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ScienceDirect

Advances in Space Research 58 (2016) 145–154

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Vibratory compaction method for preparing lunar regolith drilling simulant

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Received 24 December 2015; received in revised form 22 April 2016; accepted 24 April 2016
Available online 29 April 2016

Abstract

Drilling and coring is an effective way to acquire lunar regolith samples along the depth direction. To facilitate the modeling and simulation of lunar drilling, ground verification experiments for drilling and coring should be performed using lunar regolith simulant. The simulant should mimic actual lunar regolith, and the distribution of its mechanical properties should vary along the longitudinal direction. Furthermore, an appropriate preparation method is required to ensure that the simulant has consistent mechanical properties so that the experimental results can be repeatable. Vibratory compaction actively changes the relative density of a raw material, making it suitable for building a multilayered drilling simulant. It is necessary to determine the relation between the preparation parameters and the expected mechanical properties of the drilling simulant. A vibratory compaction model based on the ideal elastoplastic theory is built to represent the dynamical properties of the simulant during compaction. Preparation experiments indicated that the preparation method can be used to obtain drilling simulant with the desired mechanical property distribution along the depth direction.
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Keywords: Lunar regolith; Drilling simulant; Simulant preparation; Vibratory compaction

1. Introduction

Lunar regolith refers to the 4–15 m thick layer of granular materials covering the underlying bedrock of the moon (Heiken et al., 1991). Drilling and coring is known to be an effective way to acquire regolith samples while maintaining their stratification along the depth direction (Bar-Cohen and Zacny, 2009). The Chang'e-5 lunar exploration project aims to sample lunar regolith through an automated drilling and coring device and return it to Earth. The drill and lunar regolith have a complex physical interaction that may determine whether the device can obtain a sample. To verify the designed drill auger and bit and whether the drilling strategy is appropriate, ground experiments should be conducted with the desired drilling simulant (Bar-Cohen and Zacny, 2009; Gouache et al., 2011; Pitcher and Gao, 2015). Therefore, an appropriate drilling simulant must be prepared to ensure that the distribution of the mechanical properties is reproducible along the longitudinal direction.

The preparation of a regolith simulant is a prerequisite for testing the performance of a space-based device that will interact with the regolith. Landers, lunar surface excavation scoops, and rovers make contact with only a shallow layer of regolith, the mechanical properties of which can be considered consistent at one specific site (Zhong, 2012; Agui et al., 2013; Li et al., 2015). However, because the mechanical properties of lunar regolith vary with the landing site, homogenous regolith simulants with different mechanical properties may be preferable for tests of landing, surface regolith excavation, and sinkage mobility. To acquire subsurface lunar regolith samples, drilling devices must

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http://dx.doi.org/10.1016/j.asr.2016.04.021
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make contact with both a shallow and a deep layer of regolith. Generally, lunar regolith has low to medium relative density in the shallow layer and high relative density just 10–20 cm below the lunar surface (Mitchell et al., 1974). To verify the design of a drilling device, the drilling simulant should be prepared to mimic actual lunar regolith with varying distribution of mechanical properties along the depth direction; a simulant with high relative density is indispensable for ground drilling experiments. Pour, rain, vibratory compaction, Proctor compaction, and static compaction methods were used to prepare homogeneous regolith simulants with different relative densities (Gouache et al., 2010; Zhong, 2012; Scott and Saaj, 2009). The pour and rain methods were used to prepare loose or medium-density simulants, in which the relative density was governed by the falling height and flow rates (Gouache et al., 2010; Jiang et al., 2013). The vibratory compaction method was used to prepare medium- or high-density simulants (Klosky et al., 2000). In this method, the relative density could be controlled by changing the vibratory parameters (e.g., vibratory frequency and impact force) (Wersäll and Larsson, 2013). The Proctor compaction method was mainly used for measuring the mechanical properties of standard simulant specimens (Zhong, 2012; MWR, 1999). The tamping method was used to prepare large-scale soil samples (Kleinhenz and Wilkinson, 2012; Adam et al., 2007). The static compaction method was used to compact a simulant by using compression force (Scott and Saaj, 2009). Preparation using the static compaction method is time-consuming when producing a homogenous soil specimen, especially when the raw materials have weak flow characteristics (Zheng et al., 2008). While numerous methods have been used to prepare homogenous simulants, few studies have reported on the preparation of drilling simulants with mechanical properties that vary along the longitudinal direction. Because vibratory compaction can actively change the simulant density under dynamic loads, it is considered appropriate for producing a multilayered drilling simulant. Therefore, in this study, vibratory compaction was used to prepare the lunar regolith drilling simulant to simulate the subsurface lunar regolith.

The preparation of the regolith drilling simulant can be facilitated by understanding the effect of vibratory compaction on the simulant. The finite element method (FEM) and discrete element method (DEM) have been used to describe the mechanical behavior of granular materials during vibratory compaction (Kenneally et al., 2015; Masad et al., 2010; Arnold and Herle, 2009; Chen et al., 2013). However, FEM cannot well model large deformation because it suffers from mesh distortion, which may result in low calculation accuracy and convergence failure. Although DEM simulation can overcome this limitation, the high computation cost restricts DEM application to small-scale or short-duration simulation. Analytical models have also been used to describe the behavior of granular materials during vibratory compaction. Most analytical models such as the Maxwell, Kelvin, Burgers, and Huet–Sayegh models represented granular materials as a combination of springs and dampers (Sysante and Mooney, 2008; Kordestani et al., 2010; Beainy et al., 2014; Xu and Solaimanian, 2009). Because the damping parameters of soil vary during vibratory compaction and depend on the moisture content, density, and type of soil, the damping parameters are difficult to determine and validate during compaction (Beainy et al., 2014; Facas et al., 2010). The ideal elastoplastic theory can be used to describe the behavior of soils under dynamic loads, and the parameters of the model based on this theory are convenient to determine and verify (Niu, 2003). However, the ideal elastoplastic theory has not yet been adopted to describe soil behavior during vibratory compaction.

This paper presents a vibratory-compaction-based method to prepare lunar regolith drilling simulant for ground drilling and coring experiments. Based on the ideal elastoplastic theory, a vibratory compaction model is built to represent the behavior of lunar regolith simulant during vibratory compaction in simulant granular systems. Experiments are conducted using a vibratory table to validate the vibratory compaction model. Inspired by the Apollo analysis method, a relation between the preparation parameters and the expected mechanical properties of the drilling simulant is developed to facilitate simulant preparation. Terrestrial preparation experiments are conducted to obtain a lunar regolith drilling simulant with desired mechanical property distribution along the depth direction.

The remainder of this paper is organized as follows. First, a review of lunar regolith is presented. Then, the lunar regolith simulant material is introduced. The vibratory compaction model is built to describe the dynamic behavior of the lunar regolith simulant during compaction. Nextthe vibratory compaction model is experimentally validated. Finally, preparation experiments are conducted to obtain a lunar regolith drilling simulant.

2. Review of lunar regolith

To analyze the lunar regolith acquired by the Apollo missions, the Apollo method was developed to analyze the mechanical property distribution of lunar regolith along the longitudinal direction (Heiken et al., 1991). The core samples collected by the Apollo Lunar Surface Drill and the core tubes were used to analyze the relation between the depth and the density of lunar regolith (Bar-Cohen and Zacny, 2009). Ground physical tests based on the basaltic lunar regolith simulant yielded the relation between the shear strength and the relative density (Mitchell et al., 1972). The results of these two analyses indicate that the mechanical property distribution of lunar regolith can be acquired along the depth direction.

According to the Apollo analysis results, the relative density of lunar regolith is generally low to medium in the shallow layer and high just 10–20 cm below the lunar surface (Mitchell et al., 1974). The fitting equation of density versus depth can be expressed as a logarithmic function:

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