Robotic Lunar Geotechnical Tool

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ABSTRACT

Rover-mounted geotechnical systems are of paramount importance to lunar trafficability assessment, construction, and excavation/mining toward establishing permanent human presence on the Moon. These tools can also be used to determine density, when the regolith is used as radiation shield, for example. Two popular in-situ devices for establishing geotechnical properties of soil are the Static Cone Penetrometer (SCP) and Dynamic Cone Penetrometer (DCP). However, both systems have shortcomings that may prevent them from being robotically-deployed in a low gravity environment. In this paper we describe an alternative system, called the Percussive Dynamic Cone Penetrometer (PDCP) that can be used to robotically-measure geotechnical soil properties in a low gravity environment. It is shown that PDCP data correlates well with the data obtained from both SCP and DCP testing, and by extension with California Bearing Ratio (CBR) and soil bearing strength.

ACRONYMS

ATHLETE: All-Terrain Hex-Legged Extra-Terrestrial Explorer
CBR: California Bearing Ratio
CI: Cone Index
DCP: Dynamic Cone Penetrometer
ISRU: In-Situ Resource Utilization
PDCP: Percussive Dynamic Cone Penetrometer
SRP: Self-Recording Penetrometer
SCP: Static Cone Penetrometer

INTRODUCTION

The planners of the 1960's and 70's lunar landing missions recognized the importance of measuring the geotechnical properties of the lunar regolith and included instrumentation for that purpose. During the Apollo missions, astronauts used a Self-Recording Penetrometer (SRP) to measure geotechnical properties of the top 74 cm of lunar soil (Costes, 1973), while the Soviet Lunokhod rover missions had a cone-vane penetrometer for measuring geotechnical properties of soil down to 10 cm (Cherkasov and Shvarev, 1973).

Knowledge of lunar regolith geotechnical properties is of practical importance to trafficability, construction, and excavation/mining operations. For the purpose of trafficability, near-surface strength measurements will help with rover wheel design; not only to prevent dangerous conditions, such as the rover becoming stuck or slipping, but also to make traverses more energy efficient. For the purpose of construction, the strength of the layers below the surface will drive the placement, size, and depth of foundations. For mining and excavation purposes, knowledge of soil strength will help to establish preferred excavation protocols, size the excavators' scoops or blades, and estimate energy requirements. Alternatively, excavation sites with less dense soils, and in turn soils that are easier to excavate, could be identified.

There are many historical instances indicating that the lack of geotechnical soil properties could have, or in fact had, severely affected mission operations. A few examples include: (1) In the 1960's, due to the lack of quality information about the lunar surface, there was some concern that the first Apollo lander would catastrophically sink into the regolith. (2) During one of its traverses, the Apollo Lunar Roving Vehicle (LRV), actually became bogged down in the soil and the astronauts had to lift the vehicle and move it onto firmer ground (Kring, 2006; Carrier, 2008). (3) One of the Soviet Lunokhod rovers had to make a 90º change in course after encountering wheel sinkage up to 200 mm (Carrier, 2008). (4) Earlier in the mission, the Opportunity rover became stuck in a "sand trap" but was eventually able to free itself. (5) The Mars Exploration Rover (MER) Spirit is currently stuck in a "sand trap". Although extrication attempts are ongoing for Spirit, there is considerable doubt whether the rover will be able to free itself and drive onto firmer ground. Each of these instances could have been prevented through a more in-depth understanding of the terrain.

The plan to send humans back to the Moon for long-term stays only increases the importance of understanding soil properties. This is especially true for NASA's new lunar mission architecture. The original Lunar Architecture Team, phase 1 concept was to establish a lunar outpost and then send astronauts for short- and long-duration stays (**Figure 1**). Astronauts could then use the rovers to move across the lunar surface. At the end of the day they would return to the lunar base. The new Lunar Architecture Team phase 2 (LAT 2) Option 4 approach, however, uses a "caravan" approach (Kennedy, 2008; Toups, 2008). In this scenario, the ATHLETE (All-Terrain Hex-Legged Extra-Terrestrial Explorer) (Athlete, 2009) and Chariot (2009) mobility systems would transport habitats from one location to another. Once the new base is established, astronauts would then be sent for short- or long-duration stays. After completing a number of required tasks, astronauts would return to earth, while the "caravan" would move to a new location (**Figure 1**). In the latter scenario, it would be imperative to have smaller rovers with geotechnical systems scouting ahead of the large rovers to find the best paths to new destinations. The same rovers could be used for surveying sites to identify potential outposts, determine optimum launch pad locations, and identify the soil that would be easiest to mine for in-situ resource utilization (ISRU) purposes.

All of the plans involving the construction of human habitats, laboratories, mining operations, transportation and their related infrastructure, will depend on geotechnical knowledge of the lunar regolith. It will provide baseline information and experience to prepare for what will be needed for the future exploration of the Mars' surface.

Note also that from scientific standpoint, soil physical properties may be used to help interpret surface geological processes and to constrain the possible origins and formation processes of the lunar soils. Geological examination of the near subsurface will increase understanding of the formation and history of the Moon.

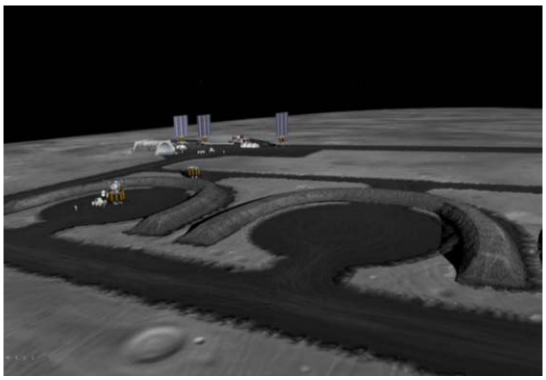

Figure 1. Artist's renditions of lunar bases. A more permanent base is shown on the left, while a mobile base is shown on the right. Geotechnical tools could be used to assess the quality of blast protection berms, launch pads, and radiation shielding on top of human habitats, as well as trafficability of soil prior to proceeding to the next outpost site and density of soil prior to excavation for ISRU purposes. Images courtesy of NASA.

HISTORY OF LUNAR SURFACE SOIL STRENGTH MEASUREMENT INSTRUMENTS

Self-Recording Penetrometer Used on Apollo 15 and 16 Missions

The SRP was essentially a rod with a cone or a plate at the end that astronauts pushed into the regolith (**Figure 2**). The depth of penetration was recorded by a scriber on a metal cylinder in the upper housing assembly. The drum rotation was proportional to the amount of force exerted on penetrometer. The independent motions of the drum and stylus produced a continuous force-depth curve on the surface of the drum. (Carrier et al., 1991).

The SRP used 12.8 and 20.3 mm diameter cones (cone areas of 129 mm^2 and 323 mm^2, respectively) attached to the end of the rod that was pushed into the soil to an approximate depth of 20 to 74 cm (deeper in softer soils), as shown in **Figure 3**. The Apollo suit weighed 22 kg and its Portable Life Support System (PLSS), 26 kg

(Wade, 2009). Thus, Apollo astronaut, weighing ~128 kg could apply ~200 N force before lifting himself off the surface. Robotic platforms would have to weigh much more to respond with these kinds of forces, because penetrometers or drills are normally deployed from the side of the platforms and in turn away from platforms' center of gravity (CG). A total of 17 cone and plate tests were performed on the Apollo 15 and 16 Missions (Mitchell and Houston, 1974). A maximum depth of 74 cm was reached using the smallest cone (12.8 mm diameter) and only 8 tests penetrated deeper than 20 cm.

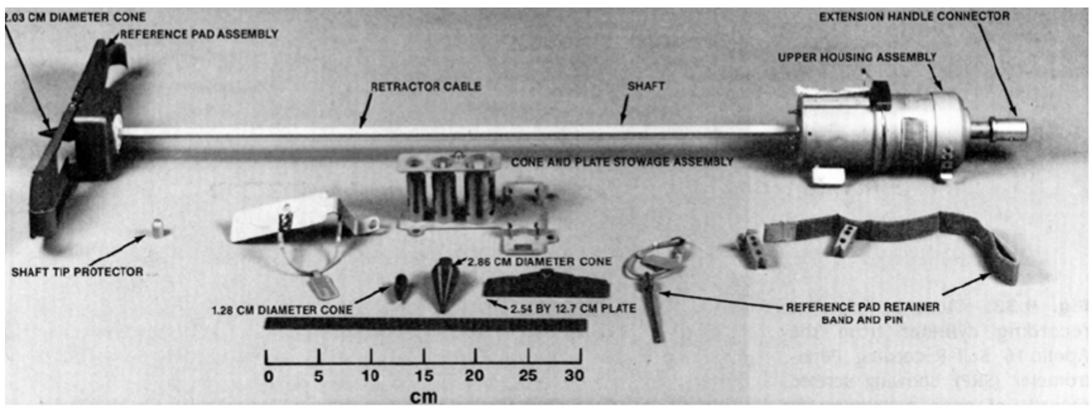

Figure 2. The SRP was used on the Apollo 15 and 16 missions. The astronauts pushed cones of two different diameters (12.8 and 20.3 mm) and a plate (2.54 × 12.7-cm) into the surface. A total of 17 cone and plate tests were performed on the Apollo 15 and 16 missions. The depth of penetration was recorded by a scriber on a metal cylinder in the upper housing assembly. The drum rotation was proportional to the amount of force exerted on penetrometer. The independent motions of the drum and stylus produced a continuous force-depth curve on the surface of the drum. (Carrier et al., 1991).

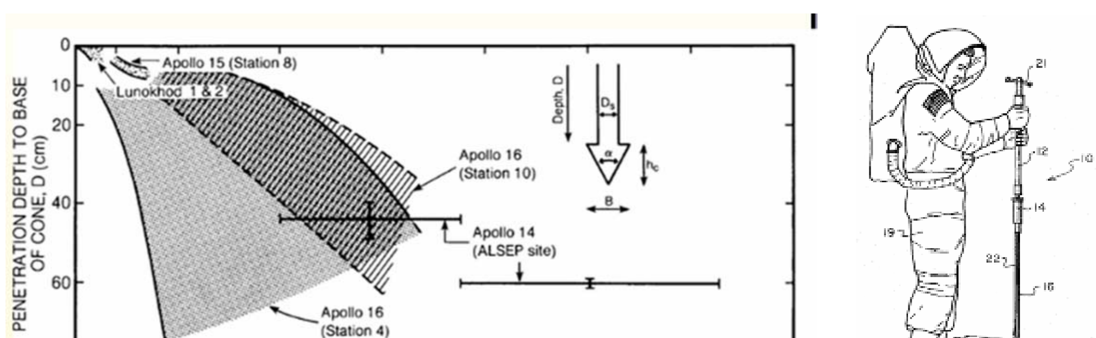

Figure 3 : Left: The SRP used either 12.8 or 20.3 mm diameter cones. Using smaller cone, the astronaut was able to push the SRP to a maximum depth of 74 cm (Carrier et al., 1991); Right: Sketch of an astronaut deploying SRP (Costes et al., 1971).

Lunkokhod Shear Vane
The Soviet Lunokhod rover had a cone-vane penetrometer, called the PROP for establishing the bearing capacity and shear strength of the top surface of the lunar soil (**Figure 4**). The tool, in the shape of a conical indenter having an apex angle of 60°, had a diameter of 5 cm at the base (Cherkasov and Shvarev, 1973). It also had two vertical vanes, with a width of 7 cm and a height of 4.4 cm (Leonovich et al., 1971 and 1972). The maximum vertical load applied on the cone was 32 N (5 kg), while the greatest torque was 5 N-m. Bearing capacity was determined as the ratio of vertical load to the area of the impression of the cone; shear resistance was determined as the quotient of the moment of surface shear strength divided by the torque on the vane.

Lunokhod 1 and Lunokhod 2 traversed over 47 km on the lunar surface and performed approximately 1000 cone-vane penetrometer tests to depths of 10 cm. From these measurements it was determined that the bearing capacity ranged from 0.2 to 1.0 kN/m^2, with a most probable value of 0.34 kN/m^2, while the range of shear strength was 0.03 to 0.09 kN/m^2, with a most probable value of around 0.048 kN/m^2 (Cherkasov and Shvarev, 1973). It was also found that the level areas between the craters had the greatest strength while the circular embankments around craters had the lowest strength.

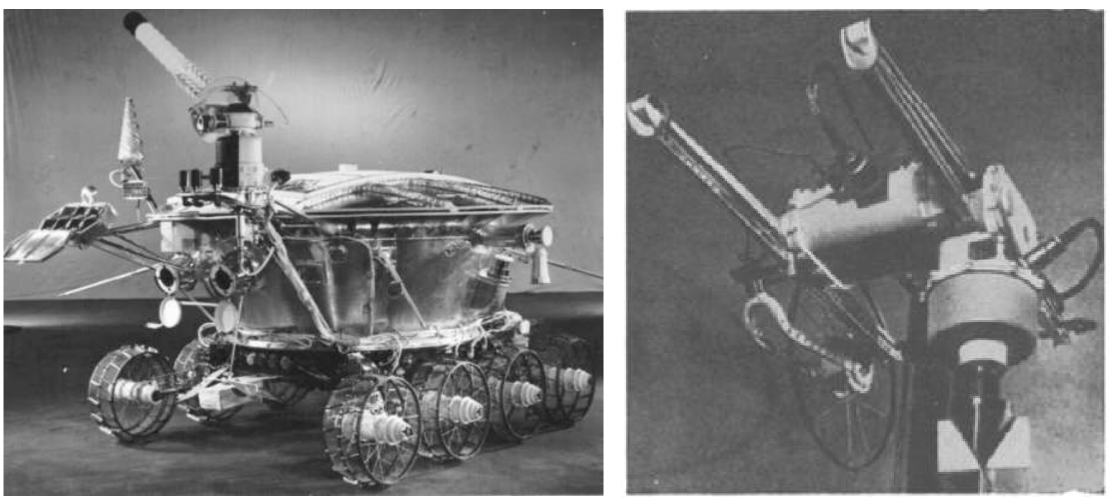

Figure 4. Soviet Lunokhod (left) used a cone-vane penetrometer or "PROP" (right), to perform ~1000 geotechnical measurements of the lunar surface soil (Cherkasov and Shvarev, 1973).

GEOTECHNICAL SYSTEMS FOR LUNAR APPLICATIONS

Several approaches may be used to characterize terrain. These include measuring combined normal and shear strength vs. depth using a hand-held cone penetrometer (ASAE 1985, SAE 1967), shear strength at discrete depths using a shear vane (used mainly for cohesive soils), or determining surface response to normal or shear loading using a bevameter (Shoop, 1996).

Two popular in-situ methods for establishing geotechnical properties of soil are the Static Cone Penetrometer and Dynamic Cone Penetrometer as shown in **Figure 5** (ASTM D6951). The SCP is very similar to the Apollo SRP in that the principal of operation and cone sizes are the same.

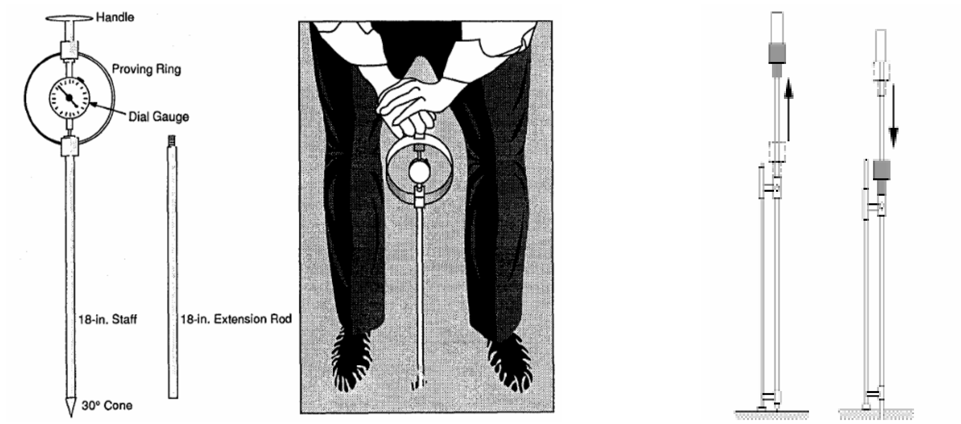

Figure 5. Left: Static Cone Penetrometer (ASAE 1985; SAE 1967); Right: Dynamic Cone Penetrometer (Salgado and Yoon, 2003).

The SCP is pushed into soil at a constant rate of 3 cm/s and the force is measured with respect to depth and converted to Cone Index, CI (average pressure in kPa), or Penetration Resistance Gradient, G (average slope in kPa/mm). The required insertion forces may easily exceed the weight of a planetary rover or an astronaut (the Apollo astronauts' push-force could not exceed around 200 N due to the combination of low gravity and mass of the astronaut and spacesuit). The large increase in the required push force with depth makes this tool applicable to near-surface or loose soils only.

The DCP consists of a long (1-2 m) steel rod with a standard size hardened steel cone at the end and two drop hammers (4.6 kg for soft soils and 8 kg for strong soils) at the top. By measuring the penetration depth of the cone against the number of drops of the hammer it is possible to directly measure resistance to penetration and indirectly calculate the strength or compaction of the soil. The DCP may also be used to obtain an approximate value of the California Bearing Ratio – an index of soil trafficability or shear strength (using an appropriate correlation) with a scale of 1 to 100. Soil with a CBR of 1 is very soft and soil with a CBR of 100 is very hard. The DCP can penetrate hard, compacted soils, but the system is very heavy (30 kg) and automated systems weigh over 50 kg (Kessler, 2009). CBR and the DCP have been around for many decades and there exists ample data that relates penetration rate of the DCP with CBR and soil strength (Kleyn, 1971; Harison, 1987; Livneh, 1987; Livneh, 1989). The main advantage of the DCP is that it does not require significant external reaction forces (it only relies on kinetic energy provided by the drop hammer).

Over the past few decades a number of correlations between the California Bearing Ratio and other soil properties have been developed (see **Table 1**). These include bearing capacity, dynamic modulus, and modulus of subgrade reaction. The bearing capacity, q, is a parameter used in the design of shallow foundations. The relationship between the bearing capacity and CBR shown in equation 1 was adopted by the United States Army Corp of Engineers (USACE) and developed by the Portland Cement Association (PCA, 1955). Dynamic modulus, E, or resilient modulus, M_R, provides a means of characterizing surface soil under a variety of temperatures and stress states that simulate the conditions in a soil subjected to moving wheel loads. If loading is continuous, such as in the form of a sinusoidal wave (i.e. constant traffic), the dynamic modulus should be used. However, if loading has a rest period (i.e. intermittent traffic) the resilient modulus should be used instead. Equations 2 and 3 relating the dynamic modulus and CBR were proposed by Huekelom and Klomp (1962) and Powel et al. (1984), respectively. The modulus of subgrade reaction, k, is used during design and evaluation of rigid pavements. Correlation equations 4 and 5 (for CBR<20 and for CBR>20, respectively) are based on the charts provided in the Department of Defense Unified Facilities Criteria Manual (UFC, 2001).

Neither of the systems described above (SCP and DCP) are suited for robotic lunar applications because they are either too heavy or require a large push-force. However, each of the systems has certain characteristics that when combined could be used to develop an optimum lunar geotechnical system.

Table 1: Correlations between CBR and other geomechanical soil properties

Eq. 1	Bearing Strength	$q(kPa) = 26.16 * CBR^{0.664}$; (PCA, 1955).
Eq. 2	Dynamic Modulus	$E(MPa) = 10.34 * CBR$; Huekelom and Klomp (1962)
Eq. 3		$E(MPa) = 17.58 * CBR^{0.64}$; Powel et al. (1984),
Eq. 4	Modulus of Subgrade Reaction (UFC, 2001)	$k(Pa/m) = -65.91 - 1.49 * CBR + 35.23 * CBR^{0.5}$ For CBR < 20
Eq. 5		$k(Pa/m) = -3.05 - 0.59 * CBR + 16.34 * CBR^{0.5}$ For CBR>20;

Percussive Dynamic Cone Penetrometer

To address the requirement of robotic deployment to great depths from low mass mobile platforms, Honeybee Robotics developed the concept of a Percussive Dynamic Cone Penetrometer. The system uses a percussive hammer to drive a rod into soil. It can be used as a substitute for SCP and DCP. For SCP-like applications, the PDCP can be driven at a constant rate (3cm/sec) with the push-force data converted to penetration resistance gradient, G. However, unlike the SCP, the PDCP does not require large push-forces. This is an advantage of the percussive system. For DCP-like applications, the PDCP can be driven at a constant load with the penetration rate data converted to CBR. As opposed to the heavy DCP system, the PDCP uses a lightweight and compact high-frequency and low-amplitude percussive mechanism. The high-frequency vibration of the percussive rod reduces the force required to push the rod into regolith by a factor of 40 (Zacny et al., 2008; Nathan et al., 1992). This translates directly into the ability to use a smaller rover/lander or less effort on behalf of an astronaut.

The PDCP is a very simple device consisting of three elements: a rod with a cone, a percussive actuator, and a deployment system (**Figure 6**). It can be either robotically deployed from a small mobile platform or manually deployed. A manually-deployable PDCP system was built for the US Army Corp of Engineers, but could be adapted for astronaut deployment.

Note that the use of percussive (or dynamic), as opposed to static, geotechnical tools was proposed before in the context of lunar geotechnical exploration. Again, the driving factor was limited by static loads against which the test device would have to act due to lower lunar gravity and lander/rover mass. In particular, the dynamic iterative bearing strength instrument was developed and proposed for the Surveyor Lunar Roving Vehicle (GM, 1964).
An overview of the cone-vane, SRP, DCP, and PDCP tools are given in **Table 2**.

Table 2. Comparison between Cone-Vane, Self Recording Penetrometer, Dynamic Cone Penetrometer, and Percussive Dynamic Cone Penetrometer.

	Cone-Vane	**Self Recording Penetrometer SCP or Static Cone Penetrometer SCP**	**Dynamic Cone Penetrometer DCP**	**Percussive Dynamic Cone Penetrometer PDCP**
Mission	Lunokhod	Apollo	N/A	N/A
Deployment method	Robotic	Human	Human	Human or Robotic
Operation	Controlled penetration or rotation rate	Controlled penetration rate at 3cm/s	Repeated impact with dead weight	Controlled penetration rate or force with percussion
Measured data	Penetration force/displacement or rotation torque/angle	Penetration force/displacement	Penetration depth after each impact	Penetration force/displacment
Application	Trafficability	Trafficability, Excavation/Mining	Trafficability Excavation/Mining	Trafficability Excavation/Mining
Depth of utility	10 cm	74 cm	>1 m	>1 m
Metrics	Bearing strength (kPa) and shear strength (kPa)	CI (kPa) and G (kPa/mm) Density (g/cc), friction angle (degrees) and Cohesion (kPa) may also be estimated. (Rohani and Baladi, 1981)	CBR (dimensionless) Bearing Strength (kPa) and Resilient/Dynamic Modulus (Pa/m) may also be estimated. (Kleyn, 1971; Harison, 1987)	All aforementioned metrics

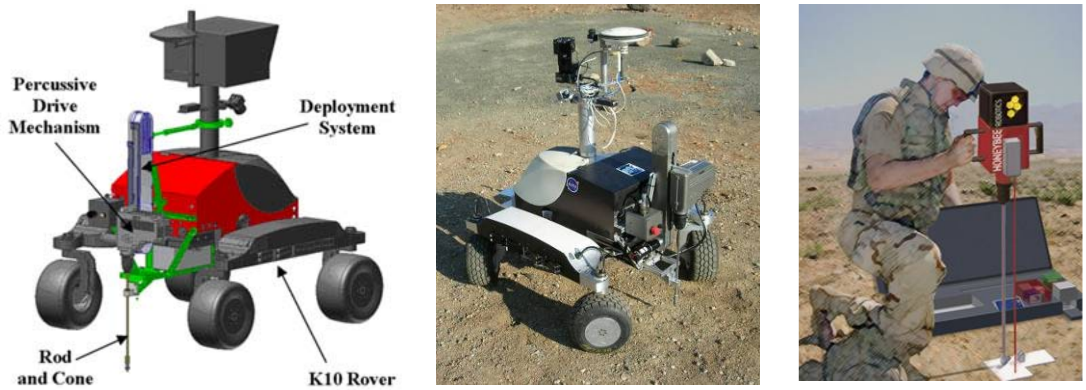

Figure 6: Honeybee Robotics PDCP mounted on NASA Ames K10 Rover (left and center) and human deployable PDCP designed for US Army.

TESTING OF THE PERCUSSIVE DYNAMIC CONE PENETROMETER

To enable the PDCP system to be used as a replacement for SCP and DCP, results from testing must be correlated with SCP and DCP data collected using the same test soil/surface and conditions.

Percussive Dynamic Cone Penetrometer as a Replacement for the Dynamic Cone Penetrometer

During development of the Honeybee Robotics PDCP, tests were conducted to correlate data from the PDCP with that from the DCP, and in turn California Bearing Ratio. Once the necessary correlations were developed, the CBR values measured using the PDCP could then be used to determine other soil properties such as bearing strength (PCA, 1955).

For the manually deployable PDCP tests, a percussive system (hammer drill) was integrated with a long rod and pushed into soil. The push-force was applied only by the weight of the tool (**Figure 7).** The graph in Figure 7 shows data from both DCP and PDCP tests in the same soil to the same depth. The DCP data is shown as CBR as a function of depth, where the CBR values are estimated from measured DCP penetration rates (in mm per hammer blow.) The PDCP data, plotted in blows/mm as a function of depth, is calculated by converting the PDCP penetration rate in mm/s to mm/blow by multiplying by a known percussive frequency (i.e., number of hammer blows per second) and multiplying the reciprocal of this by a constant calibration factor (derived empirically). Note that the calibration factor for the PDCP system shown is 2.6; i.e. for the penetration rate of the PDCP to be equivalent to CBR, the penetration rate needs to be multiplied by 2.6. The DCP and PDCP data is very similar, however, the four PDCP tests have less data scatter than DCP tests, probably attributed to more uniform deployment. Note that DCP relies on manually lifting a heavy hammer and after a number of lifts a person gets tired and in turn the hammer may not be lifted all the way to the top. This could be a potential source of error. PDCP on the other hand, relies on mechanical system to generate hammer blows, which in turn are more repetitive.

Note also that the graph shows a softer zone between 20-25 in depth, just below the stronger layer. It is these softer layers that can be problematic from the bearing capacity stand point when deploying surface structures or traversing with heavier mobility platforms.

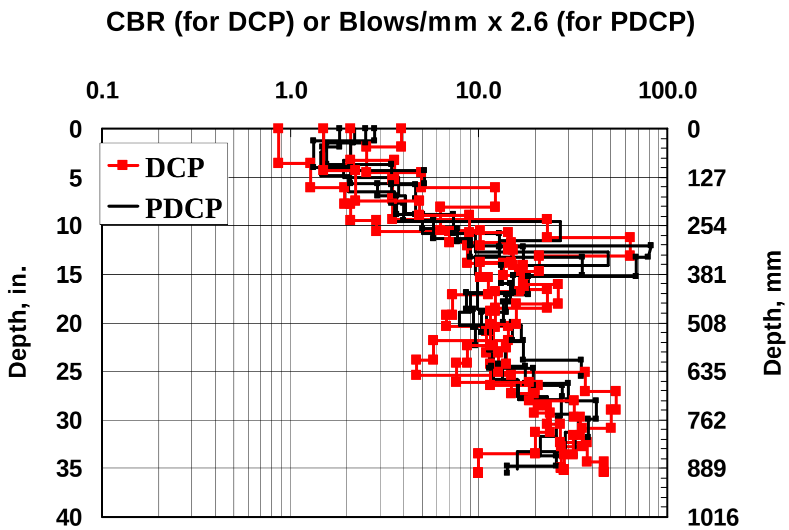

Figure 7. Left: Prototype of the human deployable PDCP. Right: Soil strength measured in California Bearing Ratio or CBR (for DCP) and blows/mm (for PDCP) for soft to medium strength soils. It can be seen that the DCP and PDCP data coincide.

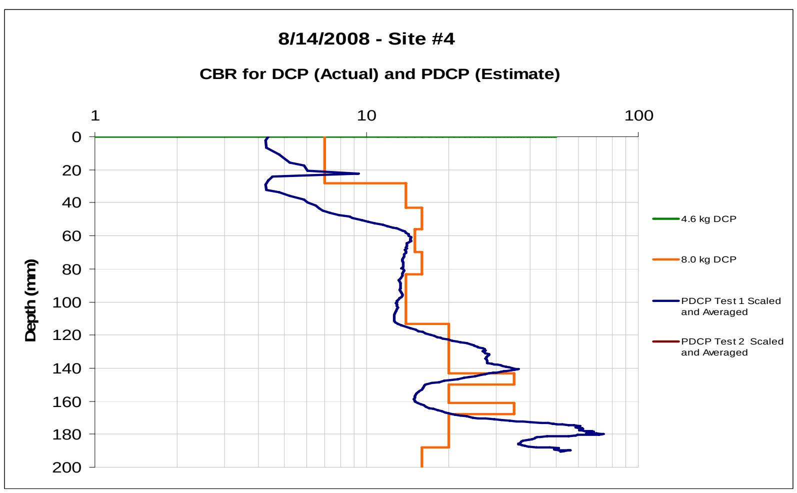

Figure 8. Left: Field tests using a percussive dynamic cone penetrometer on the NASA Ames 80kg K-10 rover. Right: The data shows close correlations to California Bearing Ratio and in turn other soil geotechnical properties such as bearing strength.

Following successful demonstration of the manually deployed PDCP, the tool was scaled down to fit NASA Ames' 80 kg K10 rover (**Figure 8**). The system was designed as a standalone fully autonomous geotechnical tool requiring no human intervention. Testing was performed at the outside testing facility called the ‘Marscape' (2009) at NASA Ames Research Center with various soil types and conditions to calibrate the unit and to demonstrate rugged, unstructured field operation from a small mobile platform, as may be the scenario for lunar geotechnical surveys. With this data, a basic correlation was established between the PDCP and DCP, and therefore CBR.

Percussive Dynamic Cone Penetrometer as a Replacement for the Static Cone Penetrometer

Tests were conducted at the NASA Glenn Simulated Lunar Operations (SLOPE) laboratory to determine how well the PDCP correlates with the SCP. Both the Static Cone Penetrometer and manual DCP use Apollo-size 20.3 mm diameter (323 mm^2 base area) cones. The SCP measures the force or cone pressure as a function of depth in the soil (kPa/mm) and in this case, the PDCP measured penetration rate in blows/mm.

Note that in the future tests a rate-controlled method, rather than force-controlled, will be used to establish correlations. In the existing force-controlled set-up, the preload remains constant and the variable penetration rate data is used to estimate soil strength as a function of depth. During future rate-controlled deployment, the penetration rate will be kept constant at 3 cm/s and the variable force required to maintain this constant penetration rate will be used to measure soil strength.

Figure 9: During a soil preparation stage, a known mass of soil was carefully and uniformly distributed into a cylindrical bin up to a desired height. If required, a vibrator was used to compact it to a desired density.

Soils were prepared by following a procedure utilized by NASA Glenn (**Figure 9**). A known amount of soil was weighed and carefully and uniformly distributed in a rigid cylindrical bin using a hopper. The soil was then left uncompacted or was vibrated until it compacted to a predetermined soil level corresponding to a known density. All tests were conducted in GRC-1 soil (Oravec et al., 2009). Different densities were prepared and tested with each penetrometer. The PDCP and SCP tools are shown in **Figure 10**.

Figure 10: Tests were conducted at the NASA Glenn SLOPE laboratory in April 2009. (Left) K10 PDCP deployed into GRC-1 and (right) static cone penetrometer (Rimik model CP40II) measurements taken in the same soil

Figure 11 is a gradient versus denstiy graph of the test results obtained in the SLOPE laboratory. The manual PDCP data matched the trends of the SCP data over the range of soil densities tested. Unfortunately no PDCP data was collected for the highest (~1.9 g/cm^3) soil density. Although more tests are required to determine better correlations, the initial data is promising.

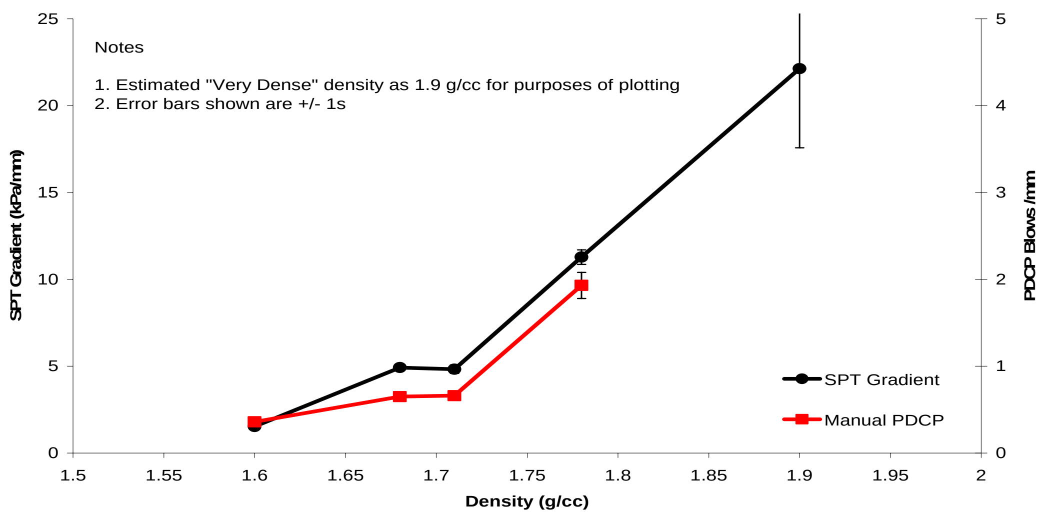

Figure 11: Results from tests at the NASA Glenn SLOPE facility. The PDCP deployment method has a strong effect on the behavior and accuracy of the tool. In this graph, SPT is interchangeable with SCP.

VACUUM RATED PDCP

The usefulness of the PDCP is based on how closely the PDCP data can be correlated to DCP and SCP data as well as whether the PDCP can be deployed in lunar vacuum environment. To address the latter issue, a vacuum-rated PDCP breadboard has been developed and tested under ambient and vacuum conditions (**Figure 12**). Note that only the percussive head was tested in a vacuum chamber, while the soil penetration tests were performed in ambient conditions. However, the same system could be used alongside the DCP and SCP to acquire data in various lunar analogous soils (JSC-1A, CHENOBI, NU-LHT, etc.). Multiple densities of each soil type could be readily placed in a large vacuum chamber to determine the effect of vacuum on soil properties. This would be a major step towards increasing the Technology Readiness Level (TRL) of the entire PDCP system.

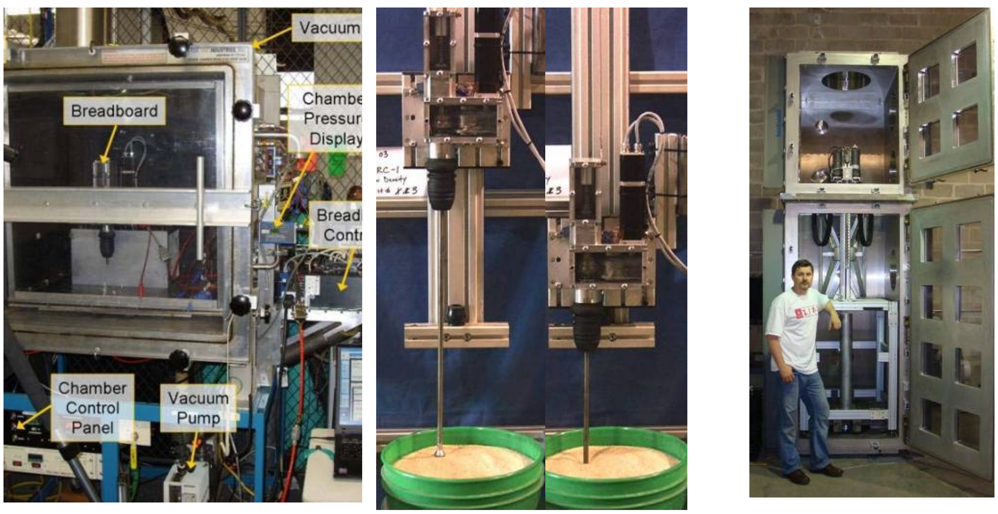

Figure 12: Left: Percussive breadboard undergoing vacuum tests; Center: Ambient test in low density GRC-1 with 45 N force. The PDCP penetrated 24 cm in about 6 seconds. Right: Future tests could be performed in a 3.5 m-tall vacuum chamber under development at Honeybee Robotics.

CONCLUSIONS

Rover-mounted geotechnical systems are of paramount importance to lunar exploration and to enabling a permanent human presence on the Moon. Geotechnical tools can be used to assess trafficability of lunar soil and to determine regolith strength prior to excavation tasks.

Two popular in-situ methods for establishing geotechnical properties of soil are the SCP and DCP. The SCP is pushed at a constant rate of 3 cm/s into soil and the increasing force is measured and converted to the Penetration Resistance Gradient, G (kPa/mm) or Cone Index (CI). The large increase in the required push force with depth makes this tool applicable to near-surface or loose soils only. The DCP, on the other hand, uses a drop hammer (8 kg for hard soils and 4.6 kg for soft soils) to drive a rod into soil. The penetration rate is converted to California Bearing Ratio. Soil with a CBR of 1 is very soft and soil with a CBR of 100 is very hard. The DCP can penetrate hard, compacted soils, but the system is very heavy (>30 kg) as well as the automated versions of this system which weigh over 50kg.

Neither of these systems are suited for lunar applications (they are either too heavy or require a large push force), however, each system produces useful data. To address this problem, Honeybee Robotics developed the Percussive Dynamic Cone Penetrometer. This system uses a percussive hammer to drive a rod into soil. It can be used as a substitute for both the SCP and DCP. For SCP-like applications, the PDCP can be driven at a constant rate (3cm/sec) and measure penetration force as a function of depth, which can be converted to Penetration Resistance Gradient, G. However, unlike SCP, the PDCP does not require large push-forces. For DCP-like applications, the PDCP can be driven at a constant force into soil with the penetration-rate data converted to CBR. As opposed to the heavy DCP system, the PDCP uses a lightweight and compact high-frequency and low-amplitude percussive system. The high-frequency vibration of the percussive rod also reduces the force required to push a rod into regolith by a factor of 40 (Zacny et al., 2008; Nathan et al., 1992). This translates directly into the ability to use a smaller rover/lander or less effort on behalf of an astronaut.

The major hurdles for making the system applicable to lunar environments are the development of a vacuum-rated percussive mechanism and correlation of the data with existing soil property measurement methods. In this paper we have described a vacuum-rated system and have shown that preliminary data correlates well with SCP and DCP data. However, more tests in relevant lunar soil simulants and also under vacuum conditions are required to strengthen the data correlations.

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