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Analytical models and laboratory measurements of the soil–tool interaction force to push a narrow tool through JSC-1A lunar simulant and Ottawa sand at different cutting depths

R.H. King [a,*], P. Van Susante [a], M.A. Gefreh [b]

[a] Engineering Division, Colorado School of Mines, Golden, CO 80401, United States
[b] Sierra Nevada Corporation 8130 Shaffer Pkwy. Littleton, CO 80127, United States

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Abstract

Excavation equipment for developing NASA's lunar outpost must be carefully designed to reduce launch cost, minimize operation cost, and enhance reliability. Excavation equipment requires knowledge of the stresses and strains in the equipment caused by the forces experienced during excavation. The types of excavation anticipated indicate that blade tools would move the most material. There are several analytical models available to predict forces from blade tools interacting with soil; however, it is not clear which if any, can predict lunar excavation forces precisely enough. Consequently, we measured the forces to push narrow (2.5-cm wide) square and round rods through a control material, Ottawa sand, and JSC-1A lunar mare regolith simulant at different cut depths in a controlled laboratory setting. The measurement results were compared with the forces predicted by eight analytical models. The Zeng, Luth and Wismer, and the Qinsen and Suren models fit the measurements best, considering that our study was limited to pushing stimulant and sand with small rods. The results show that depth of cut has a dramatic effect on the soil–tool interaction forces. Consequently, lunar missions should use a series of shallow cuts to reduce equipment size and power requirements.

Keywords: Excavation-force measurement; Excavation-force models; Lunar outpost; Lunar simulant

1. Introduction

NASA proposed a series of missions to establish a lunar outpost that includes in situ resource utilization (ISRU) [1]. Outpost development requires excavation for landing and launch sites, roads, trenches, foundations, radiation and thermal shielding, etc., furthermore, ISRU requires excavation as feed stock for water processing and oxygen production plants. The lunar application requires excavation equipment to have minimal mass, low power, small size, and operate unattended in low gravity and at extreme temperatures for at least six month durations. The design goals and criteria for terrestrial equipment are considerably different; consequently, the lunar application requires new approaches. The new designs require precise knowledge of excavation forces.

There are no missions planned in the near future to measure excavation forces on the lunar surface at the outpost location. It is difficult and very costly to mimic the low gravity, temperature, and atmospheric conditions of the moon in a laboratory on earth. Consequently, we must rely on models. Several analytical models are available to predict the interaction between various tools and soil; however they predict different force values. This paper describes a set of measurements and a computer program that are used to compare the models for lunar application. By lunar application we mean the geometric scale and the geotechnical soil properties. The work does not simulate lunar gravity or temperature. Furthermore, the work is restricted to blade interactions since a study of excavation tools and equipment applicable to outpost development concluded

* Corresponding author. Tel.: +303 273 3305; fax: +303 273 3602x279.
E-mail address: rking@mines.edu (R.H. King).

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that tools for pushing (dozing) lunar soil would handle the largest volume of lunar regolith [2].

2. Laboratory apparatus

The CSM (Colorado School of Mines) soil excavation force measurement test bed was originally designed for measuring the excavation forces associated with a micro-scale bucket wheel excavator [3,4]. During this project, it was modified to measure the excavation force associated with rods pushing through regolith simulant [5]. The test bed keeps the rod stationary, while the tray containing the regolith translates linearly. Fig. 1 shows the modified test bed. Modifications included removing the buckets from the bucket wheel, locking the bucket wheel in a stationary position, adding two vertically aligned U-bolts to hold a ½ inch diameter round rod, and adding a ¼–20 threaded rod for the square rod mount as shown in Fig. 2.

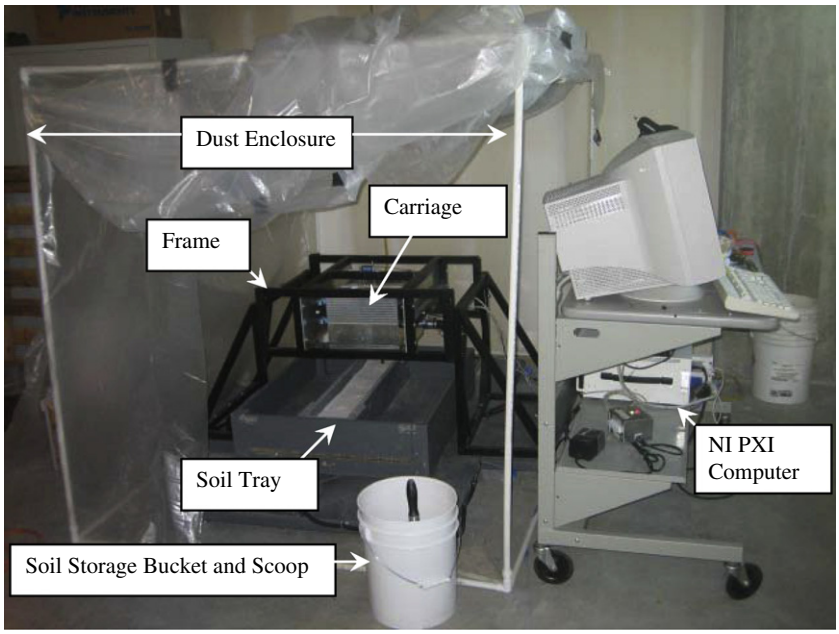

Fig. 1. Soil excavation force measurement apparatus.

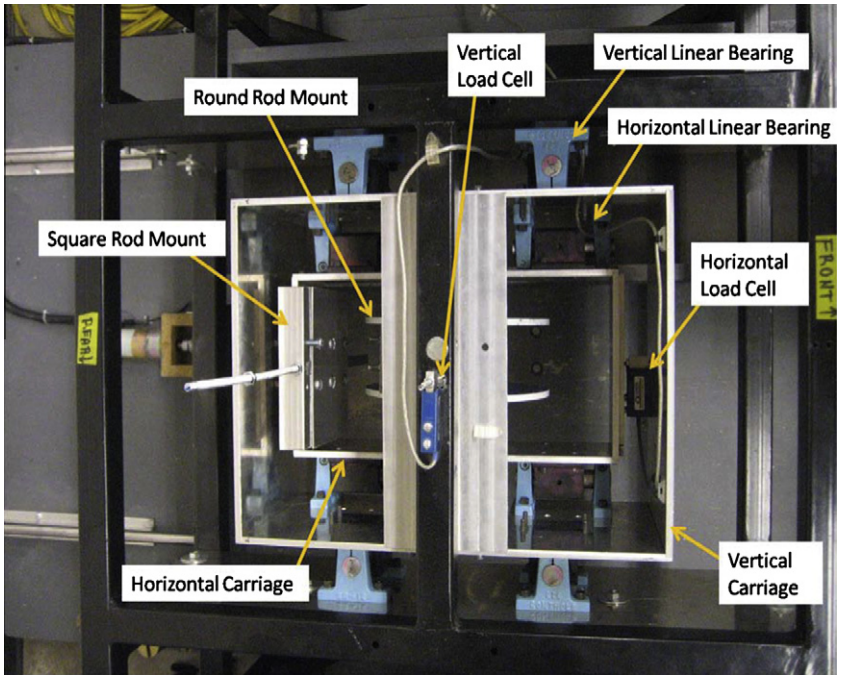

Fig. 2. Excavation force measurement apparatus chassis.