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Percussive Penetration of Unconsolidated Granular Media in a Laboratory Setting

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Abstract. This controlled study examined the feasibility of a simple percussive approach to drilling through unconsolidated regolith deposits on Mars. The experiments showed that the approach is feasible at the low power levels and low confining pressures used, and that the rate of impact is more important to the penetration rate than is the mass of the impactor (hammer). More massive impactors tend to lower energy efficiency, as they do in terrestrial pile-driving. Unexpectedly, penetration plotted against applied energy tends to cluster into parallel linear trends. Within a given cluster, penetration is very sensitive to applied energy, while between clusters, the same penetration requires different energy levels. The clusters are separated by gaps whose widths may be related to the average grain size of the material being penetrated. The layered nature of natural sedimentary deposits is reflected in the cumulative energy-penetration plots, which could thus serve to record bedding thickness and frequency during Mars exploration. This study has shown that percussive drilling using a down-the-hole hammer design may be feasible in unconsolidated fine regolith near the ground surface.

Keywords: Drilling, percussion, regolith, granular media, Mars.
PACS: 45.70.Cc, 45.40.Cc.

INTRODUCTION

As missions to explore Mars and the Moon multiply, interest in drilling in regolith (and, indeed, in competent rock) also increases. The difficulty of site access for both humans and robots emphasizes the need for simple, robust, yet flexible drilling systems. One of the simplest drilling approaches – percussion – is accordingly being re-examined for this purpose. Together with rotation, percussion is one of the most basic approaches to physically sampling material below the ground surface. Several efforts have begun developing drills for extra-terrestrial exploration (e.g., Bar-Cohen, et al., 2001; Boucher, Richard, and Dupuis, 2003; Shenhar, et al., 2005; Stoker, et al., 2005; Liu, Weinberg, and Mavroidis, 2006; Zacny, et al., 2006). Wilcox (1997) proposed a tethered mole that would dig itself into unconsolidated sedimentary material by alternately lifting and dropping a mass onto an anvil, both contained within the body of the device. The mole would be shaped similarly to a cone penetrometer. One necessary capability was predicting its penetration rate in the materials that it could expect to encounter on Mars.

This study was designed to test the assertion that long-term, low-power percussive driving of a long, stiff, slender rod could advance a small mole at useful penetration rates in materials similar to martian regolith deposits. It was designed as a preliminary experimental study to establish the feasibility of the approach in preparation for more complete research to follow.

BACKGROUND

A stiff rod being slowly tapped into unconsolidated material advances by pushing particles from its path and compacting the near-field grains into a tighter packing configuration. In general, bulk compaction of such material is accomplished by a combination of particle size reduction (crushing) and bulk compaction. Grain crushing occurs through fracture of the solid material, while compaction occurs when the particles are moved by increase in local

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stress or by fluidization through vibration. This study concentrated on low-energy regimes, so that downward advance would be accomplished solely by bulk compaction of the regolith, with no associated grain breakage.

In material with mono-modal particle size distribution, the force needed to overcome frictional and cohesive bonding forces increases with the exposed surface area of the particles. Since the specific surface area is inversely proportional to particle size, a unit mass of fine particles would be harder to penetrate than a unit mass of coarse particles, with all other factors equal, including the ratio between the diameter of the penetrator and the size of the particles. There is a trend to increasing porosity as particle size decreases, but it is significant only for diameters below 100 μm (clay or clay-sized particles). As particle diameter increases, the effects of friction/cohesion decrease and a limiting value of initial porosity is reached. The maximum porosity of frictionless packed spheres is 39.9%, regardless of their diameter. Initial porosity in terrestrial sediments is controlled by particle size, particle shape, and particle size distribution. Sediments deposited in less energetic environments contain a broader range of grain sizes, often bi-modal. Beard and Weyl (1973) determined that porosity increases monotonically with wider grain size distributions. Sorting is accomplished by fluidization of grains by liquids, gases, or vibrations. Packing of nonspherical particles gives higher porosities than for spheres, though still independent of size.

In general, compaction of unconsolidated material is accomplished by pressure (static input of energy) and vibration (dynamic input of energy). The stiffness and strength of granular materials rise significantly when even a minor amount of cementation exists at the grain-grain contact points, as would be the case in permafrost or any intergranular ice deposit (Dvorkin, Mavko, and Nur, 1991; Dvorkin, Yin, and Nur, 1994; Zang, Wong, and Davis, 1995). In controlled studies of artificial quartz sandstones of different degrees of siliceous cementation, David, Menendez, and Bernabé (1998) showed that as the volume fraction of cementation increases, the transition from brittle to ductile behavior occurs at higher stresses, the critical pressure increases, the bulk modulus of the material increases, and its compressive strength increases. Also, they found that heterogeneity of rock properties is greater for higher-porosity (lower cementation) rock. Naturally occurring granular soils and rocks often contain significant amounts of non-quartzitic, angular grains, as well as cements of varying compositions and concentrations. Filling pore spaces in normally weak rock with ice increases its strength (Jeremic, 1987). This is due to the cementing effect of the ice and the increase in confining pressure due to water's 9% volumetric expansion upon freezing.

Granular convection is expected to be most obvious during advance through loosely packed materials, such as dry sand. In this instance, the mole itself can be thought of as an acicular particle in a bed of equidimensional particles of various sizes in relation to itself. A fundamental difference between the mole and published laboratory experiments with tapped or vibrated granular convection systems is that the forcing is internal to the system rather than external. Laboratory studies of long cylinders filled with round grains of consistent size show that wall friction is a controlling feature during discrete tapping events as well as during continuous vibration (Jaeger, 1997). This type of experiment may be applied to modeling of the mole by everting it and considering the walls of the laboratory tube equivalent to the walls of the bit body. The plug flow of the center of the tube now becomes the mole-surrounding sedimentary mass, whose essentially infinite inertia means that all aspects of the flow take place near the boundary between the grains and the mole.

From an engineering perspective, the percussive mole design is similar to the driving of piles by impact hammers (Swedish Commission on Pile Research, 1999). The simplest pile driver is a drophammer, which consists basically of a solid mass of forged steel (1 000 to 5 000 kg) with a means of lifting, and lugs to facilitate its sliding downward again in a set of guides to hit the top of the pile squarely. Drop heights range from 0.2 to 2 m. The peak stress at the pile head (which corresponds roughly to the anvil portion of the mole) increases significantly without a corresponding increase in pile advance if the impact is eccentric. For this reason a long narrow hammer is preferred, making the impact more likely to be axial.

During the driving process, ground conditions dictate how the compressive stress waves produced at the pile head by the hammer impact are reflected from the pile tip (analogous to the nose of the mole). Under "easy" conditions, the wave reflects from the toe as a tensile wave. If the pile length is slightly longer than half the length of the stress wave, tensile stress may occur near the toe, increasing the likelihood of damage to the pile. Accordingly, when using drophammers in soft ground, the drop height is reduced, especially if the pile aspect ratio (length:effective diameter) is high.

Under "heavy" driving conditions, the initial compressive wave reflects from the upper end in compression, but may then be reflected as a tensile wave at the pile head if the hammer is not in contact with the pile head when the returning wave arrives. The resulting tensile forces can damage the pile. When dense layers or obstructions – such as boulders – are encountered, significant compressive stress can occur at both the pile head and toe.

EXPERIMENT SETUP

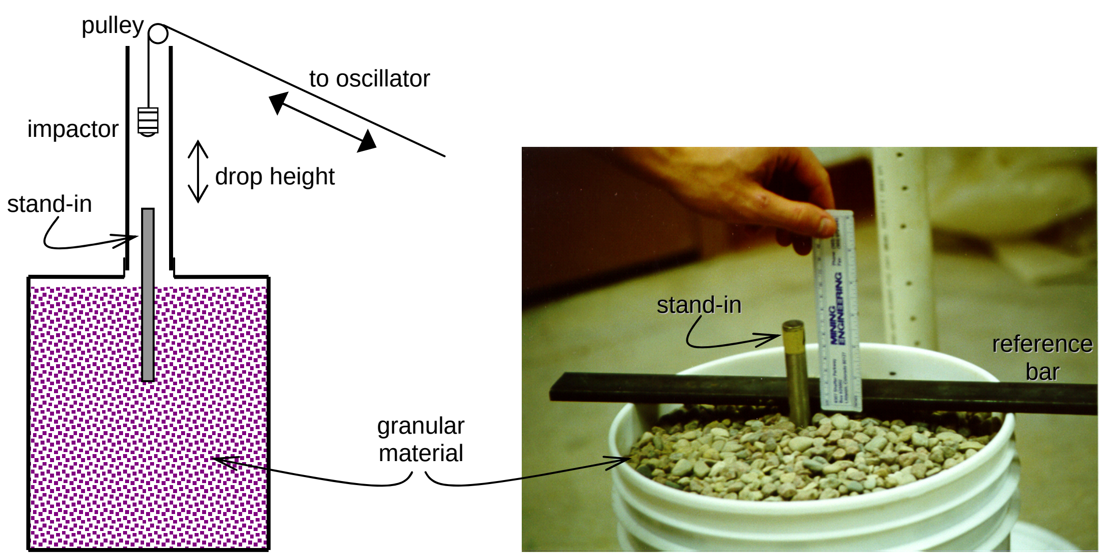
A series of experiments was performed to evaluate the relative advance rate characteristics through several unconsolidated granular materials of a simple physical stand-in for the mole. Most of the experiments were performed using a steel rod (1.6-cm diameter, 22.4-cm length) as the stand-in, although some early data were collected using a capped PVC tube of similar size and aspect ratio. The granular materials were selected to be mechanically representative of unconsolidated surface deposits, as well as inexpensive and easy to obtain (Table 1). All were air-dried; no special precautions were taken to measure or to maintain the atmospheric humidity during testing. The sand was coarse-grained and sub-angular to sub-rounded, while the pea gravel was well rounded. The grain sizes and shapes of the dry plaster fines were not characterized. The impactors each comprised a stack of steel washers of the appropriate number to total the required mass. They were not fastened to each other, and on impact with the top of the stand-in a minor amount of the kinetic energy from the fall was dissipated in low-amplitude bouncing of individual washers. An additional small amount of energy was lost to friction with the sides of the drop tower during the fall. These effects were considered negligible. During a test, the impactor was cyclically lifted and dropped by the action of a rotating or oscillatory arm that caught and released the string on which the impactor was suspended (Figure 1). The drop height varied during resets (see procedure below) from 7.5 to 17.9 cm; the average drop heights were 8.7 cm (dry sand), 8.0 cm (pea gravel), and 9.1 cm (mixed pea gravel and dry plaster fines).

The experiment protocol was developed through several equipment iterations, resulting in the following:

1. A 19-liter industrial plastic bucket is nearly filled with the granular material, packed in approximate 5-cm lifts.

TABLE 1. The Experiment Matrix. About Half the Cells of the Matrix Were Addressed by the 55 Tests Conducted.

Parameter	**#1**	**#2**	**#3**
Materials:	dry sand	pea gravel	pea gravel & dry plaster fines
Impact frequencies:	0.13 Hz	0.7 Hz	1.3 Hz
Impactor masses:	140 g	200 g	300 g



(**a**) Schematic Diagram (Scale Approximate).

(**b**) Measuring Initial Position of Mole Stand-In Prior to Starting Percussion in Pea Gravel.

FIGURE 1. The Experiment Setup.

2. At 10-15 cm from top of bucket, the stand-in is placed vertically in the center of the medium. The remainder of the bucket is filled and packed around it.
3. The stand-in height is measured in reference to a flat bar placed across the top of the bucket (Figure 1).
4. The reference bar is removed and the drop tower collar is attached to the bucket.
5. The drop tower is fitted to its collar above the stand-in.
6. The impactor is selected and suspended on a line that runs through a pulley at the top of the tower and attaches to a powered rotating or oscillatory arm.
7. The impact frequency is set with a variable resistor that controls the power supply to the motor.
8. The impactor is raised to the selected drop height above the stand-in, using an axial slit running vertically along the tower.
9. The motor is switched on and allowed to pick up and drop the impactor one hundred or two hundred times (one “reset”).
10. The rotator arm is stopped and the time, number of impacts, and change in stand-in height above the reference bar are recorded.
11. The apparatus is reset (Step 8) and another series of impacts (another reset) is recorded. The resets continue until the top of the stand-in is less than three centimeters above the reference bar. The typical test contains four to twenty resets.

It proved difficult to compact the medium evenly and to set the impact rate at precisely the same values for each test. This is reflected in some of the variation evident in the results, and is one reason that additional repeated tests would enhance the confidence of the results.

RESULTS AND DISCUSSION

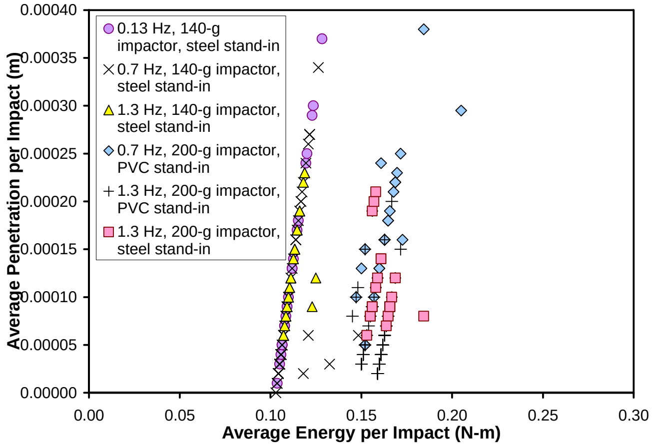
The most intriguing result is the unexpected segregation of the energy and penetration for each impact into discrete clusters. The characteristics of the rather tight straight lines that can be fit to these clusters do not vary significantly, yet the clusters are clearly separate from one another. Following this is a discussion of the families of three-dimensional surfaces that characterize the relationship of applied power to specific energy of advance to penetration rate. The clustering effect is less evident in these charts, though still present. Finally, the cumulative energy-penetration curves for some typical tests are presented, to illustrate the effect of the layered nature of the test materials on mole performance in unconsolidated granular media under low confinement. Each point in the charts below represents a single reset (see Experiment Setup), and is the result of averaging 100 to 200 impacts.

Applied Energy Versus Penetration per Impact

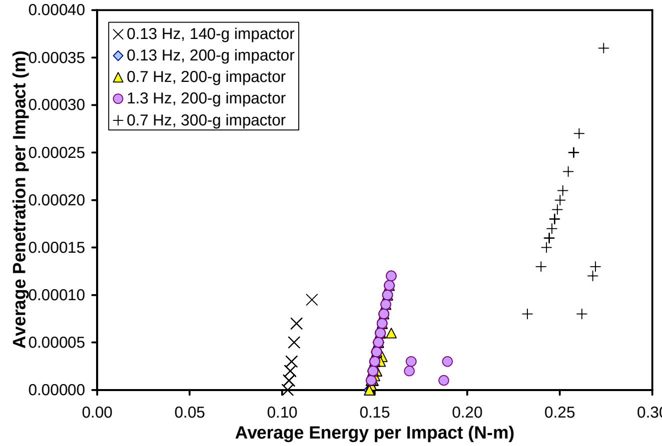
These plots of applied energy (N-m) versus penetration (m) per impact reveal a family of sub-parallel curves; the linear regression bestfit equations are shown for some of these.

These curves are all parallel or sub-parallel, and rather evenly spaced, suggesting a quantization phenomenon that likely reflects the interaction of experiment conditions with fundamental granular medium mechanics. The well-populated clusters consist of data from the steady-state portions of the tests, while the sparse clusters on their flanks are defined by data points from near the starts or, more often, the ends of tests. These latter points occur rightward of the main clusters; in other words, impacts during later resets achieve less penetration for the same impact energy than did those during previous resets. This may be due to partly the increased proportion of friction in the total resistance to advance as the rod goes deeper. It is particularly interesting that points from different tests (with different impact rates and/or different impactor masses) can occur in the same cluster. When some as yet unspecified state change occurs, the mole performance plots on a different cluster to previous data. Comparison of the inter-cluster gaps in Figure 2 indicates that their sizes may correlate positively to the average grain size of the material. None of the materials could be considered to have a mono-modal grain size distribution, however, so this does not fully explain the precise quantization effect.

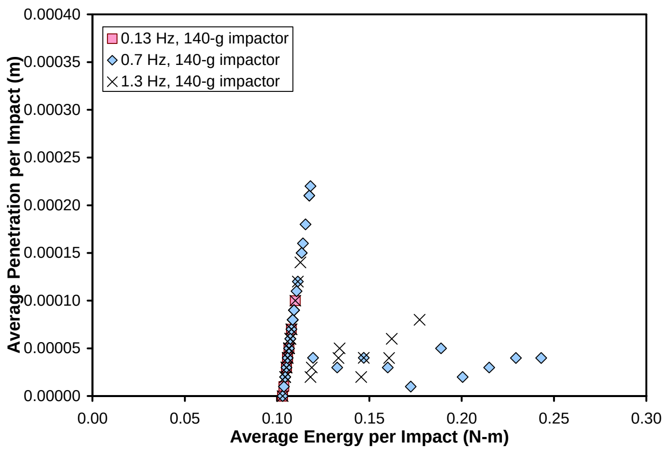
The schematic diagram in Figure 2 shows the sensitivity of penetration to applied energy within a given cluster. Clusters positioned farther to the right, though retaining the same sensitivity, must overcome a threshold energy level before applying work to penetration. Data from more massive impactors occur in clusters with lower basic penetration:energy ratios; in other words, toward the lower efficiency region of the chart.



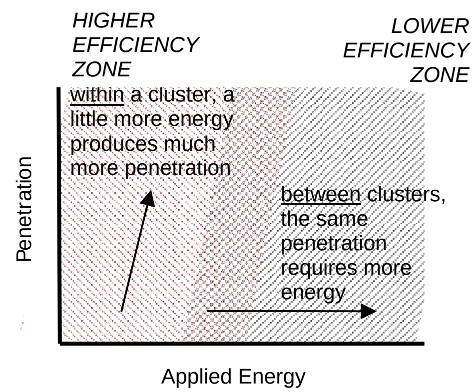
(**a**) Dry Sand.



(**b**) Pea Gravel.



(**c**) Pea Gravel Mixed with Dry Plaster Fines.



(**d**) Energy Efficiency Regions and Their Relation to Clusters.

FIGURE 2. Average Penetration per Impact Versus Average Energy per Impact. All Data Charts Use the Same Ranges.

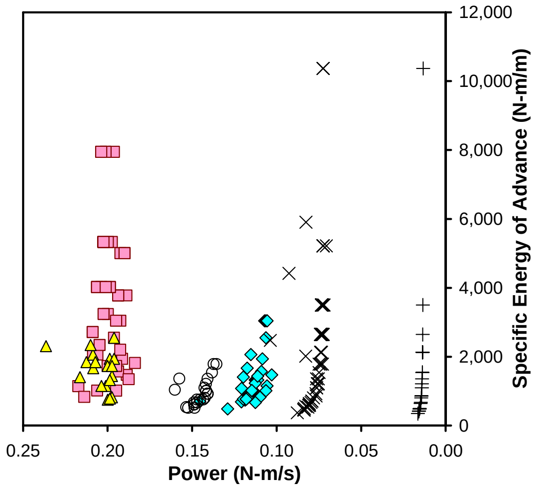
The pea gravel tests show the most variation, with the penetration:energy ratio falling to half of its value when the 200-g impact rate decreases from 1.3 Hz to 0.7 Hz. The 200-g 0.7 Hz impactor data is intermediate between the 300-g 0.7 Hz and the 140-g 0.13 Hz data. Yet this trend does not extend to the 200-g 0.13 Hz rate, which instead matches the 200-g 1.3 Hz rate. These variations are not apparent in dry sand or pea gravel / dry plaster fines.

These results indicate that we do not yet understand everything that governs the penetration:energy ratio even in controlled laboratory tests. This must be remedied before we can confidently predict advance rates or energy requirements for field drilling.

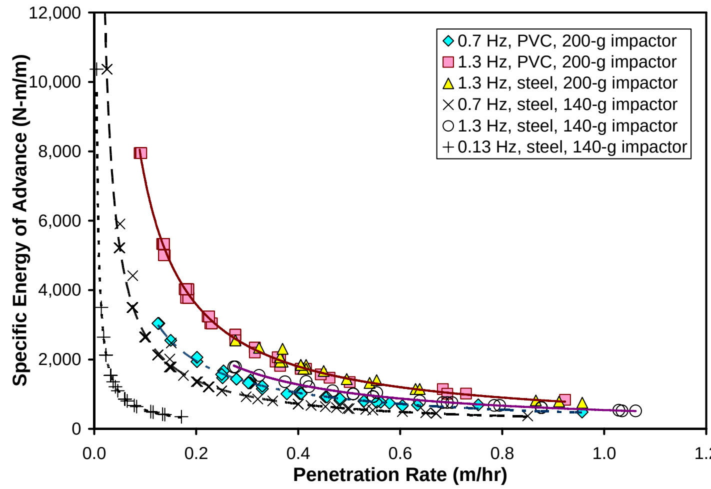
Average Power Versus Specific Energy Versus Penetration Rate

These plots of power (N-m/s) versus specific energy of advance (N-m/m) versus penetration rate (m/hr) are two-dimensional representations of a family of three-dimensional surfaces. A full chart group (Figure 3) consists of three plots (penetration rate – specific energy, power – penetration rate, and power – specific energy) sized so they can be fitted together as shown; a full chart group is shown only for the dry sand tests, to conserve space. Figure 4 shows the specific energy – penetration rate charts for pea gravel and for pea gravel mixed with dry plaster fines, to provide a means for comparison among the three materials. The family of nonlinear surfaces that has been generated for each material is characteristic of that particular material under relatively constant conditions (humidity, stress state, etc.). Specific energy of advance is the applied energy required to advance the mole through one meter of penetration. Obviously, at infinite specific energy, no advance is achieved, and the power requirements are zero.

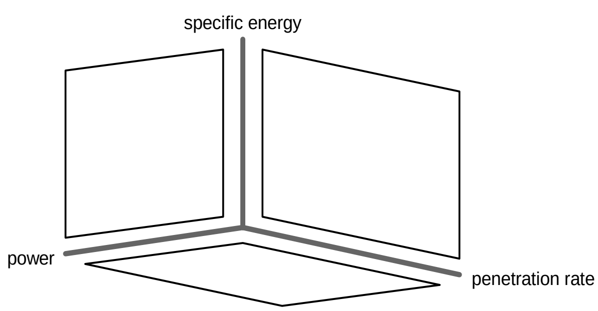
In general, these plots show expected trends: Higher applied power leads to lower specific energy of advance and increased penetration rates. Impact rate affects penetration rate more strongly than impactor mass does. Penetration rate is very sensitive to applied power, especially for the finest grain size. As power increases, its variance increases as well, due to the greater absolute losses due to dissipative mechanisms in the system, such as friction. Also, the sensitivity of specific energy to power increases, and the penetration rate increases, as power increases.



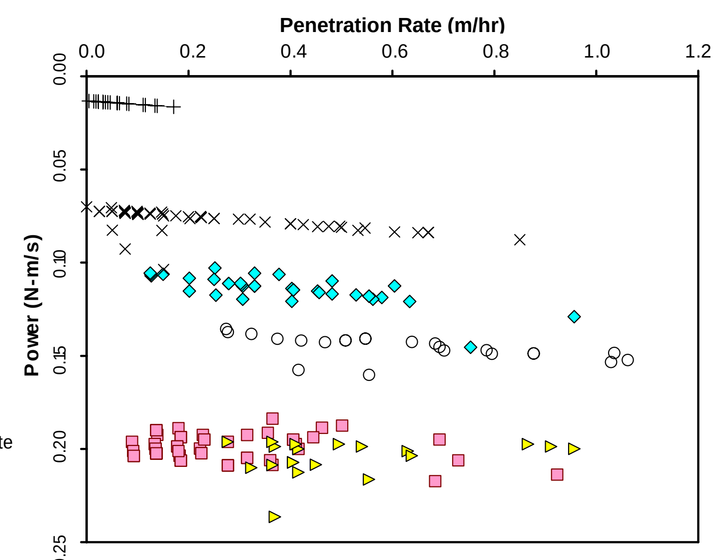
(**a**) Dry Sand Power Versus Specific Energy.



(**b**) Dry Sand Penetration Rate Versus Specific Energy.

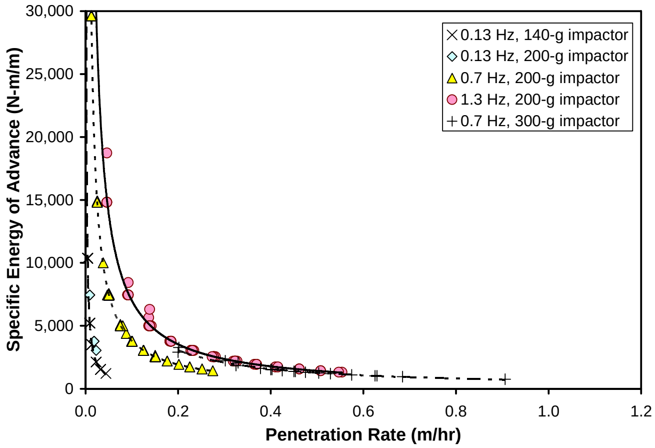


(**c**) Key to Three Dimensional Relation of Figure 3 Charts.

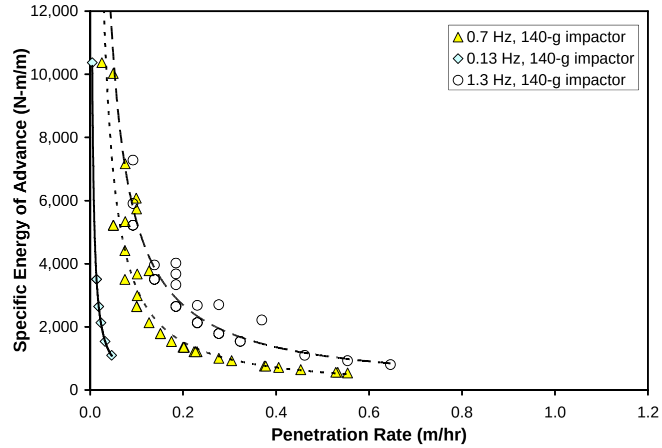


(**d**) Dry Sand Power Versus Penetration Rate.

FIGURE 3. Average Power Versus Specific Energy Versus Penetration Rate for the Dry Sand Tests



(**a**) Penetration Rate Versus Specific Energy for Pea Gravel. Note the Y-Axis Range is 2.5 Times Greater than (**b**).



(**b**) Penetration Rate Versus Specific Energy for Pea Gravel Mixed with Dry Plaster Fines.

FIGURE 4. Penetration Rate is Related to Specific Energy by a Power Law.

The stand-in material (steel rod vs. capped PVC tube) is shown to be of little relevance to the results by the dry sand data in Figure 3. There may be limits to the stand-in stiffness and density with respect to the granular material for which this holds true, however.

Cumulative Energy Versus Cumulative Penetration

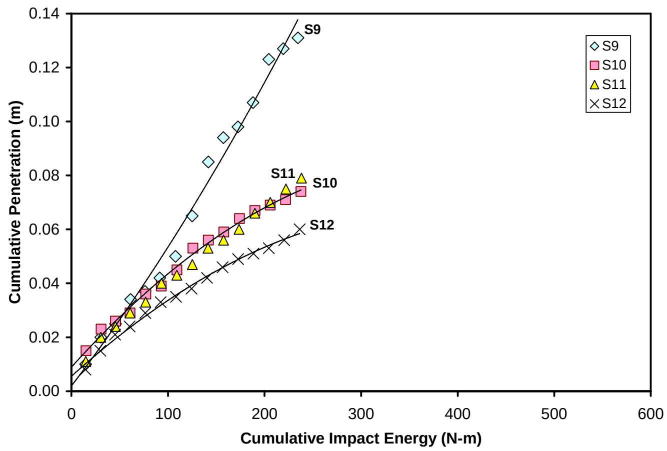
Many of the experiment results can be approximated by quadratic curves when plotted as cumulative data (energy in N-m versus penetration in m), as illustrated in Figure 5. Few of these curves actually intersect the origin; most y-intercepts are positive, indicating that the first few centimeters of advance during each test were relatively easier than the remainder. In other words, the specific energy of advance for the initial few centimeters of most tests is lower, due to initialization effects and low confinement, than it is later in the same test. The diminishing returns realized as impact energy is increased appear to be a realistic representation of soil and rock drilling performance.

Some of the data curves can be fitted by a cascading series of quadratic curves better than by a single quadratic curve (see for example test S9, Figure 5). This is likely an artifact of the layer method of filling the test container with the granular material, which is representative of natural sediments laid down by multiple deposition cycles.

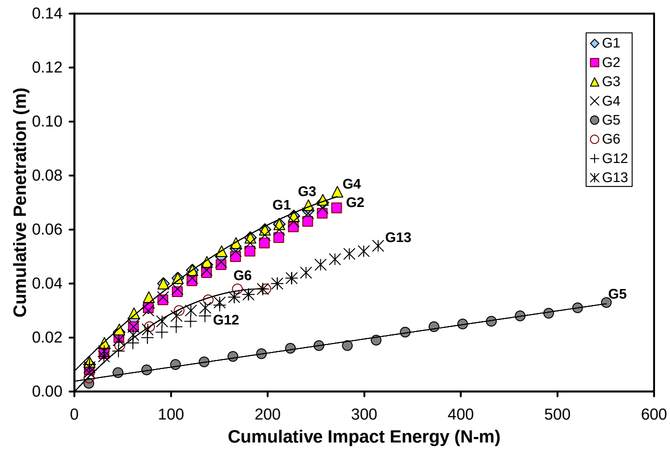
CONCLUSIONS

This study, though limited in scope, has shown that percussive drilling using a mole, or down-the-hole hammer, design may be feasible in unconsolidated regolith of limited size distribution near the ground surface. The data also reveal some aspects of the relationships among applied energy, modes of its application, some broad material characteristics, and the resulting penetration rate. An unanticipated finding is the existence of discrete clusters of penetration:energy ratios that are not confined to single materials, impact rates, or impactor masses. The fundamental cause of these clusters needs to be identified, but engineering design of drills can proceed.

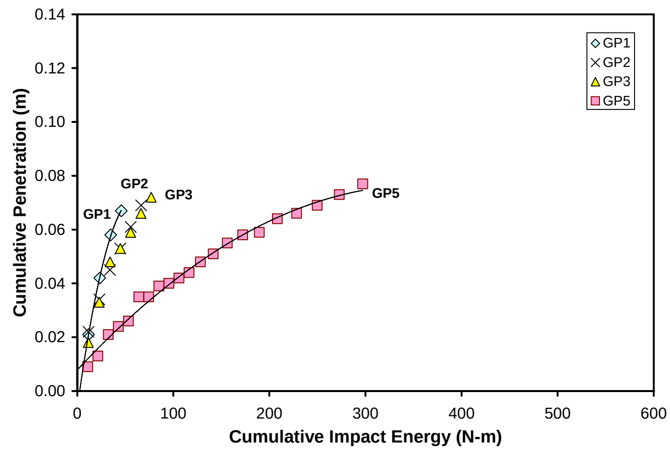
This type of study is a useful supplement to development and testing of field drilling systems, as it can advance understanding of the mechanisms involved and improve the ability to predict the consequences of drilling in untested materials. To this end, additional tests should be conducted in more materials, such as smooth and angular mill sands, and engineered mixtures of these materials, as well as several types of indurated materials (set-up plaster, set-up plaster with each of the unconsolidated materials as aggregate, harder grouts with and without aggregate, and



(**a**) Cumulative Impact Energy Vs. Penetration For Dry Sand.



(**b**) Cumulative Impact Energy Vs. Penetration for Pea Gravel.



(**a**) Cumulative Impact Energy Versus Penetration for Pea Gravel Mixed with Dry Plaster Fines.

FIGURE 5. Penetration Accumulates Quadratically from Impact Energy. Selected Tests Shown to Illustrate Trends.

basalt). These would simulate the more resistant materials that may be encountered on Mars. As well, the range of impact frequencies should be enlarged. Ultrasonic drills utilize much higher frequencies, and other research has shown some potentially useful effects at significantly different frequencies and accelerations (Nayagam and Sacksteder, 2006). The effect of confining pressure, which increases with depth of burial alone, in the absence of tectonic stresses, can be quantified with only a somewhat more complex test setup. And, finally, the number of tests should be increased to add confidence to the results.

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REFERENCES

Bar-Cohen, Y., Sherrit, S., Dolgin, B.P., Bao, X., Chang, Z., Pal, D.S., Krahe, R., Kroh, J., Du, S. and Peterson, T., "Ultrasonic/sonic drilling/coring (USDC) for planetary applications," in *Proceedings of SPIE's 8th Annual International Symposium on Smart Structures and Materials*, The International Society for Optical Engineering, Bellingham, WA, 2001, Paper No. 4327-55.

Beard, D.C. and Weyl, P.K., "Influence of texture on porosity and permeability of unconsolidated sand," *AAPG Bulletin*, **57**, 349-369 (1973).

Boucher, D.S., Richard, J., and Dupuis, E. "The Development of ISRU and ISSE Technologies Leveraging Canadian Mining Expertise," in proceedings of *Space Technology and Applications International Forum (STAIF-2003)*, edited by M. S. El-Genk, AIP Conference Proceedings 654, Melville, New York, 2003, pp. 1150-1156.

David, C., Menéndez, B., and Bernabé, Y., "The mechanical behaviour of synthetic sandstone with varying brittle cement content," *Int J Rock Mech Min Sci*, **35**/**6**, 759-770, (1998).

Dvorkin, J., Mavko, G., and Nur, A., "The effect of cementation on the elastic properties of granular materials," *Mech Mater*, **12**, 207-217, (1991).

Dvorkin, J., Yin, J., and Nur, A., "Effective properties of cemented granular materials," *Mech Mater*, **18**, 351-366, (1994).

Jaeger, H. M., "Chicago experiments on convection, compaction, and compression," in *Proceedings of the NATO/ASI Workshop on Dry Granular Materials*, NATO Advanced Study Institute series E, **350**, edited by H. J. Herrmann et al., Kluwer Academic Publishers, Dordrecht, Netherlands, 1997 (preprint at http://mrsec.uchicago.edu/granular/papers.html, accessed 2 October 2006).

Jeremic, M.L., *Ground Mechanics in Hard Rock Mining*, A.A. Balkema, Rotterdam, Netherlands, 1987, p 164.

Liu, Y., Weinberg, B., and Mavroidis, C., "Design and Modeling of the NU Smart Space Drilling System (SSDS)," in *Engineering, Construction, and Operations in Challenging Environments (EARTH & SPACE 2006)*, *Proceedings of the Tenth Biennial ASCE Aerospace Division International Conference*, edited by R.B. Malla et al., American Society of Civil Engineers, League City, TX, 2006.

Nayagam, V. and Sacksteder, K.R. "A Vibrofluidized Reactor for Resource Extraction from Lunar Regolith," in proceedings of *Space Technology and Applications International Forum (STAIF-2006)*, edited by M. S. El-Genk, AIP Conference Proceedings 813, Melville, New York, 2006, pp. 1101-1110.

Shenhar, J., Hill III, J., Lombardo, M., and Dolgin, B., "UTD Incorporated – Space and Terrestrial Drilling Innovation," in proceedings of *2nd Planetary and Terrestrial Mining Sciences Symposium*, edited by D. Boucher, Northern Center for Advanced Technology, Sudbury, Ontario, Canada, 2005 (paper 3-11).

Stoker, C.R., Lemke, L.G., Cannon, H., Glass, B., Dunagan, S., Zavaleta, J., Miller, D., and Gomez-Elvira, J., "Field Simulation of a Drilling Mission to Mars to Search for Subsurface Life," (2005) http://www.lpi.usra.edu/meetings/lpsc2005/pdf/1537.pdf, accessed 8 Sept 2006.

Swedish Commission on Pile Research, "Pile Info: Drop Hammer," (1999) http://www.geoforum.com/info/pileinfo/index.asp?)Lang=Eng, accessed 1 August 2006.

Wilcox, B., Personal communication, 1997.

Zacny, K., Bartlett, P., Davis, K., Glaser, D., Gorevan, S., and the CRUX Project Team, "Test Results of Core Drilling in Simulated Ice-Bound Lunar Regolith for the Subsurface Access System of the Construction & Resource Utilization eXplorer (CRUX) Project," in *Engineering, Construction, and Operations in Challenging Environments (EARTH & SPACE 2006)*, *Proceedings of the Tenth Biennial ASCE Aerospace Division International Conference*, edited by R.B. Malla et al., American Society of Civil Engineers, League City, TX, 2006.

Zhang, J., Wong, T.-F., and Davis, D.M., "Micromechanics of pressure-induced grain crushing in porous rocks," *J Geophys Res*, **95**, 341-352, (1990).