on the blade.

A summary of the test procedures and conditions for the DEM simulations is provided in Table 2.

Table 2. Summary of test program for the DEM simulations

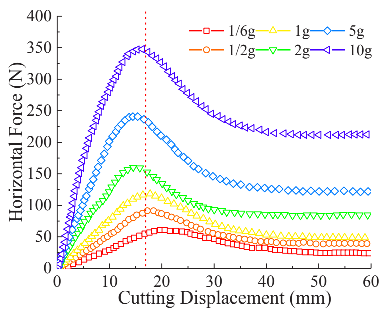
		DEM simulations
Specimen preparation	Compaction criteria	Under-compaction method (Jiang et al. 2003)
	Number of compaction layers	5
	Specimen size	Cubical specimens 460×230×210 mm
Test condition	Gravity field	1/6g, 1/2g, 1g, 2g, 5g, 10g
	Cutting depth	100mm
	Cutting angle	0°
	Blade width	50mm
	Cutting velocity	27.2mm/s

3 RESULT

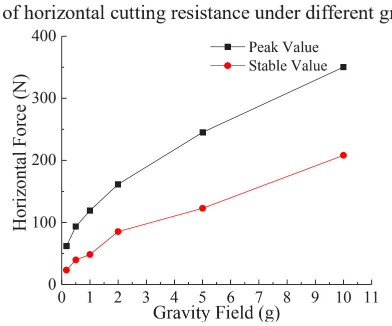
3.1 *Horizontal cutting resistance*

The evolution of horizontal cutting resistance under different gravity field is shown in the Figure 3 (a). It shows that the evaluation of horizontal cutting resistance is analogical under different gravity field. At the initial stage of these simulations, the slope of horizontal cutting resistance curves increases with the gravity level. Then the peak values of horizontal cutting resistance under different gravity field have the similar excavation displacement.

Figure 3 (b) presents the relationship between gravity field and horizontal cutting resistance, the peak and stable values of horizontal cutting resistance increase with increasing the gravity level and have a larger growth rate under low gravity field.



(a) Evaluation of horizontal cutting resistance under different gravity field



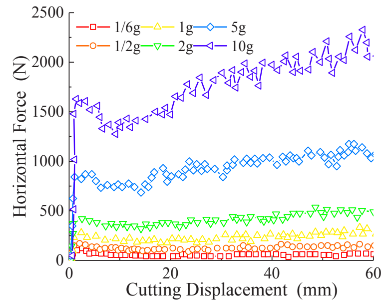
(b) Relationship between gravity field and horizontal cutting resistance (peak and stable values)

Figure 3. Influence of gravity field on horizontal cutting resistance

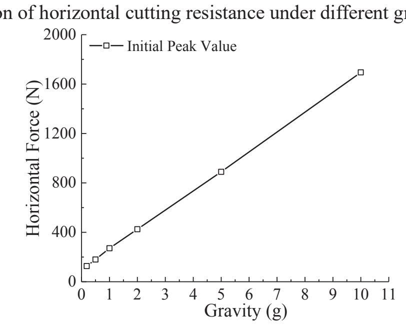
In order to compare the difference of horizontal cutting resistance between the 3D DEM simulation and the 2D simulation, the previous research result of our group on horizontal cutting resistance in 2D DEM simulation (Jiang et al. 2017) are carried out to compare with the relevant content of the 3D DEM simulation result in this study.

As the Figure 4 (a) shown, the horizontal cutting resistance increases rapidly at the initial stage of the 2D simulation. Then, the horizontal cutting resistance decreases to a lower value. Finally, the horizontal cutting resistance gradually increases with the blade moves on. The above phenomenon is more significant under the high gravity field. Figure 4 (b) provides the relationship between gravity field and horizontal cutting resistance. The horizontal cutting resistance increases linearly with the gravity level from 1/6g to 10g.

Compare Figure 3 (a) and Figure 4 (a), it is shown that the evaluation of horizontal cutting resistance under different gravity field in 2D and 3D simulations have the similar tendency in the initiate of the simulation, but with the increasing of cutting displacement, the difference is arisen. The horizonal cutting resistance in 2D simulation tardily increasing with the cutting displacement, while the resistance in 3D simulation decreases and then maintain a smaller value. Because in the process of blade moving in 2D simulation, the particles heap up in the front of the blade, and they cannot slide in the side direction, which lead to the higher peak value and the following continuous increase of horizontal cutting resistance. The above issue can be effectually avoided by using the 3D simulation.



(a) Evaluation of horizontal cutting resistance under different gravity field



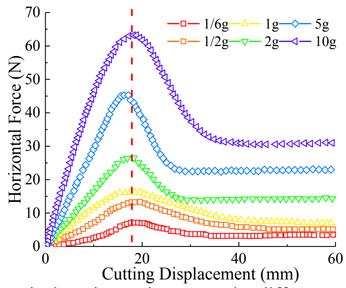
(b) Relationship between gravity field and horizontal cutting resistance

Figure 4. Influence of gravity field on horizontal cutting resistance using 2D DEM simulations (Jiang et al. 2017)

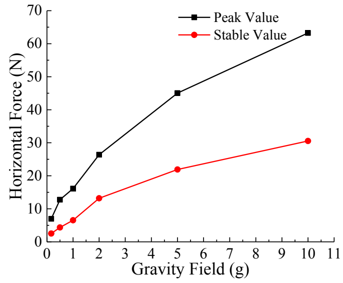
3.2 *Vertical cutting resistance*

The evolution of vertical cutting resistance under different gravity field is shown in the Figure 5 (a), the evolution of vertical cutting resistance is analogical under different gravity fields. It can be found that the curves of vertical cutting resistance have the similar tendency with the curves of horizontal cutting resistance.

Figure 5 (b) presents the relationship between gravity field and vertical cutting resistance, the peak and stable values of vertical cutting resistance increase with increasing the gravity level, but the slope of the curves gradually decreases with the increasing of the gravity level.



(a) Evolution of vertical cutting resistance under different gravity field



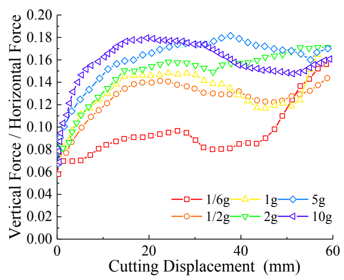
(b) Relationship between gravity field and vertical cutting resistance (peak and stable values)

Figure 5. Influence of gravity field on vertical cutting resistance

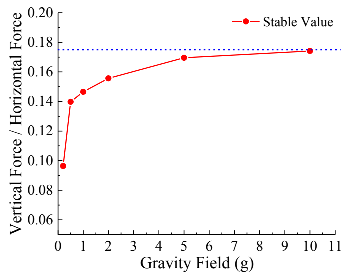
3.3 *Ratio of vertical and horizontal cutting resistance*

Figure 6 (a) provides the variations of ratio of vertical and horizontal cutting resistance under different gravity field in the excavation test. The tendency of curves in Figure 6 (a) is similar, except the curve under 1/6g gravity level. The ratio is gradually increasing at the excavation displacement from 0mm to 20mm roughly. When the excavation displacement between 20mm and 60mm, the ratios are slightly decrease then increase.

Figure 6 (b) presents the relationship between gravity field and ratio of vertical to horizontal cutting resistance. Figure 6 (b) shows that the ratio of vertical to horizontal cutting resistance increases with the increasing gravity level, and the slope of ratio gradually decreases with the increasing of the gravity level. Its value tends to be the value of friction coefficient of blade gradually, and the value of friction coefficient is about 0.175.



(a) Variation on ratio of vertical and horizontal cutting resistance under different gravity field



(b) Relationship between gravity field and ratio of vertical and horizontal cutting resistance

Figure 6. Influence of gravity field on ratio of vertical and horizontal cutting resistance

4 CONCLUSIONS

This paper presents a series of DEM simulations of lunar soil excavation test to study the influence of different gravity field on the horizontal and vertical cutting resistance. The part simulation results were compared with the previous research results on vertical cutting resistance in 2D simulation (Jiang et al. 2017). The following conclusions can be made from the investigation:

(1) To compare with the previous research result on horizontal cutting resistance 2D simulation, it is found that the 2D and 3D simulation results on horizontal cutting resistance have the qualitatively similar results by increasing the gravity level.

(2) The horizontal and vertical cutting resistances increase non-linearly with the increasing gravity level and this phenomenon is different with the 2D result.

(3) The ratio of vertical and horizontal cutting resistance increases with the increasing gravity level, and its value tends to be the value of friction coefficient of blade gradually.

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