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Effect of gravity on the mechanical properties of lunar regolith tested using a low gravity simulation device

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Abstract

Simulations of the bearing capacity and shear strength of regolith under Earth's gravity produce different results from those under low gravity. A low-gravity simulation device was developed in this study, and an internal stress model of regolith simulant was established to correct the errors. The model revealed additional force on both shear plane in the shear test and the press plate area in the pressure–sinkage test. The sinkage and shear test results showed that low gravity decreased the deformable index n, frictional modulus k_φ and cohesion c, whereas there were no obvious changes to the cohesive modulus k_c and internal friction angle φ. The sinkage generally increased as the gravity decreased under a consistent normal load larger than 50 N, but when the wheel load was lower than 50 N, the sinkage of the TYII-1 simulant was larger under 1 G than 1/6 G. Gravity had little effect on the shear strength of the regolith. However, the tractive thrust of the TYII-1 simulant was lower under 1/6 G than 1 G. The smaller difference was due to differences in the way the soils responded to changes in the gravity level for the TYII-2 simulant.

Keywords: Regolith; Low gravity; Shear strength; Bearing capacity

1. Introduction

Lunar and in-situ regolith exploration missions have recently become a focus of deep space exploration. For instance, China sent a rover to the lunar surface in December 2013 as part of this new movement. Research on the mechanical properties of lunar regolith is essential for rover exploration. However, the conditions of the lunar surface are quite different from a terrestrial environment in terms of surface materials, low gravity, high vacuum conditions and so on (Caruso et al., 2007). For example, the bearing capacity and shear strength of regolith on the lunar surface differ from those of regolith or regolith simulants subject to Earth's gravity. These differences are unfavorable for designing mobility systems and evaluating trafficability (Asnani et al., 2009; Kobayashi et al., 2005). Thus, it is important to determine the mechanical parameters of lunar regolith under low gravity.

Several studies have investigated the mechanical properties of soil in low-gravity fields. Kobayashi et al. investigated the influence of gravity on the mobility of wheeled rovers for lunar/planetary exploration missions. They performed model experiments for a soil–wheel system on an aircraft during variable gravity maneuvers (Kobayashi et al., 2010). Nakashima et al. determined the effects of gravity on the angle of repose of sand pile particles by allowing dry sand to flow from a hopper during a parabolic airplane flight under simulated low-gravity conditions. The results showed that the effects of gravity on the angle of repose of the sand particles were negligible (Nakashima

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Nomenclature

A	sectional area of soil bin, cm^2
A_0	area of wheel–soil interface, cm^2
b	wheel width, cm
b_i	undetermined coefficient in Eqs. (3) and (4)
c	cohesion of the regolith, kPa
C_c	coefficient of curvature
C_u	coefficient of uniformity
D	wheel diameter, cm
d_{50}	medium size particle, μm
f_o	friction coefficient between the soil and bin
F_{an}	valid axial force, N
F_{as}	valid lateral force, N
F_n	measured axial force, N
F_s	measured lateral force, N
G	earth gravity, 9.81 m/s^2
H	tractive thrust, N
j	shear deformation, cm
k	lateral pressure coefficient
K	shear deformation modulus, cm
K_c	cohesive modulus, N/cm^{n+1}
K_φ	frictional of the modulus, N/cm^{n+2}
m	mass carried by a wheel, kg
n	exponent of the sinkage equation
p	normal pressure, kPa
p_h	lateral stress, kPa
p_m	tilt-axial stress, kPa
p_s	tilt-lateral stress, kPa
p_v	axial stress, kPa
R_c	compaction resistance of a wheel, N
SG	specific gravity
u	circumference of soil bin, cm
W	normal load on a wheel, N
z	sinkage, cm
z_0	maximum sinkage, cm
φ	angle of internal friction, °
θ	tilt angle for soil bin, °
ρ	bulk density, g/cm^3
λ	slip ratio, %
τ_{max}	maximum shear stress of soil, kPa

et al., 2011). Kuroda et al. introduced a similarity law that they used to design and produce two experimental models of a planetary rover with a 5-wheel suspension and 4WD system under 1 G and 1/2 G gravity (Kuroda et al., 2004). Tateyama designed a simple shear test apparatus to measure the shear strength of a regolith simulant under a low level of confining pressure. The gravitational acceleration could be optionally changed by controlling the weight and tilt angle of the sample (Tateyama, 2007).

Moving beyond experimental approaches, Wong described a practical method for predicting the performance of rover wheels on extraterrestrial surfaces based on test results obtained on Earth. The study found that gravity had little effect on the slip and sinkage relationship of the rigid rover wheels under self-propelled conditions (Wong, 2012; Wong and Kobayashi, 2012). Nakashima et al. estimated the performance of wheels on the lunar surface using a discrete element method (DEM) analysis in which the value of gravitational acceleration varied from 1 G to 1/6 G. The results showed that a reduction in gravity resulted in an increase in wheel sinkage (Nakashima et al., 2007). Bui et al. investigated the mechanism of soil excavation under various gravity conditions using a numerical study in combination with soil bearing capacity experiments performed during serial parabolic flight (Bui et al., 2009). Furthermore, since the development of the Lunokhod, the initial lunar rover with eight rigid-rim wire mesh wheels (Asnani et al., 2009), during the 1960s, Russian scholars have long had the opportunity to conduct research into rover mobility under lunar gravity (Kucherenko et al., 2004).

Previous studies generally agree that effective regolith strength is reduced with a reduction in gravity. However, the methods used to analyze the effect of gravity on the mechanical properties of lunar regolith, including parabolic flight, theory analysis and inclination and computer simulation, still require further development. For example, the parabolic flight method is limited by a short valid time, equipment instability issues and poor reproducibility. Computer simulations require model parameters and verification tests that demand a great deal of test data. The inclination method causes the internal stress of the soil to exit through the inclination force, which can cause exit errors in the test results. Thus, a new method and device are needed to evaluate the effects of low gravity.

The purpose of this work was to experimentally test the mechanical properties of lunar regolith at different gravities to determine whether a change in gravity affects trafficability during lunar rover movement. The remainder of this paper is organized as follows. Section 2 introduces the experimental method and regolith simulant, with an emphasis on how to correct the influence of the lateral stress generated by simulated gravity, as established in the Janssen model. Section 3 describes the pressure–sinkage and shear test results obtained for two regolith simulants under various gravity conditions, and summarizes the influence of gravity on the parameters of Bekker's bearing model and Coulomb's shear model. In Section 4, the deformation of the regolith was predicted using a discrete element method. The results are compared with those obtained from experimental data obtained using a low gravity simulation device. Discuss the influence of the gravity on the sinkage Z, soil compaction resistance R_c and tractive thrust H of its driving wheel.