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Low Force Icy Regolith Penetration Technology

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Preface

Recent data from the Moon, including LCROSS data, indicate large quantities of water ice and other volatiles frozen into the soil in the permanently shadowed craters near the poles. If verified and exploited, these volatiles will revolutionize spaceflight as an inexpensive source of propellants and other consumables outside Earth's gravity well. This report discusses a preliminary investigation of a method to insert a sensor through such a soil/ice mixture to verify the presence, nature, and concentration of the ice. It uses percussion to deliver mechanical energy into the frozen mixture, breaking up the ice and decompacting the soil so that only low reaction forces are required from a rover or spacecraft to push the sensor downward. The tests demonstrate that this method may be ideal for a small platform in lunar gravity. However, there are some cases where the system may not be able to penetrate the icy soil, and there is some risk of the sensor becoming stuck so that it cannot be retracted, so further work is needed. A companion project (ISDS for Water Detection on the Lunar Surface) has performed preliminary investigation of a dielectric/thermal sensor for use with this system.

Introduction

Data from remote sensing and from the LCROSS mission indicate the existence of vast quantities of water ice and other volatiles in the lunar regolith, frozen into the permanently shadowed craters near the poles. This will be game-changing because of the magnitude and importance of such a resource outside Earth's gravity well. It will be important to ground-truth these findings by putting an instrument into the lunar regolith to measure the ice content directly. This will be difficult to do with a small-class or medium-class rover in the low lunar gravity because these platforms will not have adequate weight to provide the necessary downforce. In the Apollo program, astronauts found it extremely difficult to push tubes into the dense, frictional lunar soil in 1/6 G. It will be even worse as we take core samples, anchor onto, and mine asteroids and small moons like Phobos, or mine icy soil on the Moon. Low-force penetration systems will be mandatory in all these situations.

Prior work by Honeybee Robotics Spacecraft Mechanisms Corporation has shown that percussive cone penetrometers are capable of penetrating lunar regolith with only a small fraction of the force of an ordinary penetrometer. This study asks the question whether percussion is a suitable method to insert instruments into that regolith when it contains various quantities of water ice. We performed preliminary experiments to measure penetration resistance in lunar soil simulant with varying quantities of water ice. We also performed a demonstration of percussive penetration into a 1-meter deep column of ice and soil mixtures in layers of varying proportions. One meter is the expected depth to reach the ice beneath the desiccated upper layers of lunar soil. A companion study (ISDS for Water Detection on the Lunar Surface) has performed preliminary investigation of a dielectric/thermal sensor that may be inserted into the regolith by this percussive penetration method to positively identify lunar ice. This system combining the sensor with percussive penetration has to potential to provide the first-ever ground truth of vast quantities of dense ice layers in the lunar regolith.

Experiments

The experiments were performed jointly by Honeybee and NASA at the Kennedy Space Center (KSC). The percussive penetrator was provided and operated by Honeybee Robotics. The mixtures of lunar soil simulant and water ice were prepared by NASA/KSC. Descriptions of the hardware and experiments are provided below.

Percussive Cone Penetrometer

Originally we had planned to use both percussion and gas pulsing in the cone penetrometer. Further analysis of the icy soil mixtures indicated that gas pulsing was not an appropriate approach due to the low permeability of ice-impregnated lunar soil and due to its extremely high mechanical strength. Therefore, the gas pulsing approach was abandoned. For this effort, we used a percussive dynamic cone penetrometer originally developed under a separate Honeybee SBIR Phase 1 effort. In the configuration tested, this device delivers 2.6 Joules of percussive energy per blow at a frequency of approximately 1500-1750 blows per minute. This device was originally designed as a geotechnical instrument: By driving a cone into soil using a known percussive energy and recording the rate of penetration, soil strength can be derived. This device is shown in Figure 1.

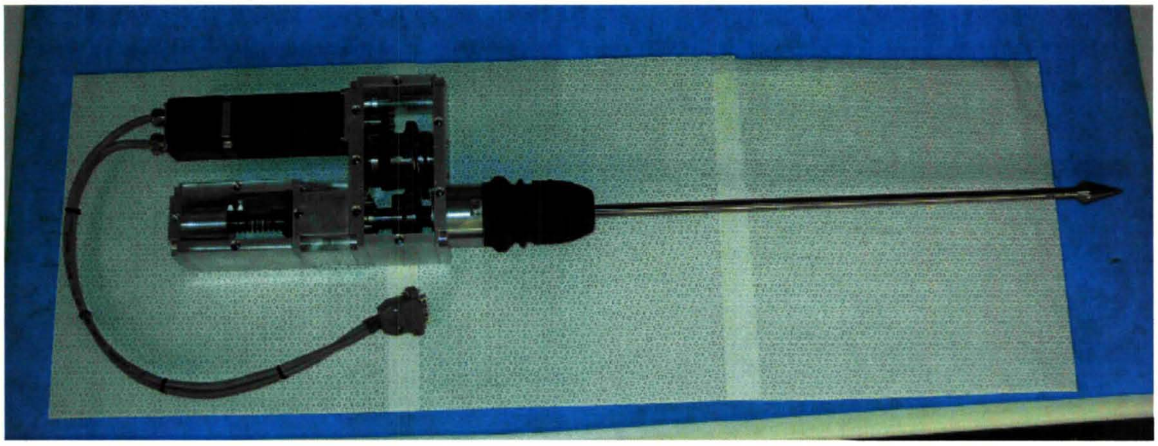

Figure 1. Honeybee Robotics percussive cone penetrometer.

Ice/Soil Mixtures

Lunar soil simulant JSC-1A was used in this project to represent lunar soil. Carrier et al [1991] have summarized the geotechnical properties of actual lunar soil without ice. The mechanics of JSC-1A without ice have been studied by Alshibli and Hasan [2009] and Zeng et al [2010]. The mechanics of the original version of this simulant, JSC-1, was reported by Klosky et al [2000]. No data have been returned from the Moon to indicate the mechanics of the soil with or without ice as it may be found in the permanently shadowed craters. Gertsch et al [2006] used JSC-1A in ice/simulant mixtures to experimentally study the resistance to a surface indentor (chipping the surface) and found that resistance is a strong function of ice content. They reported that ice concentrations of 0.6 to 1.5% by mass behave like weak shale or mudstone, whereas concentrations of 10.6% behave like strong limestone or sandstone and thus would be very difficult to excavate. Gamsky and Metzger [2010] used JSC-1A without ice on shake tables and in ovens and report that iceless regolith in the permanently shadowed craters may be less compacted than elsewhere on the Moon due to the lack of the strong, localized, diurnal quakes to shake down the soil and due to the lack of thermal cycling to directly compact it [Chen et al, 2006]. We are unaware of any other studies addressing soil mechanics in the permanently shadowed craters. The JSC-1A in this study was dried thoroughly in an oven and massed then monitored as it cooled and re-adsorbed humidity in the laboratory environment. The percent mass of adsorbed water was not significant, so pre-drying was not performed for further sample preparation. JSC-1A was mixed with water in percentages ranging between 0% and 8% by mass in 1% increments. The water/simulant mixtures were placed in layers into six 1-gallon cans (paint cans) as shown in Fig. 2 (left). Each can had three layers, the layer with the greatest moisture content at the bottom. Each layer was tamped to compact it as it was laid down. The moisture did not migrate significantly from their original layers to the adjacent layers due to the relative impermeability of JSC-1A and because they were quickly frozen. Freezing was performed to -60° C overnight. The cans were removed from the freezer for testing, and although some warming may have occurred, it should have been small relative to the freezing point of water due to the large bulk of frozen material. The cans are described in Table 1. A 1-meter tall column, shown in Fig. 2 (right), was prepared in a similar manner with ten layers. The first and every other layer were dry (0% ice). The interleaving layers were (from top to bottom) 2%, 4%, 6%, 8% and 10% water ice by mass, as shown in Fig. 3. It was frozen at -60° C overnight.

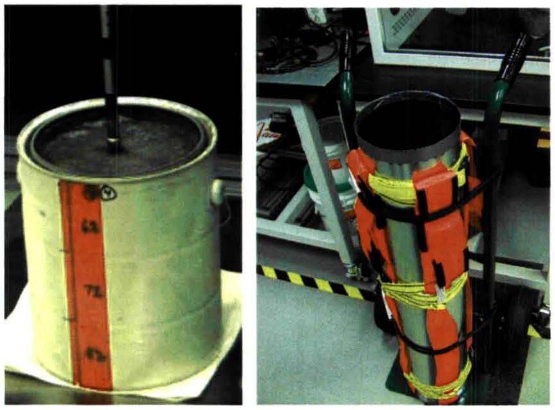

Figure 2. (Left) Ice/soil can. (Right) 1-meter column.

Table 1: Soil/Ice Sample Cans.

ID	Description	Result
Can #1	Three layers of icy regolith, each layer approximately 6 cm thick, 0%, 1%, and 2% water by weight from top to bottom.	Penetrated all three layers.
Can #2	Three layers of icy regolith, each layer approximately 6 cm thick, 2%, 3%, and 4% water by weight from top to bottom.	Penetrated all three layers, but more slowly than can #1.
Can #3	Three layers of icy regolith, each layer approximately 6 cm thick, 4%, 5%, and 6% water by weight from top to bottom.	Penetrated the 4% layer and halfway through the 5% layer. Increased frequency did not renew progress.
Can #4	Three layers of icy regolith, each layer approximately 6 cm thick, 6%, 7%, and 8% water by weight from top to bottom.	Penetrated the 6% layer and halfway through the 7% layer. Increased frequency did not renew progress.
Can #5	Pure water ice.	Penetrated very quickly.
Can #6	Three layers of icy regolith, each layer approximately 6 cm thick, 8%, 9%, and 10% water by weight from top to bottom.	Penetrated approximately 5 cm into the 8% layer.

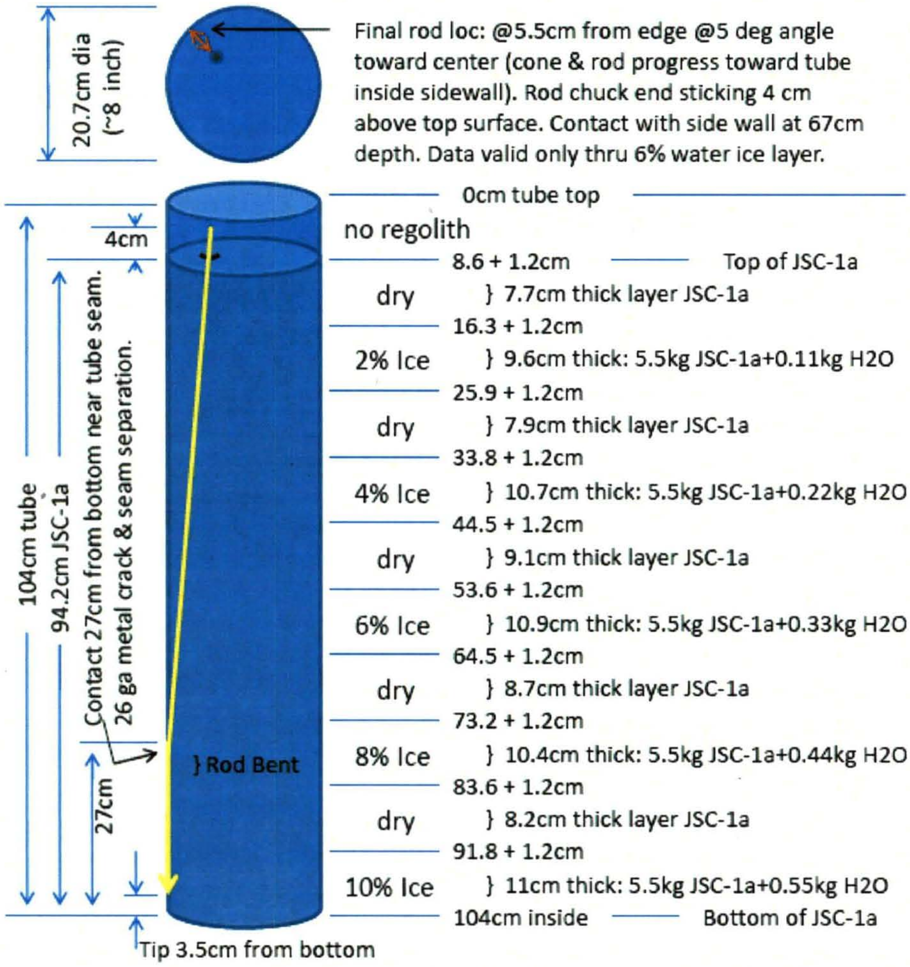

Figure 3. One-meter icy/soil column with final position of penetrometer.

Procedure

The cone penetrometer was held as shown in Fig. 4 with the cone tip touching the sample can. On some occasions, an effort was made to push it into the icy regolith without percussion but with moderate downforce provided by the operator. For all samples, percussion was activated, providing 2.6 Joules per blow at about a 15 Hz repetition rate. Each can was penetrated using only the 61.7 N weight of the penetrator for downforce or sometimes using additional downforce provided by the operator pushing down on the penetrometer's handles. In each case the can was sitting on an Acculab electronic mass scale, which provided a measurement of the downforce. Each penetration event, including the reading of the mass balance, was video recorded. The rate of penetration was obtained post-test by observing the length indicators on the shaft of the penetrator as they entered the ice/simulant mixture.

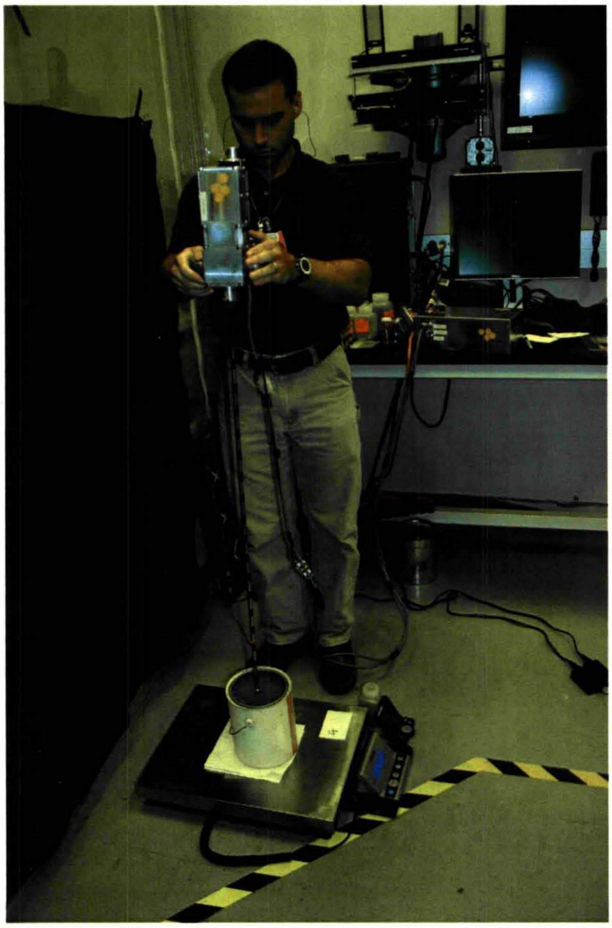

Figure 4. Penetration into sample can

Results

Penetration into cans #1 and #2, which had ice contents between 0% and 5% by mass, was not difficult. The percussive penetrator made progress under its own weight. The speed of penetration decreased as the percent water content increased.

In the case of can #3, the percussive penetrator acting under its own weight achieved a maximum depth of 7.5 cm, passing through the top layer and some portion of the second layer before progress halted. The top few centimeters of icy regolith was broken into chunks as the cone passed through it. Increasing down force was then applied by the operator. No further progress beyond this was possible with only operator applied weight. Video shows that the sheet metal top surface of the mass scale was vibrating in response to the sample can. It is possible that this motion rendered the percussive cone less effective by absorbing some of the percussive energy. To investigate this, the can was moved to the floor next to the scale. The percussive cone was operated with a large down force applied from 2 people amounting to about 750 N. There was a small, barely perceptible additional penetration. This was also tried with the can back on the scale to measure the load with no further cone penetration noted. Penetration into the third layer, 6% ice, was not achieved. Figure 5 shows the depth versus time profile for can #3, obtained from post-test video analysis. Figure 6 shows the downforce versus time profile.

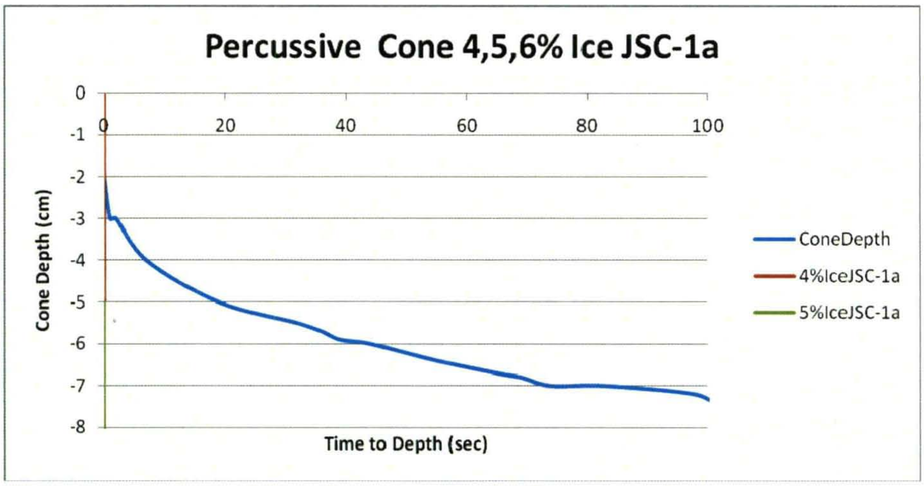

Figure 5. Penetration depth versus time for sample can #3.

Figure 6. Downforce versus time for sample can #3.

Can #4 performed similarly to can #3. The cone acting only under its own weight penetrated the first layer at 6% ice and a portion of the second layer at 7% ice. Additional down force was applied momentarily at ~300 seconds to see if further progress could be made. Minor additional penetration was achieved. After this the percussor frequency was increased to maximum without significant added penetration progress. Video shows that the sheet metal top surface of the mass scale was vibrating in reaction to the sample can. It is possible that this motion rendered the percussive cone less effective by absorbing some of the percussive energy. Figure 7 shows the penetration depth versus time for can #4, and fig. 8 shows the downforce versus time. Figure 9 shows the fracturing of the sample's surface.

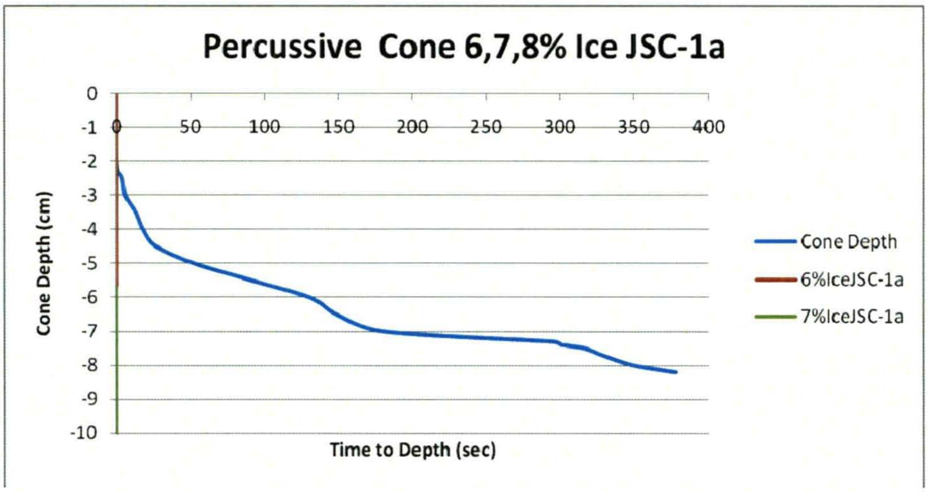

Figure 7. Penetration depth versus time for sample can #4.

Figure 8. Downforce versus time for sample can #4.

Figure 9. Fractured surface of can #4. Shaft demonstrates depth of penetration.

In the case of can #5 with 100% water ice (no simulant), the penetrator fractured the ice, and the resulting large pieces moved apart or slid past each other as the cone moved deeper into the target. The cone penetrated to the bottom of the can much more quickly than it had penetrated the different mixtures that contained lunar soil simulant. Figure 10 shows the fractured surface of can #5.

Figure 10. Fractured surface of can #5 with 100% water ice.

In the case of can #6 with 8% and higher water ice, the cone penetrated the surface but it did not do so by fracturing the top layer of icy regolith into chunks as before. The hole that the cone created in the icy regolith had very clean sides. Powdered material was observed on top of the target's original surface, and this powdered material could be brushed aside to reveal the original surface. From this, we infer that the cone was pulverizing icy regolith and ejecting it from the resulting borehole though the force of its own vibration. When the borehole became too deep for the pulverized material to be ejected, progress came to a halt.

For the 1-meter column, the cone penetrated its entire length to a depth of 90.7 cm. The rate of penetration varied, and was observed to correspond with the layering as shown in Fig. 11, where the slopes of the fitted linear segments are the penetration rates. The 8% slope is not valid since the cone was on the container sidewall and the container was splitting, relieving the soil's stress. However, the penetrator did not maintain a straight vertical path, and struck the side of the column 67.2 cm below the surface, or 2.6 cm into the 8% layer. We were unable to extract the penetrator from the frozen soil after driving it in to its full depth. Figure 12 shows the top surface (unfractured) with the rod still embedded in the icy regolith after the percussive penetrometer was de-attached.

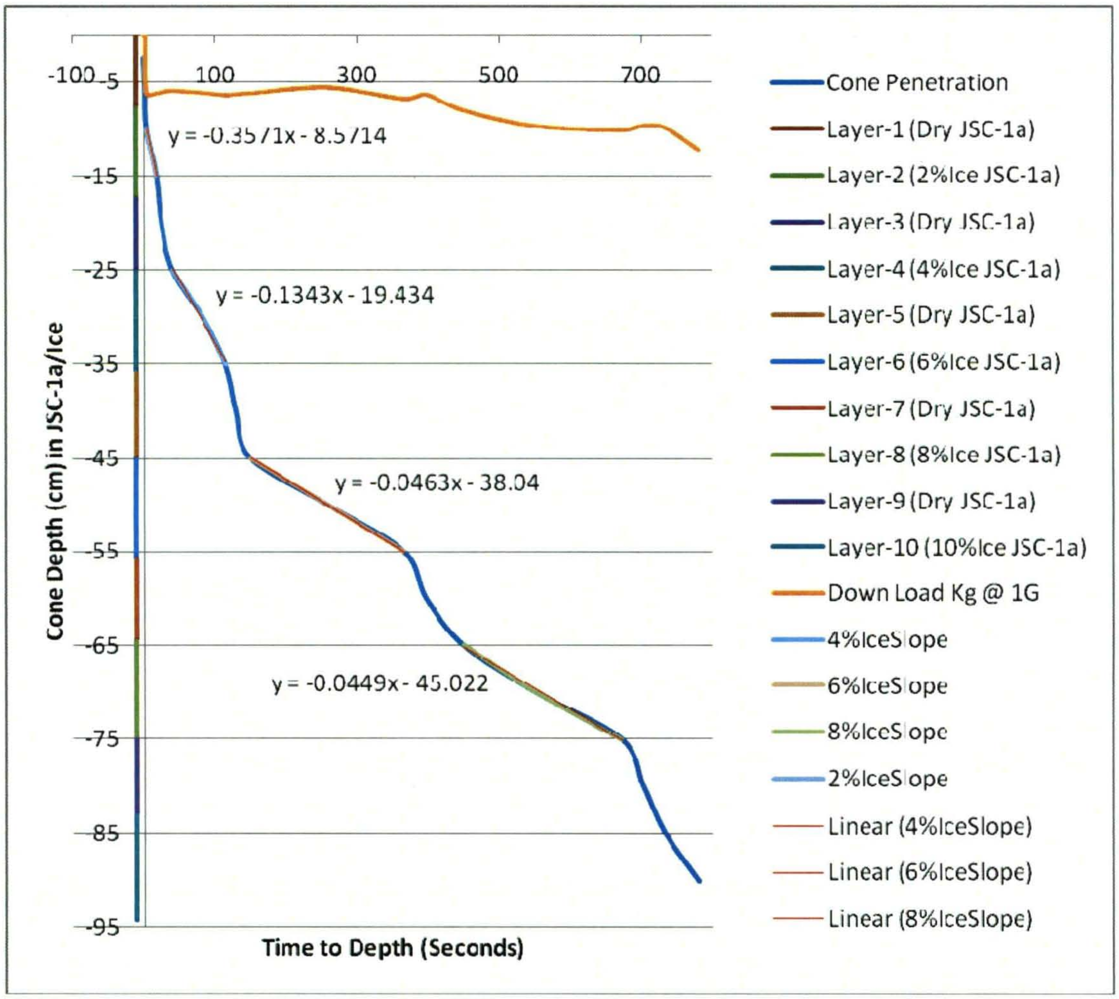

Figure 11. Depth of penetration and downforce versus time for 1-meter column.

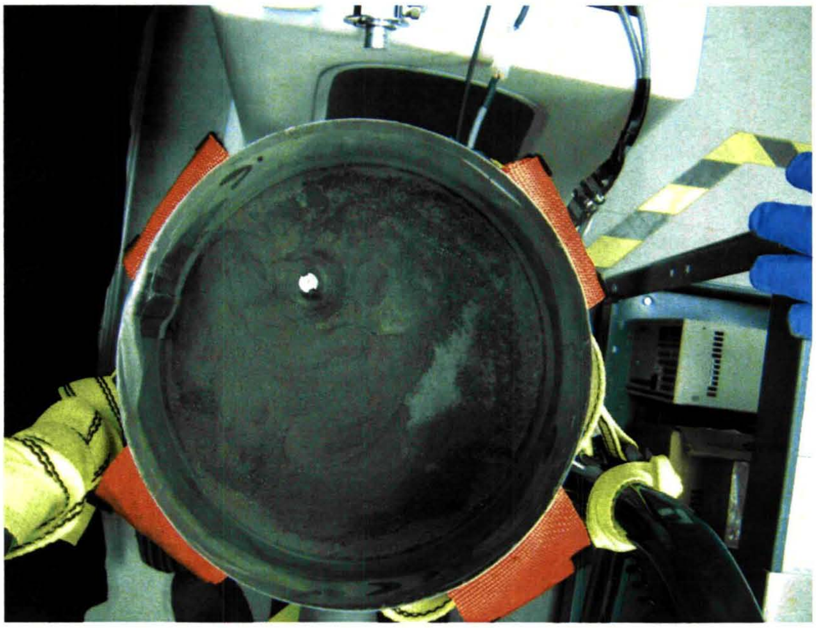

Figure 12. Top surface of 1-meter column with embedded penetrometer rod.

Discussion

Ice Content

In general we find as expected that, in the range of 0% to 10% ice content by mass, the greater ice content is more resistant to penetration. However, it is interesting that the top layer of can #4 with 6% ice could be penetrated, whereas the second layer of can #3 with only 5% ice could *not* be penetrated. Thus, we found that it is not simply the percentage of ice that matters, but whether the fracturing ice has room to move into the surrounding volume. In the case of top layers, there was always room at the free surface for fractured chunks of ice to move upward. In the second and deeper layers of the cans, the ice could not always fracture and move. Thus, a lower percentage of ice at depth could resist penetration whereas a higher percentage of ice at the surface could not.

The mechanics are apparently different than the case of penetration into dry regolith. Dry regolith is free to rearrange at the grain-scale to make room for the penetrator. The strain field of cone penetration into ordinary, terrestrial sands and soils has been studied in detail (see for example [*Tumay at al*, 1985] and [*Acar and Tumay*, 1986]), indicating soil motion (of decreasing amplitude) at long distances from the cone. Furthermore, comminution of the individual grains allows their material to move into the pore spaces between other grains, increasing the bulk density of the material around the penetrometer to make the room. For frozen soils, however, the grains cannot move individually, and comminuted material may not be able to move into pore spaces between neighboring grains. Therefore, to make room for a cone and rod, the frozen soil must exhibit a combination of pulverization with powder removal and fracturing with relative motion of the fractured domains. As long as the cone is near the surface of the icy regolith, powder could exit the downshaft around the sides of the rod, and likewise near the surface the fractured domains could move upward above the free surface of the sample.

For the small sample cans with three layers of icy/soil mixture, when the ice content was sufficiently high the cone could not penetrate through the second layer because it was trapped between the overlying and underlying frozen layers. For sample cans #1 and #2 this was not a problem. Presumably the low ice content did not stop the soil from deforming at the grain scale to densify within each layer, or to push into the neighboring layers that then deformed at the grain scale to absorb the additional volume of material. Therefore, it appears that the transition in penetration mechanics occurs somewhere in the range of 3% to 5% ice content by mass.

For sample can #5 with 100% water ice, the soil did fracture but was able to rearrange all the way to the bottom of the can, permitting the penetrator to reach the bottom. Apparently, the ice has less friction than an ice/regolith mixture, and thus the fractured chunks even deep in the can are able to push the fractured chunks above them out of the way.

For the case of the 1-meter column, the fractured domains could make room by expanding into the interleaving dry layers of regolith. A fractured domain expanding into neighboring space would presumably experience more resistance if it were moving into dry regolith than if it were moving into empty space above the free surface of the sample, as was the case with the top layers of the smaller sample cans. However, the dry regolith did not produce enough resistance to stop this penetration as evidenced by the cone passing successfully through layers of up to 10% ice. To make room for adjacent fractured domains, the dry regolith layers must have densified through the ordinary processes discussed above for cone penetration. However, in this experiment only half the volume of the column was dry regolith whereas the other half was icy. Half the domain must have been adequate to absorb the full volume of the penetrating cone and rod.

Based on these results, it is likely that bulk volumes of greater than 4-6% ice (by mass) will be resistant to percussive cone penetrometers unless a method is developed to remove pulverized material. Fortunately, the instrument that will go onto the cone, which is being developed in the companion project, is capable of detecting and measuring ice content at concentrations less than these values. Also, since the percussive penetrometer can always penetrate at least the top few centimeters of material higher than 4-6% (since the fractures can expand upward into the material that has less ice), the system is guaranteed to enter at least that concentration of ice even if no modifications are made. If the lunar ice lies beneath a meter of desiccated soil, or soil that contains less than 4-6% ice, or layers less than a few centimeters thick of any concentration interleaved by layers less than 4-6% ice, then the system will successfully pass through it to the bulk quantities of more concentrated ice. In any case, when it finds the bulk of the more concentrated ice, it should penetrate several centimeters. Therefore, the delivery method appears to be successful but with room for increased performance.

Penetration Rate

The penetration rate was not a strong function of downforce. In most cases it was a strong function only of the ice content. Therefore, penetration rate may serve as a useful secondary measurement of ice content to corroborate what is measured by the primary instrument. By comparing the primary instrument's findings with the penetration rate, it may also be possible to back out information about the compaction of the soil and thus the volume of pore space not occupied by frozen volatiles. This may support analysis of the permeability of the regolith and modeling of ice stability and transport mechanisms.

It makes sense that penetration rate would be dependent on ice content. The ice must be fractured or pulverized to permit movement of material to admit the cone. The more volume ice there is bonding the soil grains together, the more energy that must be expended to break those grains apart. Thus, more percussive blows are needed to free equivalent volumes of regolith when there is more ice. Penetration could be sped up by increasing the percussion rate, but (as seen with can #4) if the blows are incapable of moving material, then increasing their frequency will not restore motion.

On the other hand, toward the bottom of the 1-meter column, increased downforce did help penetration (see "Download" curve on Fig. 11). This might be because the fracturing ice layers deep in the column needed to be mechanically pushed into the neighboring volumes of dry regolith. Because the large chunks would be moving dry regolith far away from the percussing cone, their motion relied upon the direct downforce. Thus, there is additional information available by analyzing both downforce and penetration rate together that may indicate the structure of ice layers beneath the surface.

Retracting the Rod

In the one test with the 1-meter column, the rod could not be retracted. This may have been due to the fact that the rod became bent as it struck the wall of the column, but other factors may have contributed. For example, the base diameter of the cone is larger than the diameter of the rod, and compacted JSC-1a can exert high friction on a rod that has been driven into it. There is also some concern that ice could freeze to the cone or shaft. The instrument on the cone will have a heater element to enable volatilization of the ice as a part of measuring its concentration. The heater element could serve a secondary function of de-icing the regolith around the cone or shaft to help free it. Also, the team has indentified mechanical changes to the design of the system to enable easier retraction.

Summary of Findings

1. A percussive cone can penetrate icy regolith at ice concentration layers that a static cone cannot penetrate. The percussive penetrator was able to penetrate material under 65 N of downforce that the static cone could not penetrate under full body weight.

2. The percussive cone could penetrate:
    a. 100% water ice (-60 C);
    b. dry soil that is compacted and cold (-60 C);
    c. ice/soil mixtures up to 4-6% ice by weight (note that 5% ice is more resistant than 100% ice) with much less resistance than non-percussive;
    d. mixtures with 6% and 8% ice as long as there is a free surface above the layer to allow the icy chips room to move;
    e. a little more than a cone-length into the top surface of mixtures that have 8% or more ice;
    f. completely through layers of 8% ice as long as they are interleaved with dry layers to allow the icy chips room to move.

3. These percentages of ice are within the range that can be detected by the sensor developed in the companion project, "ISDS for Water Detection on the Lunar Surface." Therefore, the system is capable of penetrating deeply enough into the regolith to detect ice.

4. The ability of a percussive cone to displace material affects its ability to penetrate material. The device proved capable of penetrating material with 8% ice, but did not penetrate very far because it could not displace the resulting chip. A certain amount of material must be displaced for the cone to advance.

5. Increased downforce on the percussive system did not result in increased penetration capability. In hard material, the percussive penetrator made no more progress under 750 N than it did under 65 N. This suggests that increasing the energy delivered in each percussive blow would be a more effective than increasing downforce for penetrating stronger materials. When the ice

is too dense, pushing harder will not make it penetrate. The percussive system either penetrates or doesn't.

6. There may be cases with layers of ice interleaved by dry regolith in which increased downforce helps move the fractured ice and thus increases penetration rate, but this condition is not the baseline expectation for lunar regolith. If such a condition does exist on the Moon, then it can be detected by measuring both penetration rate and downforce to corroborate other instruments on the cone.

7. A percussive cone can become stuck in frozen regolith. For anchoring, this is beneficial. A rod driven in under 65N (15 lbs) of downforce could not be pulled out with at least that much force. For repeated probing, this must be addressed.

Conclusions

This investigation successfully demonstrated percussive penetration of regolith with varying ice concentrations. It demonstrated that percussive penetration is feasible in situations where non-percussive is not. It successfully demonstrated penetration to a meter in depth, which is the expected depth to lunar ice. It demonstrated that the device is capable of entering ice concentrations that are easily within the measurement range of instruments that will go on the cone. This serves as experimental proof-of-concept of the critical function, and so percussive insertion of lunar ice instruments has now achieved Technology Readiness Level 3.

The experiments developed preliminary correlation data between penetration rate and ice content, and thus the data from the penetration process can be used to corroborate the findings of another sensor. This project also produced insights into the mechanics of the penetration resistance of ice and ice/soil mixtures. It provided an opportunity to develop and test methods to prepare ice/soil mixtures for mechanical testing. It provided insights into how to improve the test stands and hardware. It also indicated a number of modifications that may be made to improve the penetration system, which will be the subject of on-going projects.

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14. ABSTRACT Recent data from the Moon, including LCROSS data, indicate large quantities of water ice and other volatiles frozen into the soil in the permanently shadowed craters near the poles. If verified and exploited, these volatiles will revolutionize spaceflight as an inexpensive source of propellants and other consumables outside Earth's gravity well. This report discusses a preliminary investigation of a method to insert a sensor through such a soil/ice mixture to verify the presence, nature, and concentration of the ice. It uses percussion to deliver mechanical energy into the frozen mixture, breaking up the ice and decompacting the soil so that only low reaction forces are required from a rover or spacecraft to push the sensor downward. The tests demonstrate that this method may be ideal for a small platform in lunar gravity. However, there are some cases where the system may not be able to penetrate the icy soil, and there is some risk of the sensor becoming stuck so that it cannot be retracted, so further work is needed. A companion project (ISDS for Water Detection on the Lunar Surface) has performed preliminary investigation of a dielectric/thermal sensor for use with this system.

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