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Lunar Regolith

John V. Gies, PE, M. ASCE[1]

Abstract

The Lunar regolith has two potential uses; the first as a building material in its native state and the second as feedstock for industrial processes, including that of the creation of manufactured building materials. For the purposes of this effort it is assumed that the early uses of lunar regolith will be used in the first sense, in its native state. Used in this manner it can provide shielding for personnel and equipment spaces, shielding from meteorites, thermal extremes, radiation, both natural and man-made, and the blast effects of rocket landings and takeoffs. The regolith is also the most probable foundation for structures. (The moon is mostly covered with regolith; there comparatively little exposed rock.) This paper is, therefore, devoted to an examination of regolith used in its natural state. However, the issues of handling the regolith are also valid for regolith used as feedstock.

Uninhabited structures such as antennae, solar power arrays, nuclear power sources, and scientific apparatus can be made to sit upon and/or be anchored to the regolith. As the size and sophistication of lunar structures increase so will the knowledge of the lunar environment that will engender their design and construction.

Enough is known about the general mechanics of the regolith to use it as a building material. However the issues of excavatablity and material handling are yet to be resolved. Much of the information required for a particular installation will be site-specific. Therefore the level of knowledge required may be quite limited but the ingenuity to obtain reliable and usable information at this level may well prove to be quite complicated.

As each of the issues is discussed "data needs" are identified.

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[1] Consulting Engineer, 86 Marinero Circle, Tiburon, CA 94920

Foundations

The lunar structures considered in this paper are limited to surface founded or shallowly embedded. Such structures may include mounding of the regolith.

Bearing

The Apollo, Surveyor, and Lunakhod experience indicates that the regolith is capable of supporting the modest structures and vehicles currently envisioned during the initial phases of a return to the moon.

For structures that are essentially pressure vessels, power sources, and antennae, there is little need for extensive bearing strength studies. The bearing strength required to support the vehicle that lands these components will be more than that required to support the components themselves. The Apollo experience would indicate that the entire mass of the lunar lander caused little settlement under the four foot pads of any of the Apollo landers. The size and depth of the tracks of the lunar rovers and the lunakhods indicate the same thing. (Carrier et al, 1991) The ultimate bearing capacity is on the order of 6000 kPa (1 m footing). (Carrier et al, 1991) There is every indication that the regolith becomes more compact with depth indicating the load bearing capacity increases with depth. (Carrier et al, 1991) However prudence would dictate site specific exploration at selected base sites.

Bearing strength, or compactibility, is not so much the issue as the consequences of differential settlement. Some differential settlement between components can be tolerated, however the ramifications of differential settlement, for example, in a vessel 8 meters in diameter and 32 meters long is yet another matter. Then again what is the probability of short range differences in the nature of the regolith? The combination of site, structure, and the means of placing a structure is unique. This is another argument for a site-specific approach in "data needs".

Bedding

The safest approach for the founding of early structures is a spread footing. For buried and light, simple structures that are envisioned as the initial elements to establish a lunar base the proper bedding to avoid concentrated loads upon the structure, as well as the supporting regolith, a means of separating the fines from the coarser fractions of the regolith is worthy of investigation, a "data need". Also required is an effective manner of placing the bedding material to conform to the base of a structure, another "data need". This is as much of a mechanical as a structural problem, but need not be a "regolith" problem.

Burying (Implies Excavation)

The burying of a structure requires not only increases the bearing loads and requires more careful bedding of the structure, it can subject the rest of the structure to increased loads. The static loads are a function of the amount of required depth of cover, the density of the covering material, and the parameters of soil pressure. (See the next section, Pressure on Structures)

Habitats will be pressure vessels, most likely covered or partially buried beneath 1 -4 m of regolith. The primary factors in the pressure of the regolith on the buried structure is relative density, angle of internal friction, ϕ, and gradation. The presence of large, hard, sharp rocks would engender a significantly different pressure vessel design than a material that is uniformly fine and free of large rocks; these are issues of gradation and angularity. Compaction is one of the controlling parameters of the stresses on a buried structure. It also has an effect on the load distribution on the structure during the burying process. The bedding of the vessel has a large effect on induced stresses. Material gradation and compaction are prime considerations in bedding. Therefore the important parameters are: gradation, angularity, angle of internal friction, and compactibility. (Carrier et al, 1973) Although this information is known in general it should be noted that ultimately these are site-specific parameters.

Pressure on Structures

The pressure of the surrounding material upon a structure is a vital design parameter. The primary stresses upon lunar habitats will be their internal pressure (about 0.8 - 1.0 atm ≈ 80 -100 kPa) and the loads induced by the surrounding regolith. For a structure of circular cross section the vertical soil pressure, p_v, may be considered a function of the depth, z, the bulk density, ρ, and the local gravitational acceleration, g (g_m ≡ gravitational acceleration at the surface of the moon). (Proctor and White)

To keep things in perspective consider the pressure resulting from 4 m of compacted regolith upon a structure:

$$p_v = 4\text{ m} \times 1.9\text{ g/cm}^3 \times 1.62\text{ m/sec}^2$$

$$\simeq 12\text{ kPa}$$

This is compared to 1 atm or ≈ 100 kPa which is equivalent to a column of compacted regolith over 32 m high. The difference is an order of magnitude. This also indicates that mounding regolith upon pressure vessels is not a useful internal pressure counterbalancing measure.

The horizontal pressure, p_h, on a vessel is a function of depth, z, density, γ, and a constant, K, that is a function of the angle of internal friction, ϕ. It is also a function of whether the soil and the structure are in a balance with each other or soil pressure at rest, the soil is pushing on the structure, active (structure gives under load and the soil moves to it) or the structure pushes on the soil, passive (the structure is the active agent and the soil is "passive") In general the equation is:

$$\begin{aligned} p_h &= k p_v \\ &= k G a_g z \end{aligned}$$

while the parameter, k_O, soil pressure at rest would address the situation of a vessel with a constant pressure, the active and passive soil pressure would apply more to a vessel varying in pressure, e.g. an airlock. (The effect of varying pressure with the resulting varying strain in a pressure vessel inducing movement in the surrounding soil is a function of the design of the vessel. This may be more of an issue with buried storage tanks, or no issue at all. Further study is required to determine if this is a "data need".) The values of these parameters are, respectively: (Terzaghi and Peck, 1968) and (Mayne and Kulhawy, 1982)

$$k_A = \tan^2\left(45° - \frac{\phi}{2}\right)$$

$$k_O = \sin(1 - \phi)$$

$$k_P = \tan^2\left(45° + \frac{\phi}{2}\right)$$

Quite clearly the angle of internal friction, ϕ, is a vital predictive property of a granular material and the value of that parameter must be known for any potential lunar base site. The angle of internal friction has been found to be 30°-50° from the Apollo data (Mitchell et al., 1972b, 1974) and 20°-25° from the Surveyor data () The value of ϕ is a site-specific parameter.

Only in the passive pressure regime is the pressure greater than the vertical pressure, and then not much for the range of values of internal friction to be found in the regolith, e.g. 50° max $\rightarrow k_A = 7.5$. This would be on the order of the internal pressure for habitats buried at moderate depths. This should simplify the design of pressurized structures for lunar burial.

The question arises here of a cycling pressure vessel working its way up through the regolith in which it has been buried. For airlocks connected to habitats this could lead to a negative differential settlement problem. This is an item requiring further investigation.

It is important to realize the behaviour of simulants may be quite different from that of the regolith on the moon. The non-presence of water and the associated Van der Waals forces may make the regolith behave quite differently in the lunar environment than either regolith or simulants behave on earth after being exposed to air and moisture. Particle surface charges and their effect on adjacent particles may have similar, or different, effects on the bulk properties of the regolith. It is important, therefore, that these properties be determined in the lunar environment.

Excavation, Transportation and Placement

Burying a structure implies excavation and the controlled placing of the regolith. It is here that the little is known and the much that needs to be known. A regolith cover appears to be a convenient and cost effective strategy for impact, radiation, and, perhaps, thermal protection of an inhabited structure. This apparently simple process of digging a hole, dragging in a vessel, and then covering it over requires all sorts of information that we currently lack.

The quantities of regolith to be moved for even modest structures are in the thousands of cubic meters. Is the regolith "hard to dig"at depth? Dig with what... hand tools, bulldozers, shovels, and up to what size? These questions are site specific in nature. The general characteristics of the regolith at depth, with regard to bulk excavation, are not known. The most important parameters is the extent of the bonding of the regolith particles and the range of particle sizes.

If the regolith is bonded or cemented together it may require breaking up prior to being excavated. Terrestrial experience indicates that stiff soils and weak rock can be ripped to loosen it. This is much more energy efficient and much more rapid than the alternative of blasting. Often rock or cemented soil that is quite hard can be ripped, becoming a well graded and relatively fine material after transporting to its final placement. Coring, particularly small diameter coring, often does not provide reliable information about such bulk properties as "rippability". This is why earthmoving equipment manufacturers like Caterpillar use seismic wave velocities to estimate the rippability of material. (Caterpillar, 1993) (Nichols, 1976) Their charts speak to ripping granite, basalt, caliche, sandstone, schist, and iron ores, among others. The regolith appears quite rippable with machinery of a size to be productive for burying modules and supplying feedstock for regolith utilizing manufacturing. Verifying that the regolith requires ripping, that it is rippable, and a standard test developed to determine rippability are "data needs".

Methods of Excavation

Any use of the regolith, beyond that of a supporting surface, will require first excavating it. There are several methods of excavation. They ultimately break down into scooping or scraping. (Nichols., 1976)

Scooping is the act of "taking a bite" of the material. Various scooping schemes brake down into forward, or shovel, and backward, or hoe. These are either on an arm, e.g. shovel, bucket loader, and, backhoe, or in a rotary bucket, e.g. bucket wheel excavator and chain bucket ditchers.

Scraping is act of forcing a vertical surface into the material. There is often a provision made for a blade at the base to cut the material. Examples are dozers, which cut a layer of material and then push the pile and scrapers which cut a layer of material which then piles up in the box of the scraper.

There are schemes which have features of both, such as a dragline. All these methods are dependent upon a the gradation, cohesion, and internal friction of the material to be excavated. Again these are site-specific parameters.

Transportation of Regolith

Transporting the excavated regolith, whether to deliver it to the place where it will be used or to dispose of it, raises issues separate from other functions. The handling of large quantities (1000's of cubic meters) no longer becomes an item of scientific curiosity, it becomes an engineering imperative. The transportation of regolith can be either in a container, by conveyor or by dozing. With the exception of dozing, loading and unloading are issues in transportation. All the material parameter issues of excavation apply to transportation. In addition the ability of the material to flow, or "flowability", becomes an issue.

The ability of the regolith to stay "mounded" on a conveyor belt determines the efficiency of that conveyor in transporting the material. Slope instability, particularly in the dynamic regime of a belt moving up an incline and over idlers, would lower the efficiency of the belt. Material falling off the belt would create maintenance problems as well as inefficiencies. Much of the knowledge to predict the bulk behavior of regolith on conveyors will be empirical. Therefore it is herein proposed that conveyors would not be the mode of regolith transport for the initial phases of lunar bases.

Conversely the ability of the regolith to flow is very important for the loading and unloading of containers. The manner of loading and unloading depends upon the ability of the regolith to flow (or its reluctance to flow). For example bottom dump transporters would be inefficient of the regolith did not have a tendency to flow through the gates on the bottom of the box. Cohesiveness can force the box to have steep sides which is an inefficient container and is top heavy. Cohesive material also tends to "bridge". These problems can be alleviated with vibrators on the box, but with the addition of complexity and increased maintenance requirements. Again this is a site-specific set of parameters.

As an example a spherically ended cylinder buried at the spring line will require 5 to 8 times its volume to cover it with a minimum of radiation shielding regolith. For such cylinders, say 8 m x 32 m, this translates into 3000 to 4000 cubic meters of regolith. If this same vessel is placed upon the surface 2 to 3 times as much regolith will be required to bury it. Large volumes of material will have to be moved to cover even the most modest of bases. This is an essential point. In a design exercise it becomes abundantly obvious that the single biggest task is the moving of regolith and all the issues associated with it. The volumes involved are quite large.

Not only is it vital to establish these parameters, but the information obtained relates to the design of <u>both</u> the structures and the equipment to erect them.

Placement

The placement of a granular material not only consists of controlling the spacial arrangement of the material but the density of the material as well. The density is controlled by the type, intensity, and duration of the compaction method used.

Placement is the inverse of excavation. Controlling pressures on buried structures will be extremely important. Equipment operating in the close proximity of pressure vessels is a scary business. Vibration compaction near sensitive equipment is an issue needing investigation. The placement process is fraught with potential problems. Perhaps it is better to mound a greater amount of unconsolidated regolith on a stout vessel than it is to carefully compact a lesser amount on a more finely engineered vessel. Again a systems problem but the basic information needed to determine the range of solutions.

There are several compaction common methods. Listed and expounded in decreasing order of usefulness in a lunar environment are: (Nichols 1976)

> Vibratory compaction which compacts dry or damp granular material by shaking it. Although some lubrication (usually water) aids the process, it appears to be the most appropriate for lunar regolith.
>
> Rolling compaction is a combination of kneading and static compaction which works best upon damp granular soils with some cohesive binder. It is not the condition of the lunar regolith.
>
> Kneading, as in bread dough, works the air pockets out of a damp cohesive material thereby compacting it and allowing the cohesive bonding to reestablish between the soil particles. This is not applicable to lunar regolith.
>
> Static compaction is a process used for clays and clayey silts. The are consolidated by using the weight of a surcharge to drive the water from fine grained and cohesive soils over an extended period of time. This does not appear to be an economic compaction process for lunar regolith.

Quite clearly vibratory compaction would seem to be the answer, but all the dynamic methods should be explored to determine the most time, mass, and energy efficient that is reliably predictable. This is an important "data need".

Slope Stability

Slope stability of dry granular materials is directly related to the angle of internal friction.

For slope angles approaching the angle of internal friction the intensity, frequency, and duration of energy to which the soil is subjected ultimately determines the stability of the slope.

On earth the water content of soils as well as the mineral, gradation, and local stress field will determine the "stand-up time" of a fresh cut. This is of paramount importance in tunneling and rapid cut and cover operations. Is there a lunar analogue? (Electric charge of the particles themselves imitating the Van de Walls forces water molecules?) This is an empirical determination. For efficient excavation to depths much beyond a meter this becomes an important parameter. This issue has yet to be addressed and will have to be determined before any large scale lunar excavation can occur.

The slope stability of lunar regolith in a regime of added energy, e.g. shock, vibration, and thermal stresses and reduced gravity is a "data need".

Slope stability is also an issue in placement and burial. The stability of a slope under equipment will determine how much material will be needed to bury an object. Ultimately slope stability becomes a vital parameter in time and energy studies relating to excavation, transportation, and placement.

Anchoring (and Drilling)

Soil anchors for guying would allow the erection of large mass-efficient structures. Communication towers are an obvious example. This is especially important for tele-operated equipment which cannot stand the delay incurred in satellite relays. Reliable, high bandwidth, high speed communications require high frequencies, perhaps into the infra-red. Remote control of equipment cannot tolerate the high noise and time lag of satellite relays. The horizon is quite close on the moon. Assuming a spherical moon, the horizon distance from a elevation in meters, h, is:

$$d_H \approx 1.86\sqrt{h}\ \text{km}$$

where h is in meters. E.g. Relay stations with an antenna height of 180 m would be spaced at 50 km ($2\,d_H$). Anchoring would be a structural stratagem for towers. As there is little to generate lateral loads and gravity loads are small; therefore guyed towers would be even more efficient on the moon than on earth. However a certain amount of lateral bracing is needed for column stability and the imperfections of "pioneer construction".

The ability to reliably design and utilize such anchors requires a knowledge of the subsurface conditions. Items affecting the design of soil anchors are: the regolith density, the coefficient of friction on materials to be used in screw type anchors, and drilling parameters. The drilling parameters are:

Ability of the holes to stand up, (Mitchell et al., 1972a),
Material variations with depth, and

Power requirements which are a function of material, bit types, e.g. diamond, carbide teeth, blades only, etc, and the length and straightness of the drill string.

Drilling into the lunar regolith on a production basis will be quite different from the single use core drilling done on the Apollo missions. The requirement for lubricating and cooling the bits in high vacuum is a challenge not widely addressed in the literature. The drilling of rock is even more demanding than drilling in the regolith. The mechanics of drilling in the lunar regolith and rock is a "data need".

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The Effect of the Lunar Surface Environment upon Machinery

John V. Gies, PE, M. ASCE[1]

Abstract

The surface of the moon is a dirty place. Unlike free flying orbital and deep space craft, the surface of the moon presents all the environmental extremes of space and adds to that the lunar regolith. The lunar regolith consists of shattered basaltic rocks with most of the material a fine grit. The other significant fractions of the fines are basaltic glasses and metallic dust, mostly iron. This is a mix that has proven to be extremely harsh on equipment in a terrestrial environment. The lack of the lubricating effect, minor as it may be, of air and moisture in the vacuum of the lunar surface compounds the abrasive qualities of the regolith.

This paper is an examination of this harsh environment upon such equipment as excavators, transporters, hoisting machinery, antenna aiming mechanisms, air locks, and similar moving equipment. The goal is to define what additional data must be gathered to design reliable and effective equipment to survive the lunar surface environment.

Introduction

Lunar regolith is already known to be an abrasive material which has an insidious ability to infiltrate into every possible place. (Bean et al., 1970, Scott and Zuckerman, 1971, Carrier et al., 1991) As such these properties must be understood in the design of equipment to construct and maintain lunar bases. The reliability required to ensure the successful completion of a base will result in the creation of equipment that will have an operating life exceeding that required to perform its initial job. It will be important to test designs and materials in a lunar environment to verify and improve the terrestrial generated ideas used in their construction.

The design of early lunar structures and the equipment to construct them is, perforce, a symbiotic relationship. Hence the goal of this paper, whilst by no means exhaustive, is

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[1] Consulting Engineer, 86 Marinero Circle, Tiburon, CA 94920