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Effect of Mars atmospheric pressure on percussive excavation forces

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Abstract

Percussive excavation tests were performed at Earth atmospheric pressure, 101 kPa, and at Martian atmospheric pressure, 600 Pa. The experimental set-up included a replica surveyor scoop attached to a custom-built, vacuum-rated hammering system. The excavation system was attached to a six axis load cell to measure excavation forces and torques. All tests were conducted in JSC-1A soil. Comparisons were made between the Earth atmospheric test data and the Martian atmospheric test data to determine how atmospheric pressure influences the effectiveness of percussion in reducing the shear strength of JSC-1A soil during excavation. Test data showed a similar reduction profile in excavation force magnitude for various percussion test permutations at both 101 kPa and 600 Pa. For both test pressures the force reduction profile is attributed to degradation in the in situ soil dilatancy. Overall, it was observed that the baseline excavation force and penetrometer Cone Index magnitude were lower at 600 Pa than at 101 kPa. This reduction in both force measurements could be attributed to one or a combination of the following: reduction in adhesion between the tool and the soil, reduction in coefficient of friction between the tool and the soil, reduction in soil cohesion, and/or reduction in soil internal friction coefficient. From the practical stand point, reduction of excavation forces at Mars pressure directly translates to lower excavation energies on Mars.

Keywords: Percussion; Excavation; Dilatancy; Friction; Vacuum; Pressure; In situ resource utilization; ISRU

1. Introduction

Future human and robotic missions to Mars will require utilization of local resources for production of water, oxygen, propellant, and construction materials. By using the local assets provided by the planet the critically constrained payload that must be launched from Earth can significantly be reduced [1,2]. One of the major technologies enabling In Situ Resource Utilization (ISRU) is the mining of local resources.

The ability to mine Martian resources is hindered by different challenges, one of which is a low gravity environment. Terrestrial excavators rely on their weight to overcome the reaction forces necessary for ground penetration. On Mars, to generate the same forces, an excavator would have to be three times more massive. Bringing such a large excavator to Mars would not only be very expensive, but may not be feasible given the developmental requirements of larger scale rockets and new Entry Descent and Landing (EDL) technologies. Accordingly, new mining technology is required for Martian soil excavation [3]. One such technology that is being considered in this work is percussive excavation.

Percussive excavation should not be confused with vibratory excavation. In percussive systems, a free mass periodically impacts an excavation tool creating a pressure wave within the tool. That wave travels to the tip of the tool, creating a high stress region between the tip of the tool and the soil material. That high stress is sufficient to break up any crusty or cohesive soils and in some cases even soft rocks. This principle is similar to one used in the jack hammers employed in the construction industry or in rotary-percussive drills. The main advantage of the

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percussive system is that the pressure wave does most of the work, enabling lower digging forces. Another benefit of the percussive system is that the pressure wave after impact is reflected within the tool creating a “ringing” vibration. This vibration is then propagated to the soil particles causing the soil to dilate, reducing the internal friction angle and in turn soil shear strength. As opposed to percussive systems, vibratory tools only have the ‘vibratory’ component of the percussive system and are not as effective in soils with high cohesion [4]. It should be noted that the vibratory action in percussive and pure vibration systems is effective in high apparent (as opposed to true) cohesion soils, where the cohesion is due to grain interlocking rather than cementing agents (e.g. Fe_2O_3, $CaCO_3$) or electrostatic forces. This is the case for lunar soil, where highly angular particles with a large fraction of agglutinates make the soil have apparent cohesion (not true cohesion).

Percussive excavation provides a tradeoff between energy and mass requirements associated with an excavation procedure. An excavator system that uses percussion does not have the same weight requirements as a normal excavator due to the reduced soil reaction forces; however, the system will require more energy to drive the extra mechanism. This tradeoff is especially beneficial in the space environment where severe limitations are placed on the excavator mass but energy is readily available from the Sun. Given these considerations percussive excavation is a promising mining technology for Martian exploration.

To date there have been no investigations exploring the effect of Mars atmospheric pressure on excavation forces and the effectiveness of percussive excavation. The purpose of this work was to experimentally test a percussive excavation system at Earth atmospheric pressure and at Martian atmospheric pressure in order to determine whether a change in atmospheric pressure affects excavation forces during percussive digging. The percussive excavation system was tested at 101 kPa, Earth atmosphere, and at 600 Pa, Martian atmosphere. All tests were performed in JSC-1A soil simulant [5].

2. Materials and methods

2.1. Hardware

A schematic of the experimental test stand is shown in Fig. 1. For Martian atmospheric pressure testing, the test stand was set up inside of a 1 m × 1 m × 3.5 m vacuum chamber, shown in Fig. 2.

The test stand consisted of two main subsystems: the percussor and the soil bin. The percussor was attached to the Z′-stage (ball screw driven) via a 6-axis load cell. A replica of the Lunar Surveyor Soil Mechanics Surface Sampler [6], i.e. the scoop, was attached to the percussor via a piezo load cell. The percussor/scoop assembly was set at an angle 70° relative to horizontal. The percussive system applied a periodic impact to the scoop through a motor-driven cam-follower mechanism. Every rotation of the cam compressed a mechanical spring which was subsequently disengaged to release the stored potential energy, 2.5 Joules per blow, through an attached impact rod. The percussor possessed the ability to change the value of the impact frequency by altering the rotary speed of the percussive actuator.

The 500 mm wide, 750 mm long and 300 mm deep rigid soil bin was attached to the X-stage (ball screw driven). A uniaxial load cell was mounted between the soil bin and the X-stage to measure horizontal excavation forces.

A 6-axis load cell was used to process excavation forces induced by the soil onto the scoop while the soil bin was moved from left to right along the X-stage (sampling rate of 62 Hz). The values obtained from the 6-axis load cell were corroborated by comparing their horizontal force component against the excavation uniaxial load cell. The piezo load cell located between the percussive impact rod and the excavation scoop evaluated the impact force delivered during percussion.

An external vibrator was mounted to the soil bin in order to compact the soil. The soil bin was vibrated for specific durations of time to obtain different desired compaction states. The vibrator was integrated into the test stand so that it could be used to compact the soil while in the vacuum chamber after the target pressure was reached.

Unfortunately Mars Mojave Simulant [7] was not available in time for these tests. Therefore the excavation tests used JSC-1A, a lunar soil simulant. The soil is made of crushed, carefully selected, volcanic cinder. Because of the igneous origin of JSC-1A as well as MMS and Mars rocks, the major chemical composition of Mars soil (calculated from Viking, Pathfinder and MER missions), MMS, and JSC-1A are quite similar. The major soil parameters affecting excavation forces are friction angle and cohesion. Due to the nature of the manufacturing process (i.e. crushing) used to produce both JSC-1A and MMS, the particle shapes are angularly similar and have comparable grain size distributions. It should be noted that neither MMS nor JSC-1A are perfect Mars soil simulants. The data from the Mars Phoenix mission revealed that Martian soil has two size populations: larger, mostly rounded grains and small reddish fines, notably with a very low mass proportion in the clay-size range below 2 μm [8]. Therefore, given the lack of appropriate simulants, and availability of JSC-1A, it was decided to use JSC-1A soil for all tests.

2.2. Measuring soil density

A soil penetrometer was used to determine soil density prior to each excavation test. The penetrometer was attached to the Z-stage (ball screw driven) via a uniaxial load cell and attached to the back of the excavation test stand (see Fig. 1). To take a measurement, the soil bin was positioned underneath the penetrometer such that the measurement location was approximately 100 mm from the back wall and along the longitudinal midline of the soil bin. This approach minimized potential boundary effects.