PERCUSSIVE DYNAMIC CONE PENETROMETER FOR GEOTECHNICAL SURFACE ASSESSMENT WITH A PLANETARY ROVER.

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Introduction: During the past planetary surface missions, few instruments have been deployed to directly assess soil physical properties like density, soil strength (internal friction and cohesion), and pressure/sinkage curves, or their spatial variation. Several Soviet lunar missions were equipped with small cone vane penetrometers, and the Apollo astronauts also used two different manual penetrometers. For the most part, information on soil mechanical properties has been inferred from instruments intended for other purposes, such as landing pads, scoops and rover wheels. These measurements were difficult to interpret because of the complex test geometries, low signal resolution, and difficulty in determining forces and torques.

Near term lunar missions will need to characterize subsurface for a variety of reasons. This includes predicting trafficability for the mobile planetary platforms, excavation forces and power for In Situ Resource Utilization (ISRU) and any form of planetary construction (habitats, landing zones etc).

Methods of Assessing Soil Properties In-Situ: The cone penetration test is widely used in the geotechnical engineering field to measure in situ soil properties and to determine the variation of soil properties as a function of depth. These measurements are used to provide data for the design of structural foundations, pile foundation, and (near-surface) vehicle mobility predictions.

In the Lunar low-gravity environment, pushing a penetrometer into regolith is not practical because the soil resistance to penetration would quickly exceed the mass reaction of the rover platform or the weight of an astronaut. To overcome the difficulty of deploying a penetrometer in low gravity the alternative method is to drive the penetrometer into the regolith by successive impacts of a hammer (percussive method) and still use the penetration rate as an indication of formation strength.

On Earth one such common method to establish trafficability of terrain is to use the Dynamic Cone Penetrometer (ASTM D6951). The DCP consists of a long (1-2 meter) steel rod with a standard size hardened steel cone at the end and two drop hammers (4.6kg for soft soils and 8kg for stronger soils) at the top. By measuring the penetration of the cone against the number of drops of the weight it is possible to plot resistance to penetration and indirectly estimate the strength / 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 bearing strength (using the appropriate correlation factors). The CBR and DCP have been around for many decades and there exists an ample data set that relates penetration rate of a DCP rod with CBR and soil strength. The main advantage of a DCP is that it does not require any external reaction forces (it only relies on the kinetic energy provided by a drop hammer).

Honeybee Robotics has used the DCP to successfully measure soils with CBR ranging from 5 (soft soil) to above 50 (very hard soil). The DCP as is cannot be integrated onto small rovers because of the large size and mass required to produce enough energy to effectively penetrate soils. An alternative method was to replace the drop hammer with a percussive drive mechanism, which allowed the system to be much more compact and less massive. This percussive approach was initially developed and tested by Honeybee Robotics under a DoD-funded SBIR Phase I effort. The device, called the Percussive Dynamic Cone Penetrometer (patent pending), uses high frequency and low energy impacts to drive a penetrometer rod into soil. The collected data in millimeters penetrated per single hammer blow, can then be correlated to CBR. To arrive with an accurate correlation factor, initial research requires side by side testing with DCP in a range of soils (Figure 1).

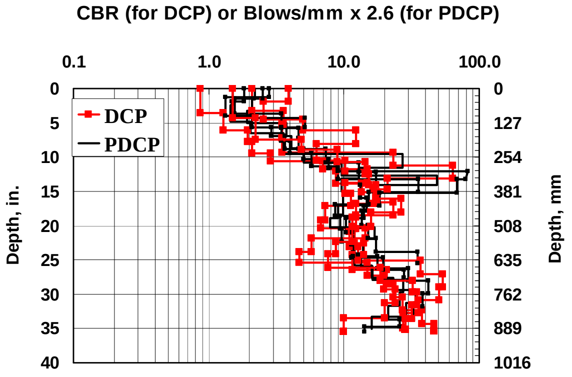

Figure 1. Example of the data acquired from PDCP.

Correlations to Bearing Capacity and Dynamic Modulus: As previously mentioned, the penetration rate of the PDCP can be correlated to CBR. Over the past few decades additional correlations were developed that relate CBR to other soil physical properties such as Bearing Capacity and Dynamic Modulus [1].

For example, Bearing Capacity in kPa is estimated as q=26.16*CBR^0.664 [2] and Dynamic Modulus in MPa is estimated as E=10.34*CBR [3] or E=17.58*CBR^0.64 [4].

Description of the K10 Percussive Dynamic Cone Penetrometer (PDCP): The K10 PDCP is a two-axis stand alone system mounted to a NASA Ames K10 rover. The PDCP system includes a percussive drive mechanism, a penetrometer rod and cone, a deployment system, and dedicated lithium-ion battery-powered avionics. The percussive drive mechanism provides the necessary percussive action to the cone required to penetrate soils and measure soil bearing strength. The deployment system provides the vertical motion for the system, allowing the PDCP to penetrate into soils with a constant weight-on-bit (i.e., “force-on-cone”) to its depth limit and to pull the rod out of the hole and stow in a home position until the next survey site is reached. The cones used by the PDCP, like the standard DCP, are held onto the rod by a gasket, which allows the cone to be disengaged from the rod at low forces while in the hole. This helps reduce the risk of the rod getting stuck in the hole and potentially anchoring the rover in place. The entire PDCP system weighs approximately 13 kg, can penetrate to 15 cm depth (although deeper penetration is possible), is mounted to the rear of the K10 rover body, and is operated remotely through the K10 controls system.

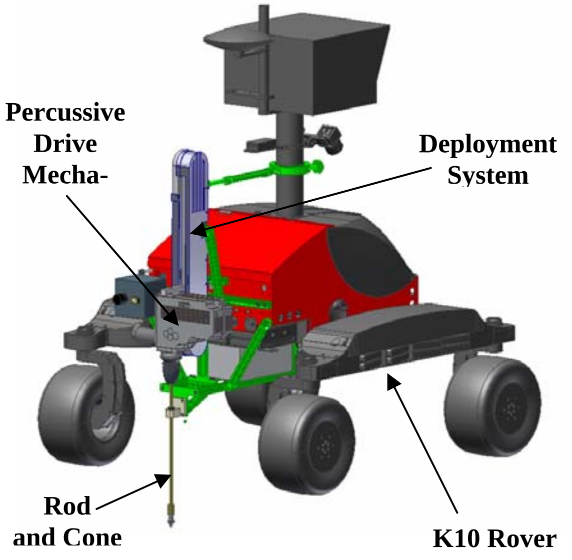

Figure 2. Percussive Dynamic Cone Penetrometer(PDCP) deployed from the NASA Ames K10 rover

Description of the K10 Rover: The K10 rover is a four-wheel mobile robot designed to satisfy three goals: (1) movement at human walking speeds (up to 90 cm/s); (2) low time-to-repair using commercial off-the-shelf parts wherever possible; and (3) the ability to operate in both high-friction indoor (concrete floors) and moderate natural outdoor (30 deg slope, hard-pack dirt) environments. The NASA Ames Intelligent Robotics Group currently operates two K10’s, which are used for applications including human-robot interaction studies and multi-robot site survey (resource mapping). K10 has four-wheel drive and all-wheel steering with a passive rocker suspension, which allows it to traverse moderately rough natural terrain at speeds up to 90 cm/s. Lithium-ion batteries provide the necessary power to run the drive system’s brushless motors and avionics. K10 weighs 80kg and can carry an additional 20kg payload. The K10 rovers use NASA Coupled Layer Architecture for Robotic Autonomy software architecture running under a Linux operating system.

Figure 3.K10 Red deployed in the field. Image courtesy of NASA Ames.

Deployment of the Percussive Dynamic Cone Penetrometer: Once the rover reaches a desired survey location, the PDCP is lowered to the ground by a chain-driven deployment system. A load cell is used to monitor the force applied to the PDCP cone. Initial ground contact is verified when the load cell starts reading non-zero force values. After the ground has been located the percussive drive mechanism is energized and the cone is pushed into the soil with a constant weight-on-bit until either the depth limit or a predetermined time-out period is reached. Each PDCP test (i.e., penetration in soils to 15 cm depth) takes less than one minute to complete. Rate of penetration and elapsed time data is recorded and correlated to CBR values.

References: [1] Jersey and Tingle, World Road Congress, Paris, France 17-21 September 2007.[2] PCA, Design of Concrete Airport Pavement, Portland Cement Association, 1955. [3] Huekelom and Klomp, Dynamic Testing as a Means of Controlling Pavements During and After Construction, Int. Conf. Structural Design of Asphalt Pavements, 1962, pp. 667-685. [4] Powell et al., The Structural Design of Bituminous Roads. TRRL LR 1132, UK 1984.