# Five-Step Parametric Prediction and Optimization Tool for Lunar Surface Systems Excavation Tasks

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## ABSTRACT

NASA systems engineers require an accurate assessment of excavator mass, power and energy requirements to correctly design lunar surface systems' overall architecture. In order to properly determine excavator mass and energy for various excavation tasks, we recommend a 5-step process. It starts with selection of appropriate soil that is analogous to lunar regolith. The second step refers to soil preparation methods; the desire is to make the soil's relative density similar to in-situ lunar regolith's relative density. The third step requires measuring excavation forces by deploying instrumented digging end effectors in carefully prepared soil bins and preferably in vacuum. After forces are measured, they need to be scaled for lunar gravity. The scaling factor varies depending on soil properties (cohesion and friction angle) and also on the size of an excavating blade/scoop. Once the forces are scaled they can be used to accurately estimate excavators' parameters for various tasks. This paper describes in detail all of the 5 steps mentioned above.

## INTRODUCTION

Apollo missions 11 through 17 (except for Apollo 13), were relatively short duration (3 day) missions on the surface of the Moon. Astronauts lived in a small Apollo Lunar Module (LM) and had little comfort. They brought everything with them from Earth, thus there was also a practical limit on how long they could stay before supplies run out.

Future lunar missions will require astronauts to stay on the Moon for much longer than 3 days. NASA envisions initially short, seven-day sorties, and longer expeditions to follow on as experience grow. For sorties missions, astronauts would have to bring more supplies with them. For much longer duration missions, however, astronauts would have to use local resources to support their stay.

During the initial sortie missions, astronauts would be performing various science investigations (much the way Apollo astronauts did) but in addition to that they will also be asked to perform In-Situ Resource Utilization (ISRU) experiments and technology demonstrations in preparation for the establishment of more permanent outposts. Sortie missions will be conducted from a lunar lander that will include a habitable crew cabin, the same way the Lunar Module (during Apollo missions) provided a small habitable volume. Sortie missions could investigate diverse science sites, or return to a single site to begin the deployment of a permanent outpost. During the buildup of the outpost infrastructure, mission duration would continue to be extended from initial outpost missions spanning an entire lunar day (28 Earth days) to permanent crew rotations that eventually would grow to six months on the lunar surface.

For these longer lunar missions a more permanent habitat is needed. The lunar outpost will allow crews of up to four astronauts at a time to conduct long duration surface science expeditions, technology demonstrations (e.g. for ISRU), and tests of operational techniques. The outpost habitat would provide more robust crew accommodations than on sortie landers and it will be reused over multiple expeditions. The goal of the lunar outpost is a continuous presence of surface crews (**Figure 1**).

Building a more permanent outpost will require excavating and moving thousands of tons of lunar regolith. For example, **Figure 2** shows the excavation requirements based on the Lunar Architecture Team (LAT) II Option 1 Concept of Operations (Mueller & King, 2008). The total mass/volume that will need to be excavated (assuming the bulk lunar soil density of 1.5 g/cc) is ~ 3000 tons or 4500 m3. These excavation tasks can be divided into two major categories:

**Figure 1. Artists' concept for future human lunar base. Courtesy NASA.**

**1. Digging:** Trenches for Habitat, Element Burial, ISRU (O2 Production)

**2. Plowing/Bulldozing:** Landing / Launch Pads, Blast Protection Berms, Utility Roads, Foundations / Leveling, Regolith Radiation Shielding

In particular, ISRU technology will be crucial in supporting an affordable human permanent presence on the Moon. ISRU refers to “living off the land” – utilizing local resources to support life, make fuel for the journey back home, or building civil engineering structures and other useful materials and subsequent products.
For example, recent discovery of potential water-ice at the lunar polar craters could be just one such resource. Mining water, instead of bringing it to the Moon, could offset large launch costs. The cost of placing just 1kg on the surface of the Moon is in the range of $100,000. Mining and processing local resources rather than transporting resources from Earth could potentially save billions of dollars. In the case of water, this resources could be used directly to support life (water could be used for drinking or hygiene, or broken down into oxygen and hydrogen and the oxygen used for life support). Water could also be broken down into oxygen and hydrogen and used as propellants for the journey back home. Mining this water, however, requires excavators.

Lunar soil contains over 40% of oxygen in the form of metal oxides. Liberating this oxygen in reactors such as Carbothermal, Hydrogen Reduction or Molten Electrolysis processes would substantially reduce the mass of oxygen that would have to be brought from Earth andthe corresponding mass of oxygen tanks.

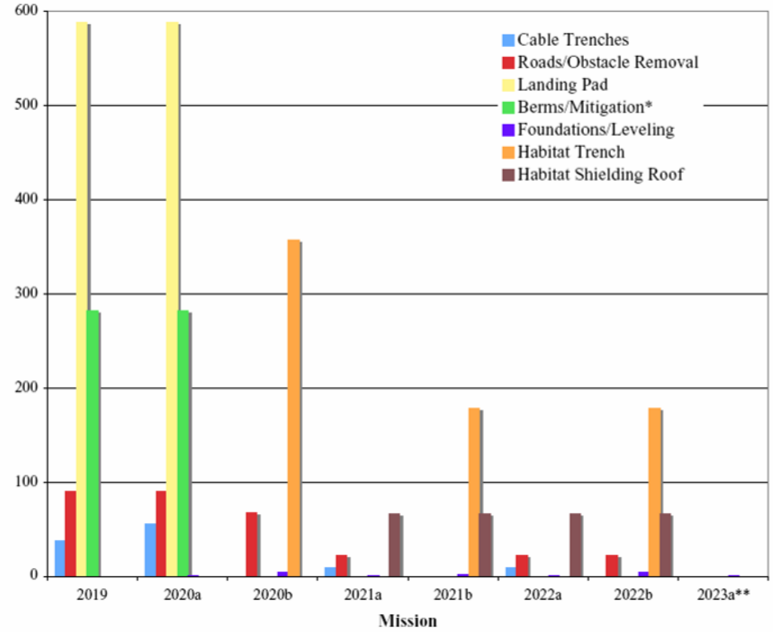


**Figure 2. Excavation requirements (Mueller and King, 2008).**

All the tasks associated with the construction of a permanent human outpost and the supporting ISRU infrastructure will require civil engineering and in particular mining and excavation. In the follow on sections, we will describe how the lunar environment will affect excavation process and the 5-step approach to lunar excavation developed to properly size lunar excavators and to determine power and energy requirements for lunar excavators.

## LUNAR ENVIRONMENT

Earth moving machines differ depending on what environment they will work in. The Arctic’s excavators are built somewhat differently from those that would be used in the Australian Outback. Excavators for the moon will no doubt be different too, and probably very different than what we see on Earth.

In order to design something that will work on the moon, we first need to understand the lunar environment. The lunar environment is different from Earth in three important respects:

### Gravity is 1/6th G.

Lower lunar gravity (1/6th that on Earth) means that everything will weigh 6 times less. When the Apollo astronauts tried to push soil sampling tubes into lunar soil they could push them with a maximum of 60lbs of force before they would lift themselves off the surface. On earth, Apollo astronauts would have weighed over 360lbs (this included their lunar spacesuits).

Soil strength depends on two main properties: friction and cohesion. Friction is gravity-dependent while cohesion is not. Thus lower gravity has a direct effect on frictional soils (soils with no cohesion, such as beach sand). Lunar soil does have some cohesion though, but frictional effects also play a large role in its behavior, as will be explained in section on Lunar Soils.

### Hard Vacuum: $10^{-12}$ torr

The Moon has no atmosphere but exists in a vacuum of the order of $10^{-12}$ torr. This means there will be no water films (absorbed water) or oxides on the surfaces of soil or other materials (or, once oxides are removed they will not be replaced). Surfaces without any oxides have unsatisfied bonds and may literally weld to other surfaces. This causes an increase in friction. Lunar regolith's high cohesion and friction angle may be due to not only its particular particle shapes and size distribution, but also its surface properties (unsatisfied bonds due to lack of atmosphere).

Heat is transferred via gaseous convection, gaseous conduction, conduction and radiation. On the Moon, the first two mechanisms listed do not exist because of the lack of atmosphere. Thus heat dissipation will be via conduction and radiation only. If a material gets hot, the only conductive path is into the ground and since conduction of granular material is very poor, radiative cooling will be much more efficient.

### High and Low Temperature: ~30K – 400K

Temperature on the Moon varies substantially between lunar day and lunar night. At the equator, during the lunar day, the maximum surface temperature is 123°C, and during the lunar night, the minimum surface temperature is -173°C. The Permanently Shadowed Craters at the Lunar South Pole (the areas where the Sun never shines) have a surface temperature reaching -243°C. In 1998, NASA's Lunar Prospector orbiter detected evidence of between 10 to 300 million tons of water ice in thick sheets on the moon's poles (**Feldman et al., 1998**). The presence of water on the Moon would tremendously benefit a manned mission to the moon. We would no longer need to bring water with us from the Earth, but could literally mine it on the Moon. However, mining equipment would have to be able to withstand these low temperatures and vacuum.

Any equipment would also have to withstand large thermal fluctuations (300 °C between lunar day and night). Careful engineering design would be required to avoid problems due to materials of very different coefficients of thermal expansion. If two interfacing parts have very different coefficients of thermal expansion, and were designed to operate at, for example, room temperature (20 °C), large stresses will be developed between the mating surfaces if the temperature is increased to over 100 °C or decreased to less than -100 °C. These large stresses may cause the parts to fail or mechanism to cease functioning.

## A FIVE STEP APPROACH TO LUNAR EXCAVATION

In order to properly size the required excavator mass and determine required energy for various excavation tasks, it is imperative to proceed by the following 5-step process developed by Honeybee Robotics for Lunar Surface Systems and shown in **Figure 3**.

1. Choose a regolith simulant : It starts with the selection of an appropriate non-organic soil that is analogous to lunar regolith. A soil with properties that are very different from the lunar regolith will result in excavation forces that will not be scalable to the lunar soil and using these forces may result in incorrect sizing of an excavator.

2. Prepare the regolith simulant: The second step refers to simulant preparation methods; the idea is to make sure the soil compaction (in-situ bulk density) is the same as on the Moon. Again, if a soil is not dense enough, excavation forces will in turn be lower and thus an excavator might be undersized.

3. Measure excavation forces: The third step refers to the measurement of excavation forces. Here, we need to consider two systems: digging (with a backhoe, for example) and bulldozing (with a bulldozer). Most excavation tasks can be grouped into these two categories.

4. Scale forces for lunar gravity: After forces are measured, they need to be scaled to account for lower lunar gravity. The scaling factor varies depending on the soil properties (cohesion and friction angle) hence it is important to start with an appropriate simulant of appropriate bulk density, and also on the size of an excavating blade/scoop.

5. Input resulting forces into excavation models:Only after these scaling factors are known can accurate excavation forces and energies be used to model various excavation tasks.

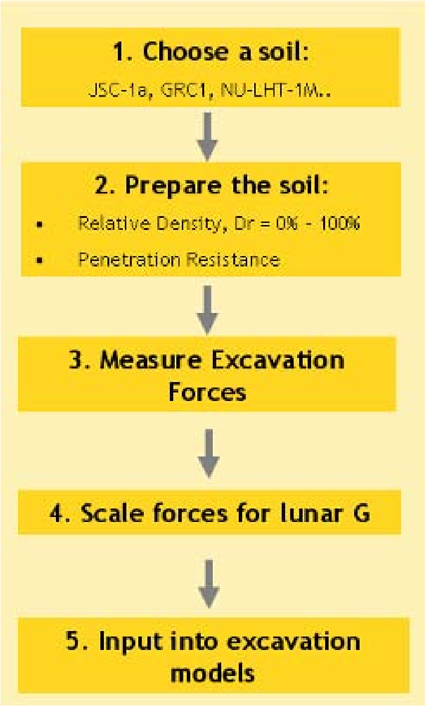


**Figure 3. Five step approach to lunar excavation.**

**Step 1: Lunar Regolith and Lunar Regolith Simulant**

Lunar regolith can be described as well graded sandy silt or silty sand, i.e. 50% of particles are smaller than 74 microns (**Heiken et al., 1991**). The soil density quickly increases with depth to 1.9 g/cc (**Figure 4**). At this density the relative density, $D_r$, is approximately 90%. The regolith also has high porosity in the range of 40%. A quarter of this porosity can be attributed to intragranular porosity (**Carrier, 2005**). The regolith has a high cohesion and friction angle attributed to the particle size distribution, and the presence of agglutinates, which are highly irregularly shaped grains made up of fused glass and rock (**Figure 5**). This makes the lunar regolith very abrasive.

Simulants do not replace the actual material – they simulate specific properties but not necessarily all the properties. For example, some simulants are made to simulate the geotechnical mechanical properties of lunar regolith, which are important for trafficability studies, whereas other simulants are made to simulate the mineralogical or chemical properties of lunar soil, and can be used in oxygen extraction test plants. It is important to select a simulant that matches the properties appropriate to the application at hand. For the regolith to fail, the forces have to exceed the shear strength of the soil, $\tau$. The shear strength thus describes the maximum strength of regolith at which it fails due to an applied shear stress:

$\tau = \sigma \tan(\varphi) + c$. (**Equation 1**)

where

- $\sigma$ is the total stress applied normal to the shear plane
- $\varphi$ is the 'angle of internal friction' where the coefficient of friction $\mu$ is equal to $\tan(\varphi)$. The angle has also been referred to as the “angle of repose”, that is the angle granular material forms a pile.
- c is cohesion and it allows the soil to have some shear strength at no confining stress (that is soil can form vertical walls). For example water gives soil cohesion; wet sand can be used to build steep castles on a beach. Some soils, such as lunar regolith, due to the shape of individual grains and size distribution, are inherently cohesive.

The regolith properties that are important for lunar excavation are therefore Friction angle ($\varphi$) and Cohesion (c). However, $\varphi$ and c are function of regolith density (see **Figure 6**). When density increases, so does cohesion and friction angle. The regolith density is affected by particle size distribution and particle shape (and mineralogy). Thus, a simulant that is sufficient for excavation testing will have at least the same particle size distribution, and particle shapes as lunar soil.

Over the past few decades, a number of different soil simulants have been developed. These are tabulated in **Table 1**.

Based on the general availability and quality of the simulant we decided that JSC-1a is an appropriate soil simulant for our excavation studies. This soil has also been in use for many years and thus it has been well characterized and there are a number of previous excavation studies with which to compare results. We also use GRC1 and GRC3 since these soils have also been well characterized for geotechnical purposes, there is a growing body of work with which to compare results, and we have 1 ton of each at our disposal.

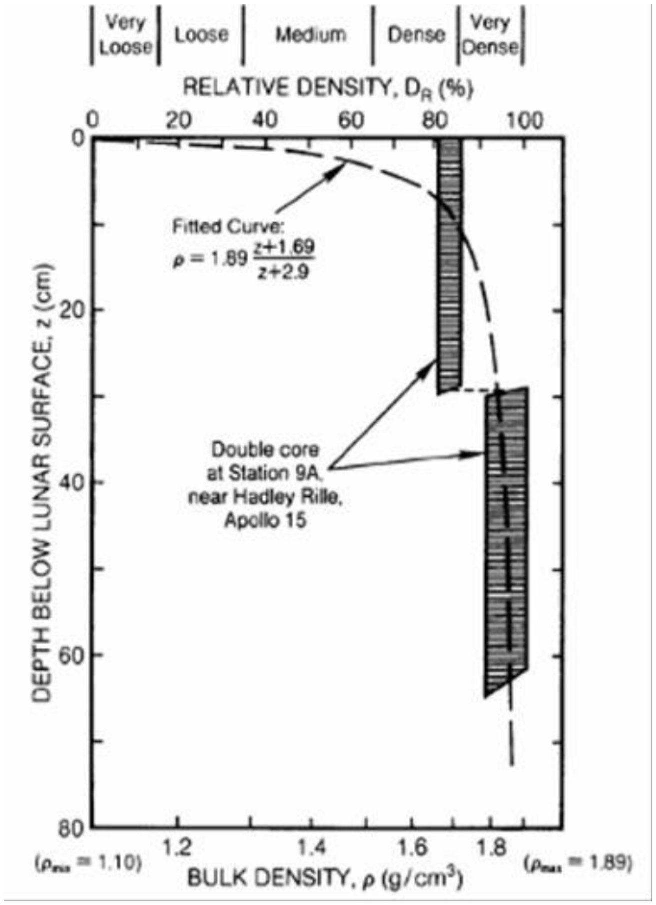


**Figure 4. Relative density and corresponding bulk density of lunar soil as a function of depth (Heiken et al., 1991).**

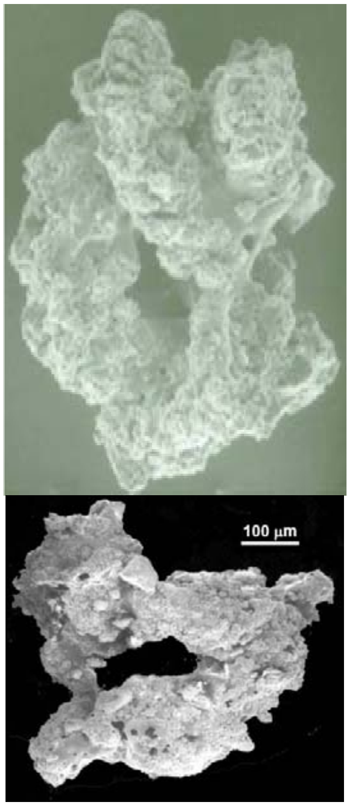


**Figure 5. Lunar soil consists of up to 50% of agglutinates: fused glass and rocks. Courtesy NASA.**

**Table 1. Lunar Soil Simulants.**

| Simulant | Type | Primary use | Manufacturer |
|---|---|---|---|
| JSC-1a | Mare, low-Ti | Geotechnical and to lesser chemical | Orbitec |
| NU-LHT-1M, -2M | Highlands | General | MSFC and USGS |
| OB-1 | Highlands | Geotechnical | Norcat |
| FJS-1 | Mare, low-Ti | Geotechnical | JAXA/Schimizu |
| GRC-1, 3 | | Geotechnical | GRC |

**Step 2: Soil Preparation Requirements**

There are two parameters that can guide soil preparation. These are Relative Density, Dr, and Penetration resistance gradient, G [Pa/mm] as shown in **Figure 6** and **Figure 7**. Thus, we can either compact the soil to achieve $D_r$ equivalent to that on the Moon, [0-100%] or compact the soil to match the penetration resistance gradient of the Apollo Self Recording Penetrometer (SRP).

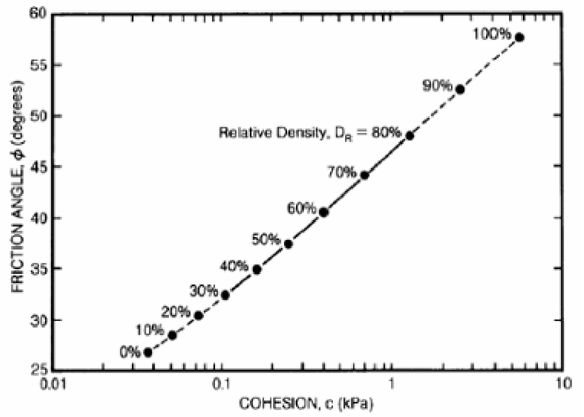


**Figure 6. Soil cohesion and friction angle as a function of soil relative density. The data was obtained from soil simulant (Heiken et al., 1991)**

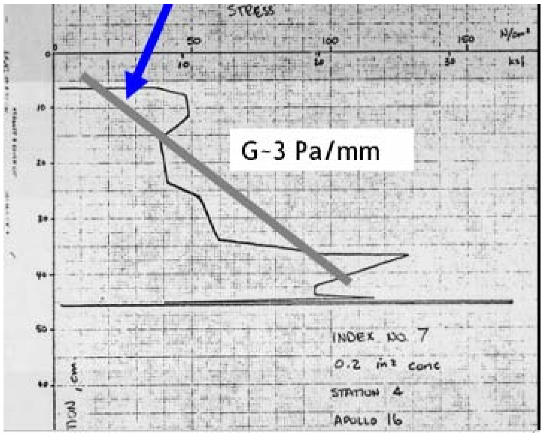


**Figure 7. The soil can be prepared to match the density or penetration resistance, G. Penetration resistance is shown as a function of depth for Apollo 16 SCP with a cone area of 0.2mm$^2$. Courtesy NASA.**

### *Relative Density, Dr*

Relative Density is a measure of soil compactness. If Dr is 0% the soil is at its loosest state and if Dr is 100% the soil is at its maximum density or compactness (**Figure 6**). Dr on the Moon increases rapidly with depth, reaching >90% just 10-20 cm below the surface. As noted previously, soil friction angle and cohesion – which largely determine soil mechanical strength – increase as $D_r$ increases. Therefore for deeper excavation (below 10-20cm), one can assume the worst case scenario and use $D_r$~90% (and corresponding cohesion and friction angle).

### *Penetration Resistance Gradient*

Penetration resistance on the Moon was measured by Apollo astronauts using the Self Recording Penetrometer (SRP) as shown in **Figure 7**. We can prepare the soil to try to match the gradient G, recorded on the Moon. However, to get the required penetration resistance, the G (gradient, not gravity) has to be scaled to account for earth gravity:

$$G_{Earth}=k * G_{Moon}, \text{ where } k= 1 \text{ to } 6;$$ **Equation 2**

Dr. David Carrier used the bearing capacity theory to determine this scaling factor, k, for 20.3mm cone (**Figure 8**). The approximate k is 2.8, but a more accurate number can be obtained by modeling actual cone penetration.

It is recommended to use $D_r$ as a guide for preparing the soil. In all tests, the JSC-1a has been compacted to $D_r$~100%, which is consistent with depth below ~10-20 cm. This creates a worst case scenario and puts excavation results on the conservative side. We use a cone penetrometer to record penetration resistance for quality control purposes. Preparation of GRC-1 and GRC-3 follows similar procedures.

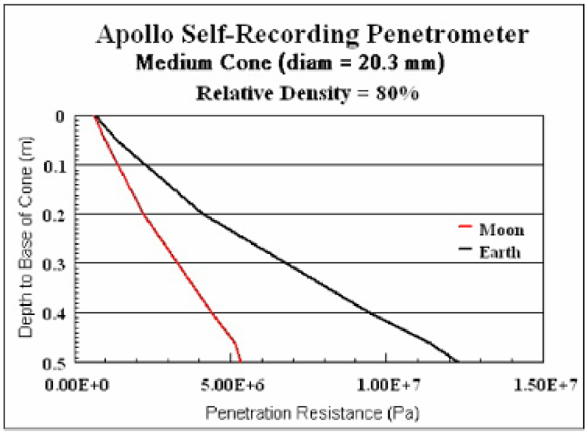


**Figure 8. Penetration resistance as a function of gravity (Earth vs. Moon). Courtesy Dr. David Carrier.**

A question that is often asked is: How large does the soil bin have to be in order to eliminate wall effects? This can be answered by again referring to the cone penetrometer data. Note the "kink" in the plots of penetration resistance vs. depth in **Figure 8**, which occur at the depth of around 0.46 m. This depth is referred to as the "critical depth", and occurs when the shear surface is fully developed. The magnitude of the critical depth is a function of several factors, including the cone diameter, apex angle, and internal friction angle.

The "critical radius" at the ground surface when the penetrometer is at the critical depth is:

$$R=D * \tan(90^\circ-\varphi), \quad \textbf{Equation 3}$$

For the medium cone with a diameter of 20.3 mm, the critical depth is 461 mm for $\varphi=48^\circ$ ($D_r$ = 80%). Hence, the critical radius is 415 mm; and the critical diameter is 830 mm. Thus, for no wall effect, the diameter of the soil bin must be at least 830 mm, or a ratio to the cone diameter of about 41. This is the case for depths of penetration equal to or greater than the critical depth. For lesser depths, a reasonable approximation is to assume the required ratio is proportional.

The above analysis should also be taken into account when sizing a soil bin for excavation studies.

**Step 3: Measuring Excavation Forces (and Exploring Means to Reduce Them)**

In order to determine excavation forces a Lunar Surveyor-style scoop was used (**Figure 9**). This was the only American digging device that was actually robotically deployed on the surface of the Moon. The purpose of the tests was to determine force required to push the scoop into specially prepared soil.

Three regolith simulants were used: GRC-1, GRC-3 and JSC-1a simulants. Two tests were conducted in each soil type. The sequence of operations was to (1) prepare a soil bin with the desired soil and maximum soil density, (2) push the scoop to a desired depth while measuring the penetration depth and force (**Figure 10**). In each case, soil was prepared by putting a surcharge on the surface and vibrating the soil bin for a few minutes. This ensured the soil relative density in each case was >90%.

The test results are shown in **Figure 11**. It can be seen that the Surveyor-like scoop could be pushed 80 mm into compacted JSC-1a with 240 N of force. In compacted GRC-11 and GRC-3, the push force was 190 N. assuming the worst case scenario, that is that the same forces will have to be applied on the Moon (this is not exactly the case, though, as will be explained in the next section), the mass of the excavator would have to be 6 times higher, or 240*6=1440N or 144 kg (317 lbs). This is quite high for relatively small scoop (**Figure 9**). The Apollo Lunar Roving Vehicle (LRV) had a mass of 210 kg. Thus, if a scoop was to be deployed from a robotic arm onboard of Apollo LRV, the LRV would be barely able to support the associated reaction forces. If an excavator end-effector were to be bigger, the mass of the excavator itself would have to be proportionally larger.

**Figure 9. Surveyor-like scoop was used for excavation tests.**

**Figure 10: Measuring static penetration forces of the Surveyor-like scoop.**

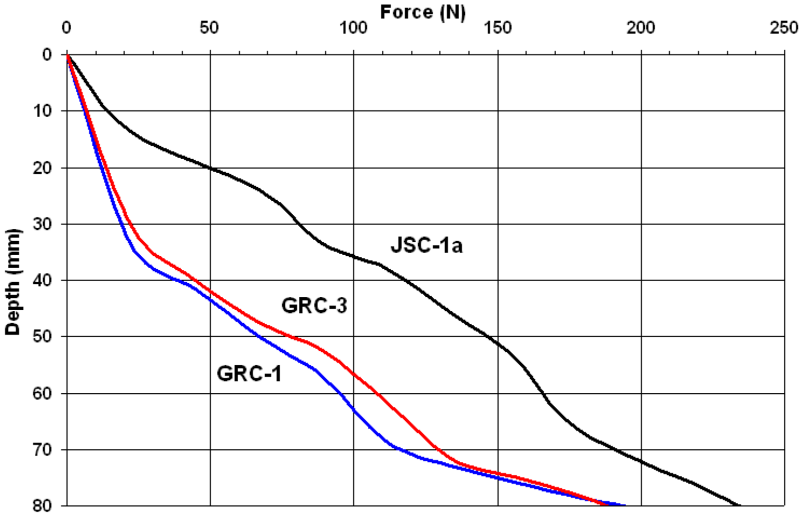


**Figure 11: The force necessary to directly push the Surveyor-style scoop into compacted JSC-1a, GRC-1 and GRC-3.**

### *Why Do We Need to Reduce Excavation Forces?*

Figure 12 shows a schematic of an excavator. There are two main forces that act on a digging scoop: vertical and lateral. If vertical forces are too high, the excavator will be lifted up and eventually will slip. If horizontal forces are too high, the excavator will also slip (pull itself forward).

The mass (W=mg), in fact has the largest influence on the tractive force, $H_O = nbLc + W \tan\phi$. Cohesion and friction angle can not be changed, and wheel diameter and width provides limited traction. Thus, excavation forces can only be reacted by mass of the excavator, and in turn large excavation forces need a heavier excavator.

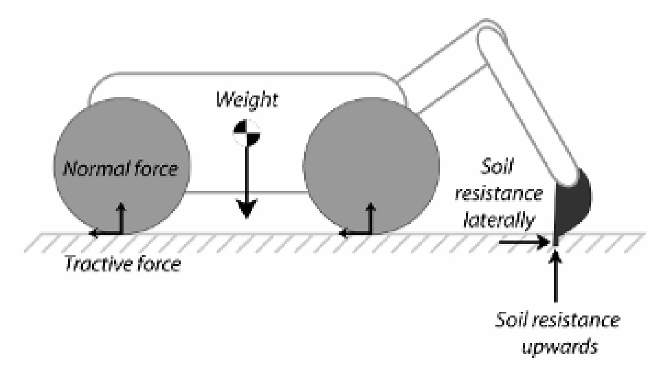


**Figure 12. Forces acting on an excavator.**

Traction equations developed by Bekker were also used by Wilkinson and DeGennaro (2007) to determine the drawbar force (maximum force a vehicle can pull without slipping) of a fully loaded Apollo rover. They determined that the 700 kg rover could pull with a force of only 239N on the Moon. Considering that the cost of placing 1kg on the Moon is on the order of $100k, reducing excavation forces is possibly one of the major drivers in reducing costs associated with establishing of lunar settlements. If excavation forces are reduced, the required vehicle mass will also be reduced. But the payback is much higher. A smaller excavator means:

- less lunar landing mass and propellant to land
- less launch mass and less propellant to launch

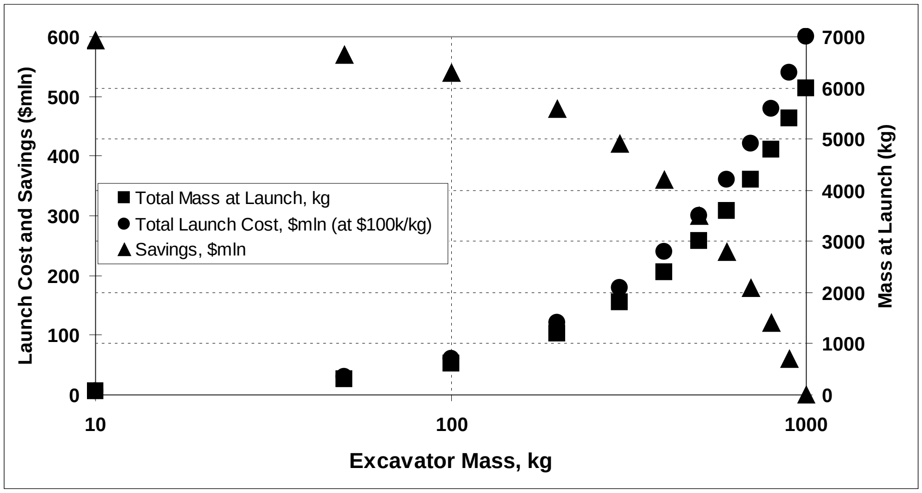


**Figure 13. Cost reduction by decreasing excavation forces.**

The payback for reduced excavation forces is shown in **Figure 13**. The figure assumes the launch cost is $100,000/kg and that the Gear ratio is 1:6 (for every 1 kg placed on the Moon, the launch mass on Earth is 6 kgs). The figure shows that if excavation forces are reduced by 90%, the excavator mass will drop from 1000 kg to 100 kg, resulting in savings of over $500M.

### *Percussive Digging*

A percussive digging tool design is a novel approach ideally suited for lunar applications to defeat compacted regolith. By using the impact energy imparted by a reciprocating hammer transferred through the scoop to defeat the target material, the need for large reaction loads from the vehicle is minimized (Craft et al., 2009, Szabo et al., 1998, Klosky et al., 1998, Zacny et al., 2008, 2009).

The percussive system imparts moderate frequency and low impact loads to weaken a hard-packed regolith matrix at the front of the scoop, thereby allowing the scoop to penetrate a target that otherwise would be too strong for a platform without more mass to react against and to defeat.

In order to determine the extent of digging force reduction of a percussive scoop a custom breadboard with a percussive actuator was fabricated (**Figure 14**). The percussive digger breadboard was attached to a linear slide which was mounted on an aluminum frame. The percussive digger deployment scheme used weights and pulleys to passively apply a constant weight-on-bit throughout an individual test. The weight-on-bit was adjustable for any given test by changing the stack of weights. A laser rangefinder mounted to the side of the linear slide was used to obtain penetration rate data.

Three soils were used: GRC-1, GRC-3 and JSC-1a. Two tests were run in each soil type. The sequence of operations was to (1) prepare a soil bin with the desired soil and maximum soil density, (2) select a desired weight-on-bit and set the proper weight amount, (3) place the cone in the soil so the full cone area is in contact with the soil surface and set at a repeatable position, then (4) start the mechanism and let the weights and pulleys provide the down-force required to penetrate the soil. All tests were run at 2.7 Joules per blow (comparable to the Hilti TE-7A) and at full speed (1750 bpm).

**Figure 15** show the rate at which the scoop penetrates the soil with percussion at two different preloads, as a function of depth. In particular, if a scoop is pushed with 5 N forces while percussive mechanism is running, the scoop will penetrate 70 mm depth (which is close to its practical limit) in approximately 14 seconds. If the force is increase to 22N, a depth of 80 mm can be reached in around 3 seconds.

We reached two major conclusions: The first one is that percussive action substantially reduces digging forces. In particular, a static scoop required a push force of 190 N to reach 70 mm (**Figure 11**). The same depth could be reached using a percussive system with just 5 N of applied force. This represents a force reduction of the order of 38 times. This also means that an excavator could be 38 times lighter and still be just as effective at digging compacted soil.

The second conclusion is that with a higher push force on the percussive scoop, the required digging depth can be reached in a much shorter time. For example, increasing the push force from 5 N to 22 N decreases the digging time from 14 seconds to 3 seconds. This represents not only the time savings for a digging operation but also energy savings since the percussive actuator has to run 3 seconds as opposed to 14 seconds. Therefore, if a lunar excavator can indeed provide higher digging forces, this will not only shorten the excavation time but also make the excavation more energy efficient.

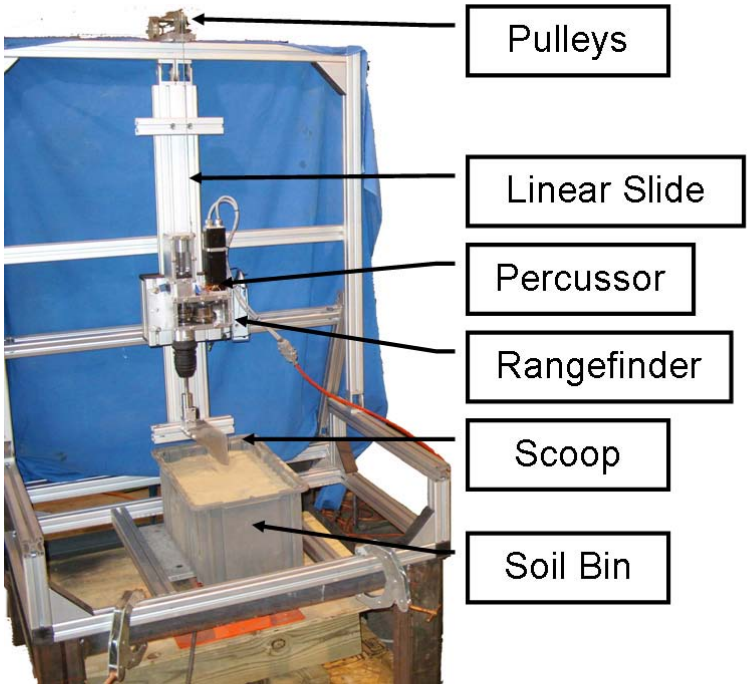


**Figure 14: Experimental setup for percussive testing.**

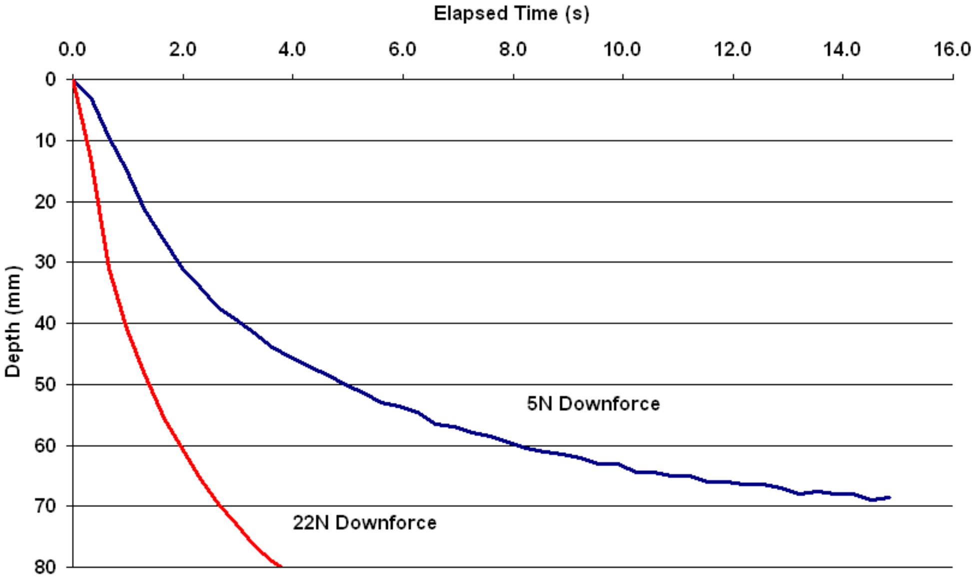


**Figure 15. Penetration as a function of time for 5N and 22N static preloads.**

### *Additional Benefits of Having Percussive or a Vibratory System*

Material was sometimes retained in the scoop due to bridging. This was observed after some of the tests in compacted JSC-1a and compacted GRC-3, but never in GRC-1, and never in un-compacted material. In each instance, the bridged material was easily cleared by "tapping" the scoop, i.e. running the percussor for one or two cam rotations at low frequency.

It is encouraging to note that the percussive digger was capable of clearing itself without physical intervention. The bridging phenomenon could also potentially be avoided through scoop design, e.g. angling the scoop walls or increasing the ratio of width to depth.

**Figure 16: (Left): Material retained in the scoop due to bridging after penetration test in compacted JSC-1a. (Center): The corresponding sharp-walled cavity in the test bin. (Right): "Tapping" the scoop by running the percussor at low frequency for one or two cam rotations was an effective way to clear the retained material.**

### *Final Remarks Concerning Percussive Digging*

Indeed the scooping action also has its heritage in terrestrial applications: backhoes, front end loaders, bucket wheel excavators and many other earth moving systems contain scoops and buckets. However, earth moving machinery is massive and in turn does not require any other enhancements such as percussive vibration of the scooping device: brute force is generally sufficient. Nevertheless, backhoe operators trying to off load cohesive soil, will often use hydraulic rams to induce back/forth motion of the scoop and thus use an improvised 'vibration' to empty the scoop.

Percussion is helpful for two things: (1) breaking up the soil, and (2) moving the soil relative to the scoop (e.g. penetration and dumping). Percussion is not helpful if you want the soil to stay still in the scoop or stick to it, such as when transporting soil or pushing it like a plow. The most efficient use of percussion would be to engage it only when breaking up, digging into, or dumping the soil, and then shut it off when moving the soil around.

In summary, impact assisted excavation is a powerful tool because it reduces the energy required and the reaction forces as compared to similar static load excavation tools. Excavation energies and reaction forces especially in reduced gravity environment are critical for lunar excavator design. For mobile platforms, power availability and reduced gravity traction (enhanced by vehicle mass) will be major challenges. Equipment transported to the Moon from Earth will need to be lightweight and in turn impact (or vibratory) assisted excavation tools being relatively simple and robust will reduce the required excavation energies and reaction forces. For lunar applications a vibratory/percussive system can be applied to a backhoe for excavating trenches and to a bulldozer blade for preparing landing pads as shown in Figure 17.

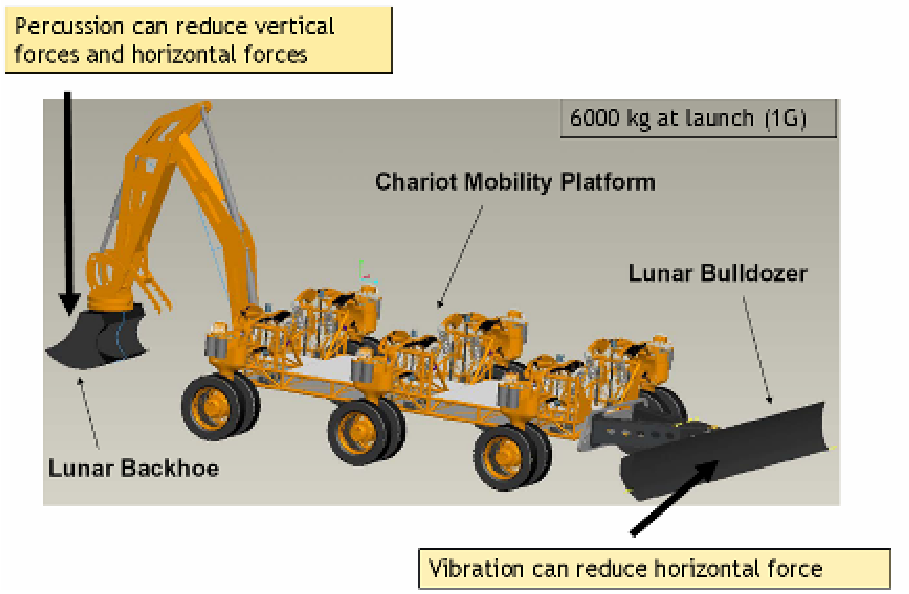


**Figure 17. Vibratory/percussive system can be applied to a backhoe for excavating trenches and to a bulldozer blade for preparing landing pads. (Source: NASA Kennedy Space Center)**

## Step 4: Gravity Scaling of Excavation Forces

Initially we considered a simple case for estimating gravity scaling factors for excavation forces. The question we posed, was how hard do we need to push (force $P_p$) to shear the soil layer of height, H. This is a simplified analysis, in that it assumes that the blade is infinitely wide in the direction perpendicular to the page. It also ignores friction and adhesion between the blade and the soil. There are more complicated equations for a bulldozer blade with a finite width (Zeng et al., 2007).

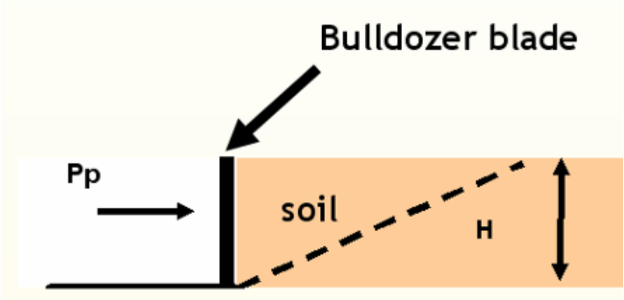


**Figure 18. Estimating Partial Pressure required to push (and shear) the soil layer of height H.**

<u>Force required to push the soil:</u>

$$P_p=0.5*\rho*g*H^2*N_\Phi + 2*c*H*N_\Phi^{0.5} \qquad \textbf{Equation 4}$$

where: NΦ=[1+sinΦ]/[1-sinΦ]

Note:

The friction term [$Pp=0.5*\rho*g *H^2*N_\Phi$] has gravity component, whereas the cohesion term [$2*c*H*N_\Phi^{0.5}$] does not have a gravity component

Based on the above equation, we prepared two curves, one with low cohesion of c=130Pa (**Figure 19**) and the second one with high cohesion of 2300 Pa (**Figure 20**). In both cases the friction angle was assumed to be 40° and density 0f 1.9 g/cc. Both graphs show that the gravity scaling factor initially starts at around 1 for small depth and reaches 6, as the excavation depth get bigger. Another major result is that a little bit of cohesion makes a big difference, especially in low gravity.

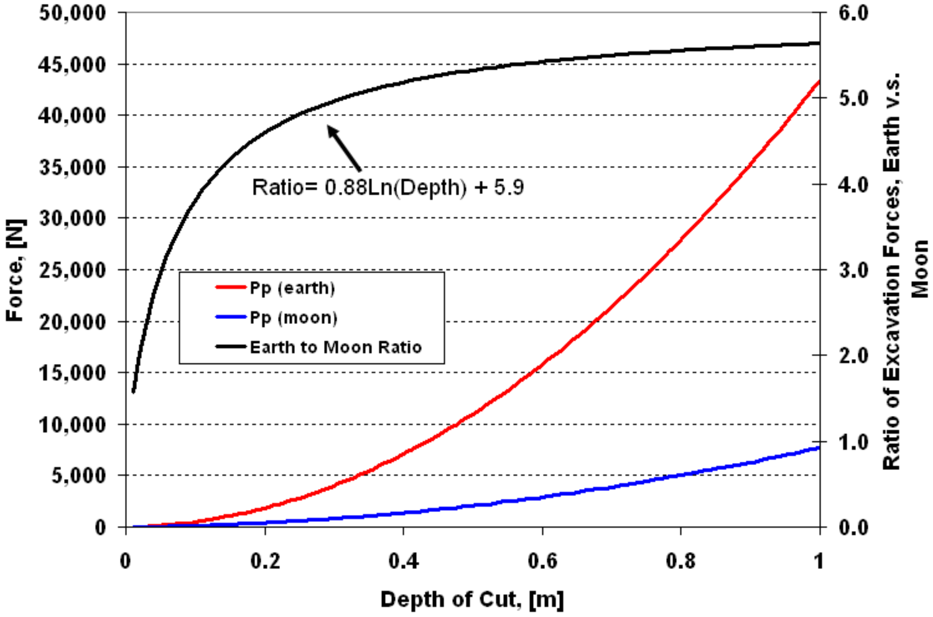


**Figure 19. For low cohesion values, the gravity scaling factor reaches 6 for the blade depth of 1m into the soil. Soil parameters are: cohesion = 130 Pa, friction angle = 40° and density = 1.9 g/cc.**

One can see by inspection that as the height of the blade, H, increases, the ratio of the forces goes to six, because the first term (where the acceleration due to gravity is) dominates. But, as H decreases, the ratio decreases. For example, at H = 0.1 m, the ratio is just 1.6, because the second term (where the cohesion is) begins to dominate.

A similar gravity scaling was conducted using a more complicated excavation equation developed by Zeng et al., (2007). The results are shown in Table 2. Again, it can be seen that for small excavation depths, the ratio is low and increases to 6, for deeper blades.

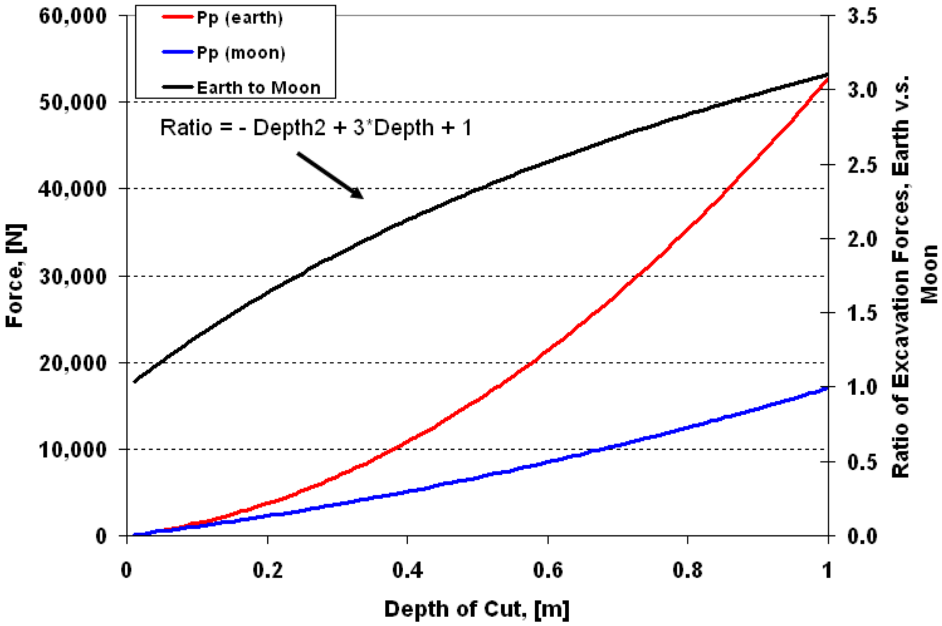
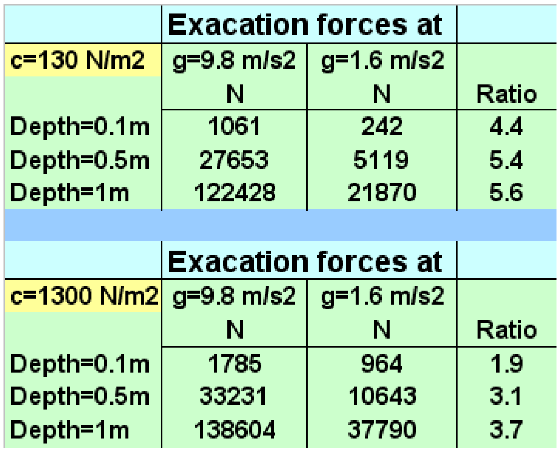


**Figure 20. For high cohesion values, the gravity scaling factor reaches only 3 for the blade depth of 1m into the soil. Soil parameters are: cohesion = 2300 Pa, friction angle = 40° and density = 1.9 g/cc.**

Based on **Figure 19**, **Figure 20**, and **Table 2** it can be concluded that the excavation forces measured on Earth will be 1 to 6 times as great as would occur on the Moon:

- ~1 for 'tiny' excavators - thus need 6x more massive excavator
- ~2 for a "typical" excavator - thus need 3x more massive excavator
- ~6 for a big excavator - the excavator mass may remain the same

**Table 2. Ratio of excavation forces on earth and on the Moon as a function of cutting g depth of a bulldozer blade and coil cohesion.**



| | Exacation forces at | | |
|---|---|---|---|
| c=130 N/m2 | g=9.8 m/s2 | g=1.6 m/s2 | |
| | N | N | Ratio |
| Depth=0.1m | 1061 | 242 | 4.4 |
| Depth=0.5m | 27653 | 5119 | 5.4 |
| Depth=1m | 122428 | 21870 | 5.6 |
| | | | |
| | Exacation forces at | | |
| c=1300 N/m2 | g=9.8 m/s2 | g=1.6 m/s2 | |
| | N | N | Ratio |
| Depth=0.1m | 1785 | 964 | 1.9 |
| Depth=0.5m | 33231 | 10643 | 3.1 |
| Depth=1m | 138604 | 37790 | 3.7 |

### *The Required Mass of a Lunar Excavator*

**Figure 21** shows required mass of a bulldozer as a function of bulldozer blade depth for Earth and Lunar cases. The required vehicle mass was assumed to be 3x Drawbar pull. The drawbar pull was calculated using the Zeng model (Zeng et al., 2007) and the following parameters: Density=1.9 g/cc; Friction angle: 40°; Cohesion: 1300 Pa; Blade width: 1m.

It can be seen that for a small depth of cut the ratio of excavator mass on earth and on the moon is large. This ratio decreases as the depth of cut increases. Thus:

- Tiny excavators are less effective (per kg excavator mass) on the Moon than on Earth
- Large excavators are almost as effective (per kg excavator mass) on the Moon as on Earth

To make regolith moving on the Moon feasible we need to find a means of reducing excavation forces and in turn excavator mass. This can be achieved using a percussive/vibratory system.

**Figure 22** is the same as **Figure 21** except that an additional curve is added for the case where bulldozer blade is vibrating. It was assumed that draft force reduction in this case was 70-90%, that is Draft Force$_{vibratory}$=0.7-0.9 Draft Force$_{static}$. A bulldozer excavating soil to a depth of 25cm on the Moon needs to weigh over 7 tons if its blade is not vibrating and only 700 kg if the blade is vibrating.

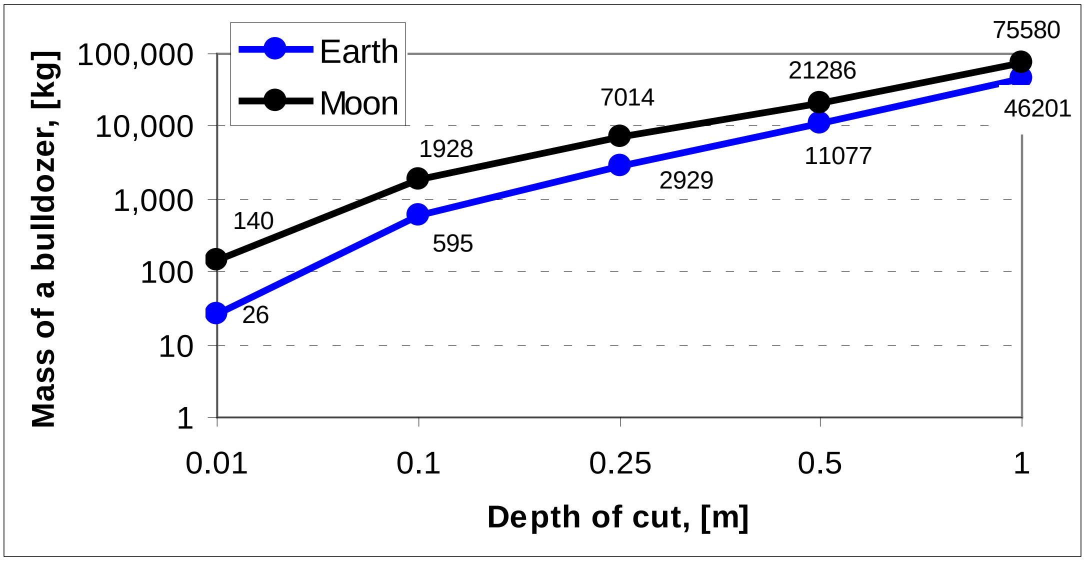


**Figure 21. Required mass of a bulldozer as a function of bulldozer blade depth for Earth and Lunar cases.**

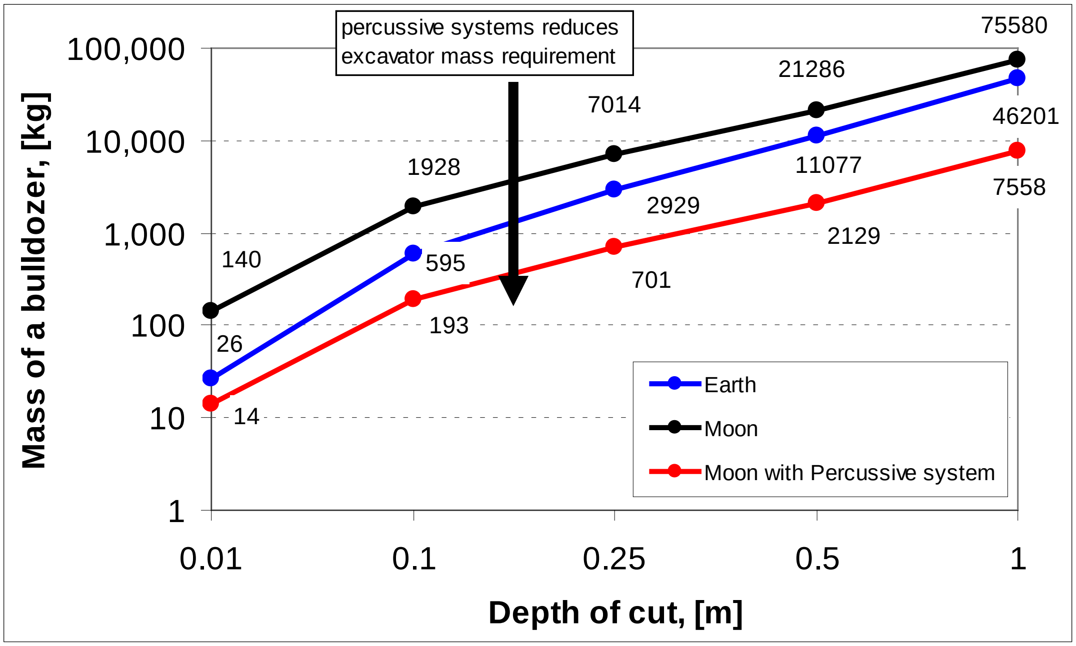


**Figure 22. Required bulldozer mass as a function of blade depth of cut for Earth gravity and Lunar gravity. For the latter, two cases were considered, one with static blade and one with vibratory blade, where vibration reduced draft force by 70-90%, that is Draft Force$_{vibratory}$=0.7-0.9 Draft Force$_{static}$.**

## Step 5: Parametric Worksheet for Sizing Lunar Excavators

We have developed an Excavation Prediction Tool (parametric spreadsheet) that uses a number of inputs and calculates power, time and energy for each of the excavation tasks identified by Mueller and King (2008). The inputs include various parameters pertaining to an Excavator, Scoop, Bulldozer, Soil, and Batteries (Power Source). In addition, each of the excavation tasks were characterized by volume of regolith to be moved, distance from lunar base etc. These are shown in **Figure 23**, **Figure 24**, **Figure 25**, and **Figure 26**.

As an example, the spreadsheet was used to perform the trade off between using a percussive system for digging trenches vs. using static excavator (i.e. with no percussion). **Table 3** show that a percussive digging system uses more energy (~60 kWhr) than a static digging excavator. However, the static excavator needs to weigh much more (3000 kg as opposed to 200 kg) in order to provide sufficient digging forces to a scoop. The mass of batteries holding 60 kWhr of energy is 800 kg. Thus, if a 200kg excavator required its own power supply, the total mass would be 1000 kg. This is 2000 kg less than the excavator that does not use a percussive system.

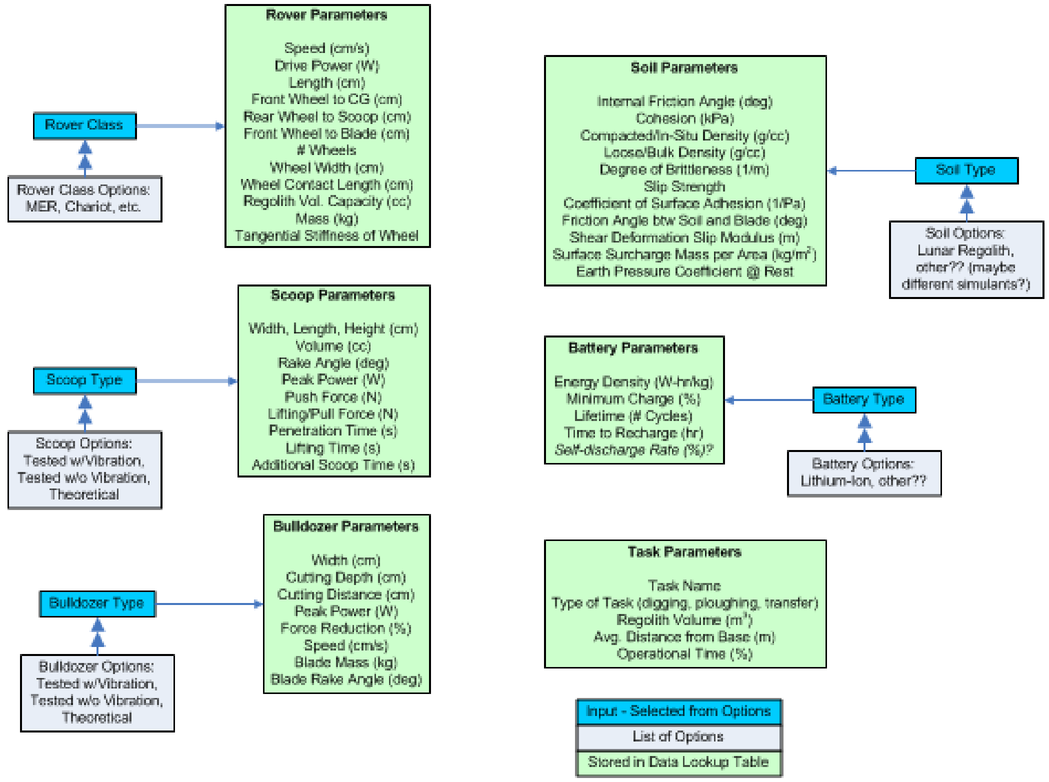


Figure 23. Parameters for Fixed Data Input Table

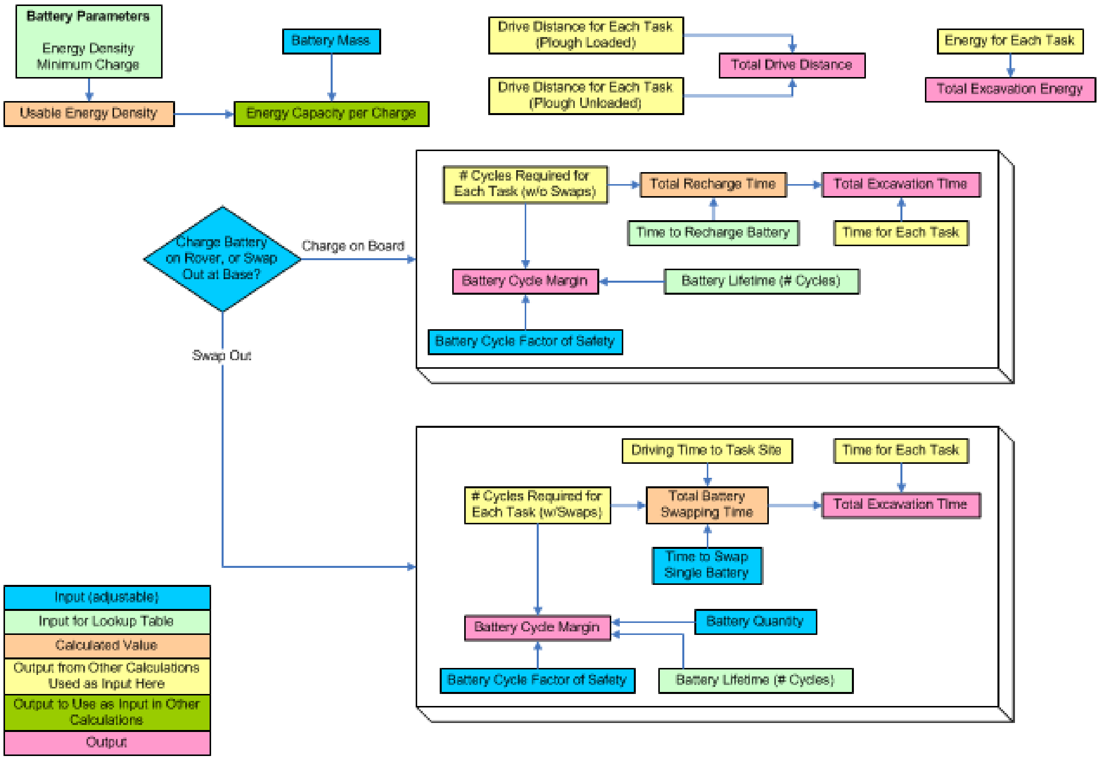


Figure 24. Time and Energy Calculations.

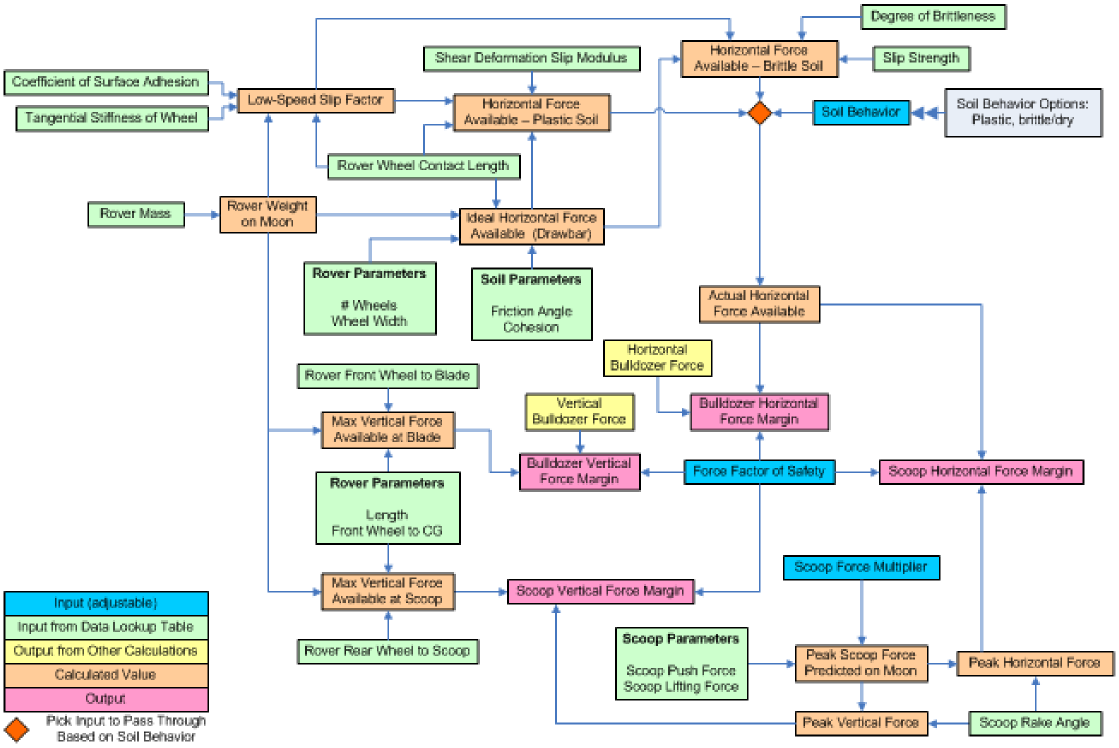


Figure 25. Force Calculations and Margins

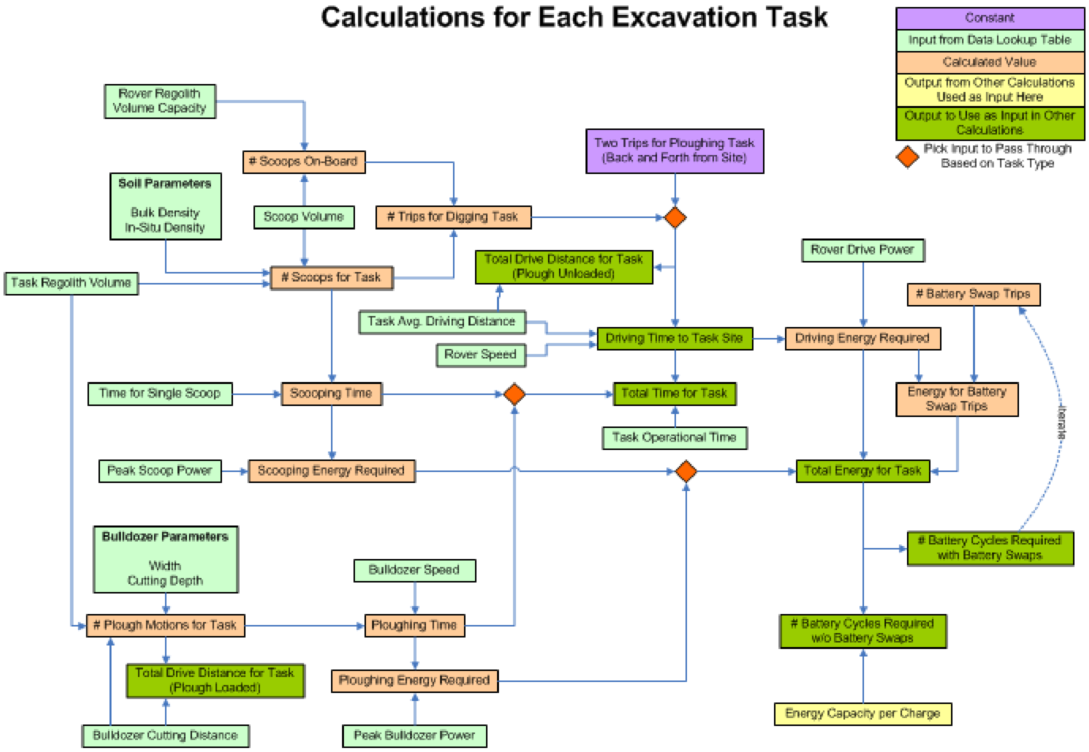
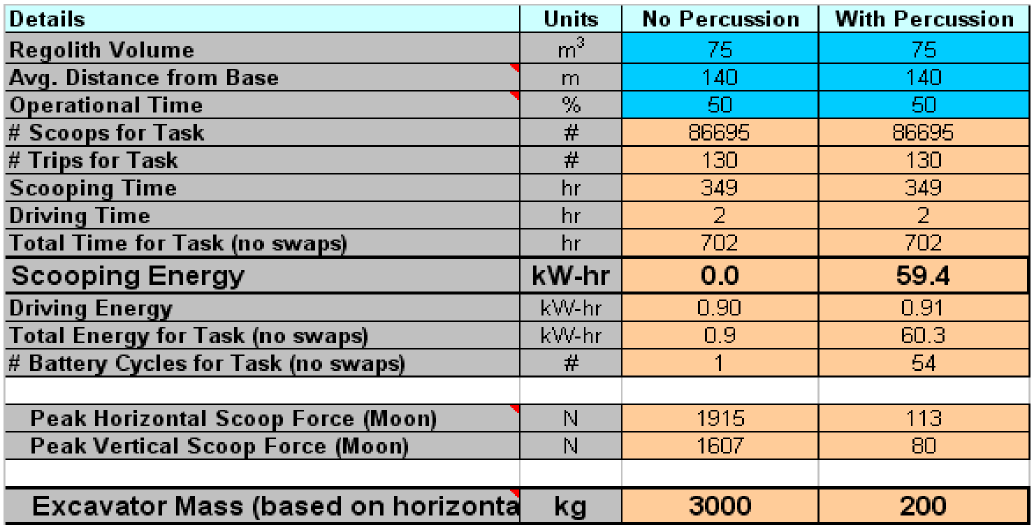


Figure 26. Calculations for Each Excavation Task.

### *Case Study: Digging Cable Trenches*

The spreadsheet was used to perform the trade off between using a percussive system for digging trenches vs. using static excavation system (i.e. with no percussion). Table 3 shows the actual trade study.

**Table 3. Trade study between digging trenches with and without percussion.**



| Details | Units | No Percussion | With Percussion |
|---|---|---|---|
| Regolith Volume | $m^3$ | 75 | 75 |
| Avg. Distance from Base | m | 140 | 140 |
| Operational Time | % | 50 | 50 |
| # Scoops for Task | # | 86695 | 86695 |
| # Trips for Task | # | 130 | 130 |
| Scooping Time | hr | 349 | 349 |
| Driving Time | hr | 2 | 2 |
| Total Time for Task (no swaps) | hr | 702 | 702 |
| **Scooping Energy** | **kW-hr** | **0.0** | **59.4** |
| Driving Energy | kW-hr | 0.90 | 0.91 |
| Total Energy for Task (no swaps) | kW-hr | 0.9 | 60.3 |
| # Battery Cycles for Task (no swaps) | # | 1 | 54 |
| | | | |
| Peak Horizontal Scoop Force (Moon) | N | 1915 | 113 |
| Peak Vertical Scoop Force (Moon) | N | 1607 | 80 |
| | | | |
| **Excavator Mass (based on horizonta** | **kg** | **3000** | **200** |

It can be seen that a percussive digging system uses more energy (~60 kWhr) than static digging excavator. However, a static excavator needs to weigh much more (3000 kg as opposed to 200 kg) to provide sufficient digging forces to a scoop. The mass of batteries holding 60 kWhr of energy is 800 kg. Thus, if a 200kg excavator required its own power supply, the total mass would be 1000 kg. This is 2000 kg less than the excavator that does not use a percussive system.

## CONCLUSIONS

In this paper we presented a 5-step, bottom-up approach to excavation. We first selected a lunar regolith simulant, prepared it to reflect the regolith state as found on the Moon, measured the excavation forces, scaled them while accounting for lunar gravity and finally we inputted the data into our excavation model to determine power, energy, time for excavation tasks and the mass of the excavator.

Lunar regolith simulant, JSC-1a was used in all experimental studies, as it was a well characterized simulant with size distribution close to actual lunar regolith. Additionally, two simulants GRC-1 and GRC-3 were used. In all cases, the soil simulants were compacted to >90% relative density.

In all tests we used a Surveyor-like scoop since this was the only well known robotic excavator ever to be deployed on the Moon. Quasi-static penetration required ~240N of force to push the scoop into compacted JSC-1a. Less force was required to push the scoop into GRC-1 and GRC3. Percussive digging tests revealed that the digging forces were reduced by up to 38 times. This allows using smaller (less massive) excavators, which with the launch costs of $100,000/kg, offers tremendous savings. The drawback is that additional power is required to power a percussive actuator. However, increased power is more readily available than increased mass for the application at hand. Power is a local resource that can be obtained through solar energy conversion on the moon.

Excavation models were used to determine a gravity scaling factor. It was found that for very small digging/bulldozing blades, the forces on the Moon will be up to six times higher and in turn the excavator itself has to be six times more massive. For very large digging/bulldozing blades the forces will be the same on the Moon as on earth and in turn, the excavator mass can be the same.

The above steps can also be used in reverse. Let's say we are designing a scoop for use on a given lunar lander or rover. The first step is to find out how much reaction force is available, and based on this calculate the size of the excavator blade that can be used without the lunar excavator slipping or tilting.

A parametric spreadsheet was also used to determine benefits if percussive as opposed to static digging approach. For a task of digging trenches, it was found that with a percussive approach the mass of the excavator (including the weight of batteries required to perform the entire excavation task) would be still be 60% lower than the required mass of the excavator to react forces from static digging scoops.

## ACKNOWLEDGMENTS

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