

**The four things you need to know about the  
GEOTECHNICAL PROPERTIES OF LUNAR SOIL**

by

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## INTRODUCTION

The *Lunar Sourcebook* (Carrier et al. 1991) describes the geotechnical properties of lunar soil in some detail, including:

**Particle Size Distribution**

**Particle Shapes**

Specific Gravity

**Bulk Density** and Porosity

**Relative Density**

Compressibility

Shear Strength

Permeability and Diffusivity

Bearing Capacity

Slope Stability

Trafficability

The purpose of this report is to describe briefly the four properties that are the most important for understanding the behavior of the lunar soil. These are: particle size distribution, particle shape, bulk density, and relative density.

## PARTICLE SIZE DISTRIBUTION

The results of nearly 350 particle size analyses are summarized in Fig. 1 (Carrier 2003). These soil samples were obtained from seven landing sites on the Moon: Apollo 11, 12, 14, 15, 16, and 17; and Luna 24. There are approximately 4,500 data points in Fig. 1.

As shown in Fig. 1, lunar soil is broadly graded from medium sand to fine silt: On average, 95% of the soil is finer than 1.37 mm by weight; and 5% is finer than 0.0033 mm. The average or median particle size,  $D_{50}$  (where 50 refers to 50% passing) is approximately 0.072 mm. This size is very close to the boundary between sand and silt (0.074 mm), and the lunar soil is usually described as either silty sand or sandy silt. The sand-silt boundary is the limit of size that can be resolved with the unaided human eye; thus, about half of the soil, by weight, is too fine to be seen. For this reason, lunar soil is also frequently referred to as “dusty” (see Fig. 2). [The mean particle size,  $D_{Mn} = (D_{84} \times D_{50} \times D_{16})^{1/3}$  is approximately 0.070 mm; and on that basis, geologists describe lunar soil as very fine sand.]

The average coefficient of uniformity,  $Cu = D_{60} / D_{10}$  is 16; and the average coefficient of curvature,  $Cc = (D_{30})^2 / (D_{10} \times D_{60})$  is 1.2. Based on these parameters, lunar soil can be described as “well-graded”. On Earth, it is known that soils having a **Cu** less than 10 are self-filtering with respect to a hydraulic gradient, but soils having a **Cu** more than 20 are likely to be internally

erodible, and, hence, unstable. With an average **Cu** of 16, lunar soil may be internally erodible; that is, potentially susceptible to “segregation piping”. This occurs even though lunar soil is not gap-graded and, indeed, satisfies the criteria for well-graded. It is simply a consequence of the very broad particle size distribution which in turn is due to the very dynamic process of meteorite impact that forms and deposits lunar soil.

The surface of the Moon covers an area nearly equal to that of North and South America combined. While internally erodible soils are relatively uncommon on Earth, the rather different geologic processes operating on the Moon have produced a soil that may be ubiquitously internally erodible.

Except for a few coarse outliers (mostly discrete layers found in some of the core tube samples), the particle size distribution of lunar soil is amazingly consistent on the Moon to a depth of at least several metres or more. As shown in Fig. 1, approximately 68% of the data points (i.e.,  $\pm$  one standard deviation) fall in a fairly narrow band.

In general, the variation in particle size distribution at a given site, such as Apollo 16, is the same as the variation across all of the landing sites. This can best be seen by plotting just the submillimetre fraction of the samples, as shown in Figs. 3a and 3b. Thus, what makes a given sample exceptional is not its fineness but its coarseness. That is, the bulk of the lunar soil, the “matrix”, is fine silty sand/sandy silt; but occasionally, coarser fragments are found that have not been exposed to sufficient meteorite impact to grind them into “matrix”.

Referring back to Fig. 1, it can be seen that the shape of the particle size distribution appears to be symmetrical; that is, the two halves of the “reverse-S” curve are very similar. In fact, the average graphic skewness is  $-0.01$  and the average graphic kurtosis is  $1.07$ . These parameters imply that the lunar soil particle size distribution is nearly perfectly log-normal. That is, a plot of the logarithm of the particle size on probability graph paper is practically a straight line.

This fact allows a frequently asked question to be addressed: “What is the probability of hitting a rock when drilling into the lunar surface?” For example, assume the drill is approximately 20 mm in diameter (similar to the Apollo drill core) and you are concerned about rocks larger than, say, 40 mm [rocks smaller than  $2\times$  the drill diameter would probably be pushed aside as the drill removes the cuttings]. Using a technique that will be described in a separate report, it is possible to estimate that rocks 40 mm and larger represent approximately 0.03% by weight of lunar soil. Or by volume, approximately 0.017%, based on an average soil density of  $1.7 \text{ g/cm}^3$  (see below). In order to find one 40-mm or larger rock, you would have to sieve, on average, a volume of lunar soil equal to approximately  $0.2 \text{ m}^3$ . Therefore, if you were planning to drill 1 m in depth, that rock could be anywhere under a surface area covering  $0.2 \text{ m}^3 = 200,000 \text{ mm}^2$ . So, because the area of the drill core is roughly  $20 \times 20 = 400 \text{ mm}^2$ , the probability of hitting the rock is  $400 / 200,000 = 0.002$ .

Another way to think about this question is to consider the Apollo 15 to 17 drill cores, none of which encountered a sizable/noticeable rock. The Apollo 15 and 16 drill cores were each greater than 2 m in depth; Apollos 17 was greater than 3 m. Thus, there were the equivalent of approximately 7 one-metre drill cores, none of which encountered a rock. If the probability of hitting a rock in one metre of drilling is **p**, then the probability of *not* hitting a rock in 7 one-metre drillings is **r**, given by:

$$(1 - p)^7 = r$$

If we assume **r** = 0.5 (average luck), then **p** = 0.09. [If we think we were especially lucky not to have hit a rock, then assume **r** = 0.1 and then **p** = 0.28.]

But there were also a number of manually-driven core tubes that did not hit a rock. Apollo 15 had two double cores that penetrated to a depth of nearly 0.7 m; Apollo 16 had four doubles; and Apollo 17 had three doubles. Furthermore, there were two 3-metre heat flow bore stems drilled on Apollo 16 and 17. So, we could reason that we have had the equivalent of  $7 + [(2 + 4 + 3) \times 0.7] + (2 \times 3) = 19$  one-metre probes without hitting a rock – what is the probability of continued success? Based on Bayes' theorem, the reliability, **R**, is given by

$$R = (19 + 1) / (19 + 2) = 0.95$$

Thus, based on past lunar experience, the probability of hitting a rock with the next one-metre drill is 0.05.

Another frequently asked question is: “What if there is ice at the poles – how will that affect the particle size distribution?” Meteorite impact is essentially isotropic on the lunar surface; thus, the particle size distribution and other geotechnical properties are expected to be the same everywhere, with the possible exception of the poles. If there is a lot of ice at the poles, it is likely the soil particles are coarser, because the ice presumably interferes with the comminution process. Lots of ice, however, is doubtful. More likely, if there is any ice at all, it is a small percentage of the soil; in which case, the particle size distribution may be very similar to the non-polar regions. Nobody really knows for sure. We will have to wait and see.

## PARTICLE SHAPE

The gross shape of lunar soil particles varies from spherical to extremely angular. The average elongation is approximately 1.35, corresponding to somewhat elongated. [Elongation is defined as the ratio of the major to intermediate axes of a particle.] The average volume coefficient is approximately 0.3, which also corresponds to elongated. [Volume coefficient is defined as the volume of a particle divided by the cube of the diameter of the circle that encloses the same area as the particle profile. A value of 0.3 corresponds approximately to a prolate spheroid with a major-to-minor axis ratio of 3-to-1.]

Because of the elongation, the particles tend to pack together with a preferred orientation of the long axes. This effect has been observed in lunar core tubes and laboratory simulations. And because of this preferred particle orientation, the physical properties of *in situ* lunar soil should be somewhat anisotropic.

But what really distinguishes lunar soil particles are the extremely irregular, often reentrant surfaces (see Fig. 4). On average, a typical lunar soil particle has nearly eight times as much surface area as an equivalent-sized sphere. The average specific surface area is approximately  $0.5 \text{ m}^2/\text{g}$ .

This irregular, contorted shape means the individual soil particles are somewhat fragile, compared to a ground-up basalt simulant. And, in fact, when the lunar soil particles are scraped or broken, solar wind gases are released. But when the particles are packed together, the soil has a very high shear strength.

Indeed, the irregular particle shapes account for the cohesive behavior of the lunar soil. After the first Surveyor landing, it was said that “the lunar soil behaves like damp beach sand”, even though everyone knew full well there was no water on the Moon. And, in fact, a small percentage of water has to be added to ground basalt simulant in order to create adequate cohesion.

Now we know that the cohesion of the lunar soil is due to the mechanical interlocking of the irregular particles, like Velcro; or the child’s game of “Jacks”.

It is for this reason that the Astronaut bootprints appear so crisp and clean (see Fig. 5), “like damp beach sand”. Even fine, delicate features leave a lasting impression in the lunar soil (see Fig. 6).

The cohesion (and the frictional shear strength), allowed the Astronauts to dig trenches in the lunar surface with smooth, nearly vertical walls (see Fig. 7). And, because of the low lunar gravity, trenches with vertical walls can be excavated to a depth of approximately 3 m (see Fig. 8).

Furthermore, drill core holes will remain open and stable to a depth of at least 3 m. This property was directly measured on Apollo 16, when it was confirmed that the drill core hole was open to the bottom at a depth of 2.2 m. And it was exploited on Apollo 17, when the neutron flux probe was inserted into the open drill core hole.

If there is a lot of ice at the lunar poles, the particle shapes would probably not be as irregular, because the ice would interfere with the agglutination process. But if there is little or no ice, as is more likely, then the particle shapes, and the cohesion, should be similar to the non-polar regions. Nobody really knows for sure. We will have to wait and see.

## BULK DENSITY

Prior to Apollo, the *in situ* bulk density of the lunar soil was the subject of considerable speculation. Based on remote sensing, a value of 0.3 g/cm<sup>3</sup> was estimated in 1964. Luna 9, which was the first unmanned soft landing, occurred in February 1966, but the Russians did not publish an estimated bulk density. Surveyor I landed a few months later in June 1966, and a value of 1.5 g/cm<sup>3</sup> was estimated. Then Luna 13 landed in December 1966, and the Russians estimated a value of 0.8 g/cm<sup>3</sup>. And so on.

The Apollo drive core tubes and drill cores have given us unambiguous measurements of the *in situ* bulk density. On average, the bulk density,  $\rho$ , is approximately 1.30 g/cm<sup>3</sup> at the surface, increases rapidly to 1.52 g/cm<sup>3</sup> at a depth of 10 cm, then more gradually to 1.83 g/cm<sup>3</sup> at a depth of 100 cm; and thereafter, the density asymptotically approaches a value of 1.92 g/cm<sup>3</sup> (see Fig. 9). Density versus depth can be expressed by the following hyperbolic relationship:

$$\rho = 1.92 ( z + 12.2 ) / ( z + 18 )$$

where  $z$  = depth in lunar surface (cm)

The weighted average bulk density,  $\rho_{ave}$ , of the soil *above* a given depth is given by (see Fig. 10):

$$\rho_{ave} = 1.92 - \{ ( 11.2 / z ) \log_e [ ( z + 18 ) / 18 ] \}$$

For example, at a depth of 100 cm, the average bulk density of the overlying soil is 1.71 g/cm<sup>3</sup>.

If there is a lot of ice at the lunar poles, the bulk density of the soil should be very different from the non-polar regions, probably lower. If there is just a small percentage of ice, the density should be very similar.

## RELATIVE DENSITY

The most important and interesting geotechnical property discovered during the Apollo program is the relative density of the lunar soil. Relative density refers to the fact that a given soil can be packed geometrically over a range of bulk densities. Both the minimum and maximum densities are measured by means of standardized laboratory test. Minimum density is measured by carefully and gently depositing the soil in a cylindrical container as loosely as possible. Maximum density is measured by vibrating and tapping the container to pack the soil as tightly as possible without breaking individual particles. [Of course, if a soil sample were placed in an hydraulic press, it could be squeezed to a higher density, approaching the density of the particles. But this would involve particle crushing, and, therefore, altering the particle size

distribution.] With terrestrial sands, the typical difference between the maximum and minimum bulk density is about 0.3 g/cm<sup>3</sup>. Because of the broad particle size distribution of lunar soil, this difference is about 0.7 g/cm<sup>3</sup>.

The relative density,  $D_R$ , of a soil defines where the bulk density lies in the range between the maximum and minimum bulk densities. It is calculated according to:

$$D_R = [ (\rho_{\max} / \rho) \times (\rho - \rho_{\min}) / (\rho_{\max} - \rho_{\min}) ] \times 100\%$$

where  $\rho$  = *in situ* bulk density  
 $\rho_{\max}$  = maximum bulk density  
 $\rho_{\min}$  = minimum bulk density

Thus, if  $\rho = \rho_{\min}$ , then  $D_R = 0\%$ ; and if  $\rho = \rho_{\max}$ , then  $D_R = 100\%$ .

A soil is said to be:

very loose	if	$D_R = 0$ to 15%
loose	if	$D_R = 15$ to 35%
medium	if	$D_R = 35$ to 65%
dense	if	$D_R = 65$ to 85%
very dense	if	$D_R = 85$ to 100%

In fact, on Earth, it is difficult to obtain very low relative density on a large-scale; for example, if sand is simply dumped from a truck, it typically has a relative density of about 30%. Similarly, it is difficult to obtain very high relative density; for example, heavy equipment used for constructing highways, runways, and earth dams typically achieve a relative density of about 65 to 75%.

There were many indirect measurements and interpretations of the relative density of the lunar soil. For example, the Apollo 15 to 17 core tubes required approximately 50 hammer blows to be driven to a depth of about 70 cm, close to the physical limit for a suited Astronaut. Furthermore, the soil surrounding the core tubes heaved slightly during driving. Based on these and many other observations (such as the depth of the bootprints), it was concluded that: (1) The relative density of lunar soil tends to be low on the rims of fresh craters, on slopes, and virtually everywhere within the top few centimetres of the surface; (2) However, in intercrater areas, the relative density is exceptionally high at depths of only 5 to 10 cm (see Fig. 11). Over a depth range of 0 to 15 cm, the average intercrater relative density is 65% (medium to dense); and from 30 to 60 cm, 92% (very dense).

The maximum and minimum bulk densities have been measured for one soil sample taken near one of the double core tubes taken on Apollo 15, near the rim of Hadley Rille (see Fig.

12). By comparing the maximum and minimum densities with the bulk density of the lunar soil in the two sections of the core tube, the *in situ* relative density at this one location could be estimated (see Fig. 13): 84% for the top 30 cm and 97% for the next 35 cm. If we make the conservative assumption that the relative density is 0% at the surface ( $z = 0$ ), then it must increase very rapidly to 75% at a depth of 5 cm; and 85% at 10 cm. This large and sudden change in relative density with increasing depth is due to continuing small meteorite impacts that generate a loose, stirred-up surface, but at the same time shake and densify the underlying soil. In fact, the relative density below 10 cm is much greater than can be accounted for by compression under self-weight.

In spite of the high relative density below 5 to 10 cm, the porosity of the lunar soil is about 40 to 50%. This apparent anomaly is due to the broad particle size distribution and the irregular particle shape. Because of the large coefficient of uniformity,  $C_u = D_{60} / D_{10}$ , the smaller particles do not fit efficiently in the interstices between the larger particles. Thus, even though the particles are packed together tightly, the “soil skeleton” is relatively open (i.e., a high porosity). Approximately one-fourth of the porosity is “intragranular porosity”; that is, porosity associated with the reentrant, irregular particle shape.

The high relative density of the subsurface lunar soil has very important practical implications. For example, during Apollo 15, the high relative density prevented complete deployment of the heat flow experiment. This experiment consisted of two 3.0-metre long, closed-end, hollow-stem augers that were to be drilled into the lunar soil. Each auger tube had a smooth interior, with a helical structure on the outside of the tube to do the actual drilling (see Fig. 14). A long probe containing sensors and electronics was then to be inserted into each hollow stem for measurements of thermal conductivity and temperature gradients in the surrounding soil.

Each hollow stem consisted of six 0.5-metre long sections for ease of assembly by the Astronaut. Because of scientific requirements, the stem was made entirely of a low-thermal-conductivity material, boron-fiberglass; consequently, the sections were connected by a press-fit joint, rather than being screwed together. As a result, the helical auger on the exterior of the stem was discontinuous at each joint.

When the Apollo 15 Astronauts attempted to drill the hollow stems into the lunar surface, they were only able to reach a depth of approximately 1.5 metre with each stem. As the drill cuttings rode up the helical auger on the outside of the tube, the soil particles encountered the joints and could travel no further upward. They had no place to go except into the surrounding soil. Because of the high relative density of the soil, not all the soil particles in the drill cuttings could be pressed into the wall of the boring, and the stem became bound to such an extent that the safety clutch in the drill powerhead slipped. So much heat was generated by the friction between the fiberglass stem and the soil that one of the joints is suspected to have collapsed.

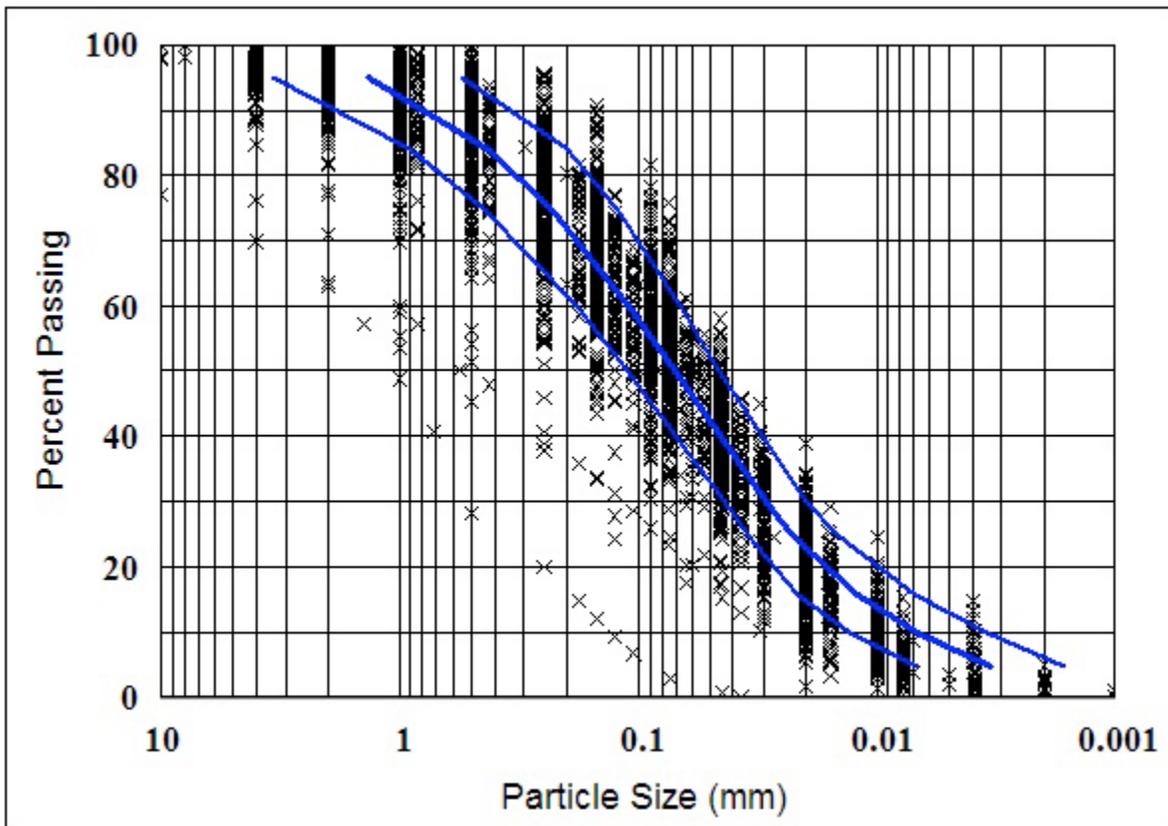
Prior to the Apollo 15 mission, all the drilling tests had been made with lightly compacted

soils, and this kind of binding failure had never been experienced. Immediately after the mission, tests were run with heavily compacted basaltic lunar soil simulant, and the same problems developed that had occurred on the Moon. The heat flow stems were promptly redesigned with titanium inserts so that the joints could be screwed together to form a continuous auger. The inclusion of a high thermal conductivity metal in the hollow stem was, of course, a compromise between science and engineering requirements. With the new design, full penetration depth was achieved on the Apollo 16 and 17 missions.

If there is a lot of ice at the lunar poles, the relative density of the soil should be very different from the non-polar regions, probably lower. If there is just a small percentage of ice, the relative density should be very similar.

## REFERENCES

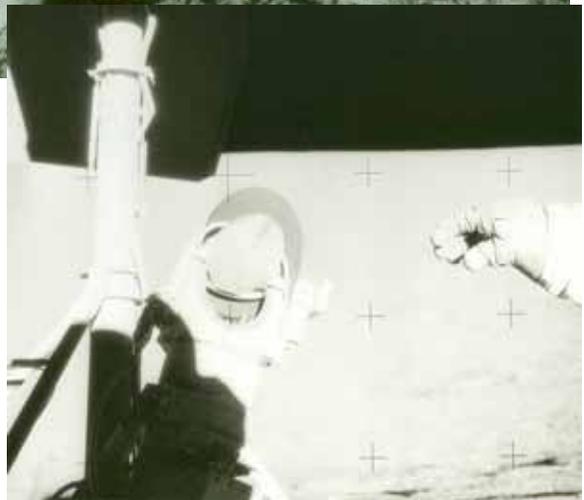
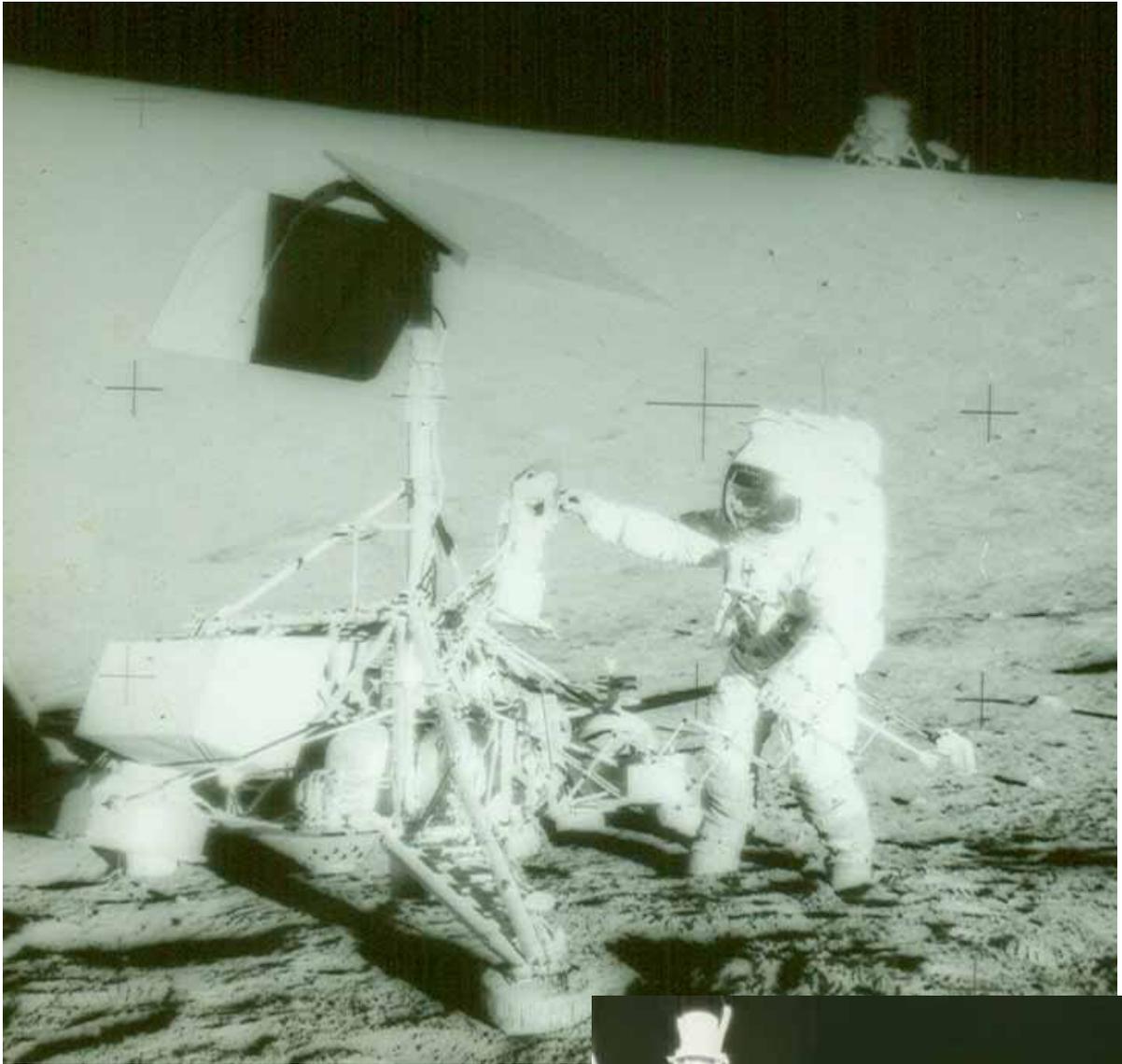
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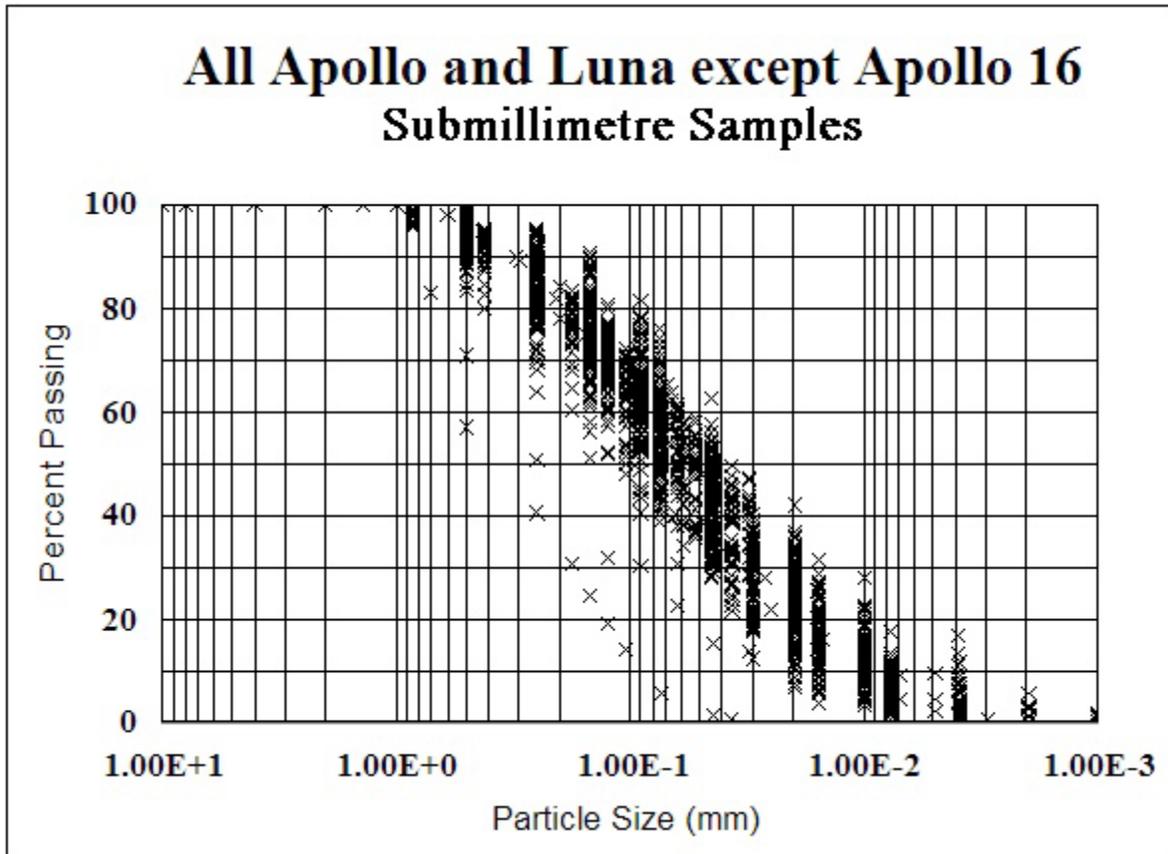
**Fig. 1:** Lunar soil particle size distribution (Carrier 2003).

The middle curve shows the average distribution; the left-hand and right-hand curves show  $\pm$  one standard deviation.

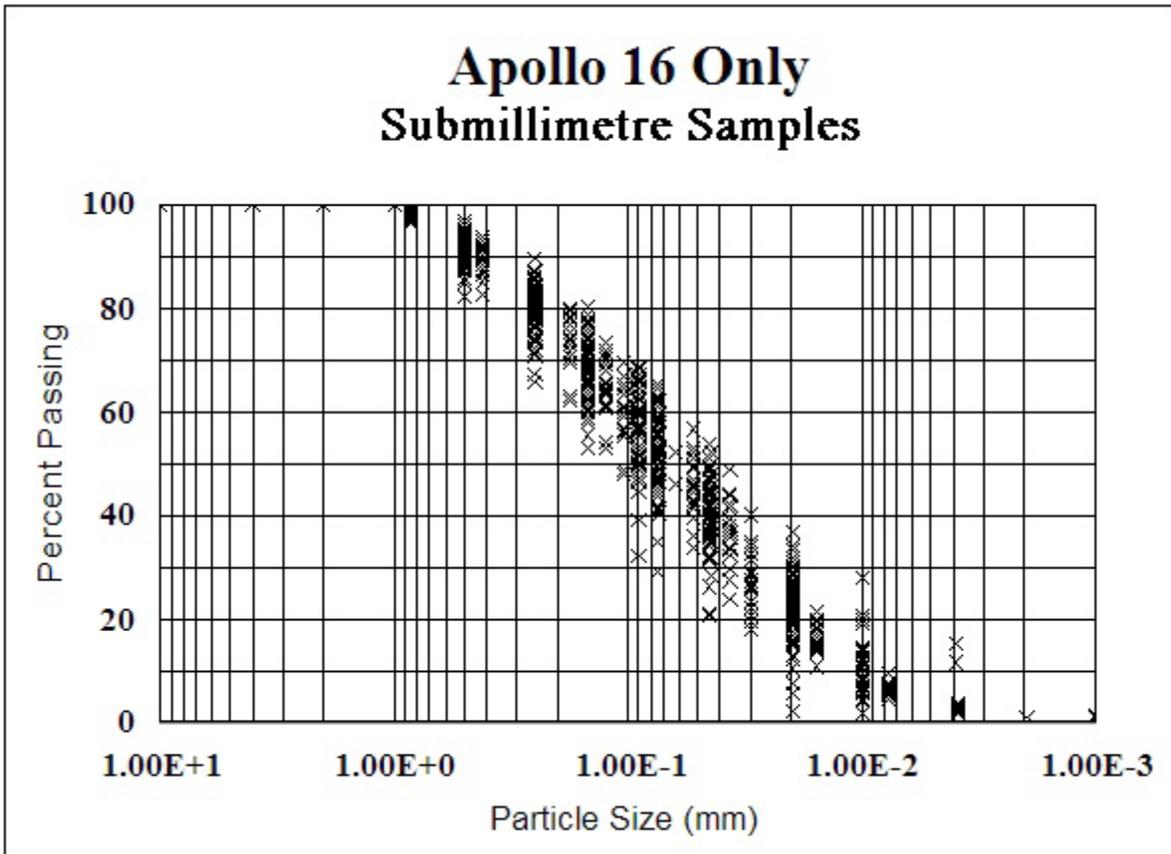
On average, approximately 2% coarse sand (2.0 to 4.75 mm); 14% medium sand (0.425 to 2.0 mm); 33% fine sand (0.074 to 0.425 mm); and 51% silt.



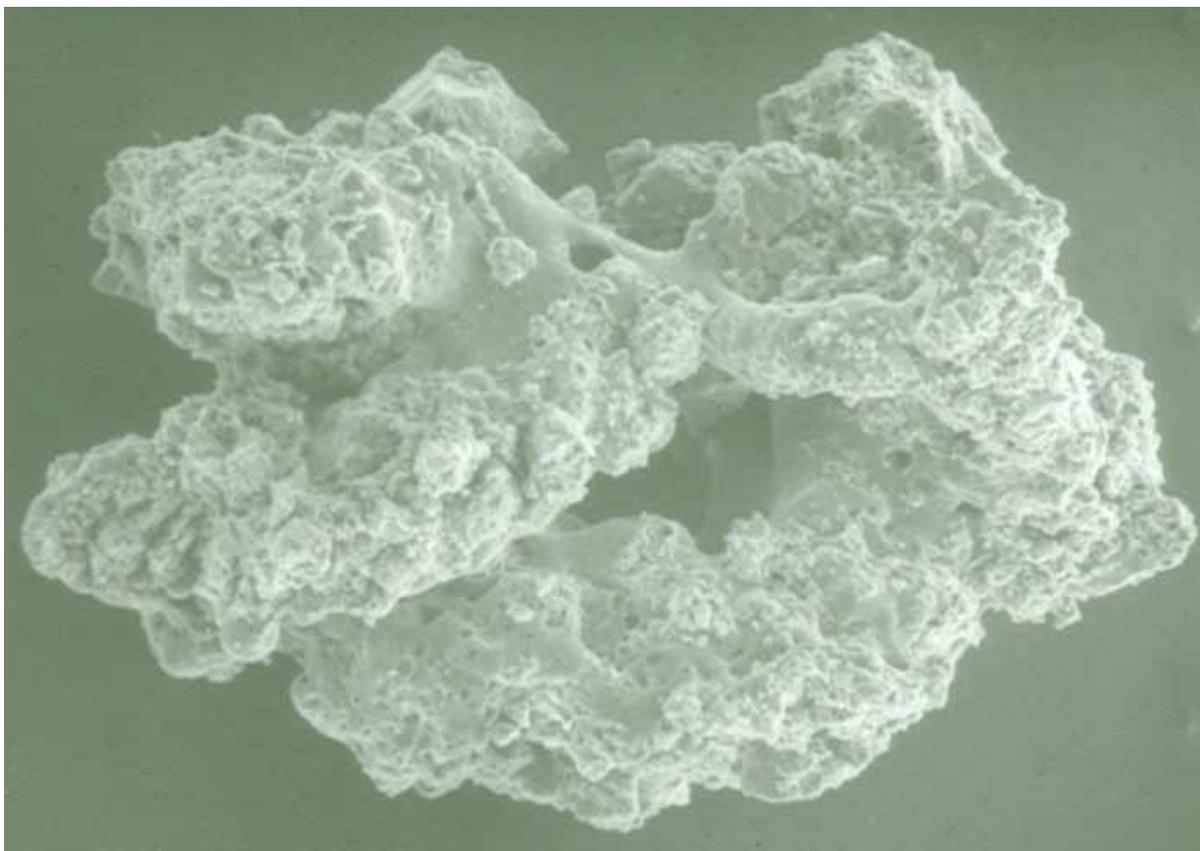
**Fig. 2:** When the Apollo 12 Lunar Module landed, it blew dust on the nearby Surveyor III. The Astronaut has traced his gloved finger through the dust adhering electrostatically to a mirror used in conjunction with the Surveyor television camera, which was housed in the tube below the mirror.



**Fig. 3a:** Submillimetre particle size distributions of all lunar soil samples with the exception of those from Apollo 16. (Compare with Fig. 3b.)



**Fig. 3b:** Submillimetre particle size distributions of only those samples from Apollo 16. (Compare with Fig. 3a: The variation for Apollo 16 is very similar to all of the other landing sites.)



**Fig. 4:** Lunar soil particles are typically very irregular in shape, even reentrant as with this agglutinate. (Courtesy of Dr. David S. McKay)



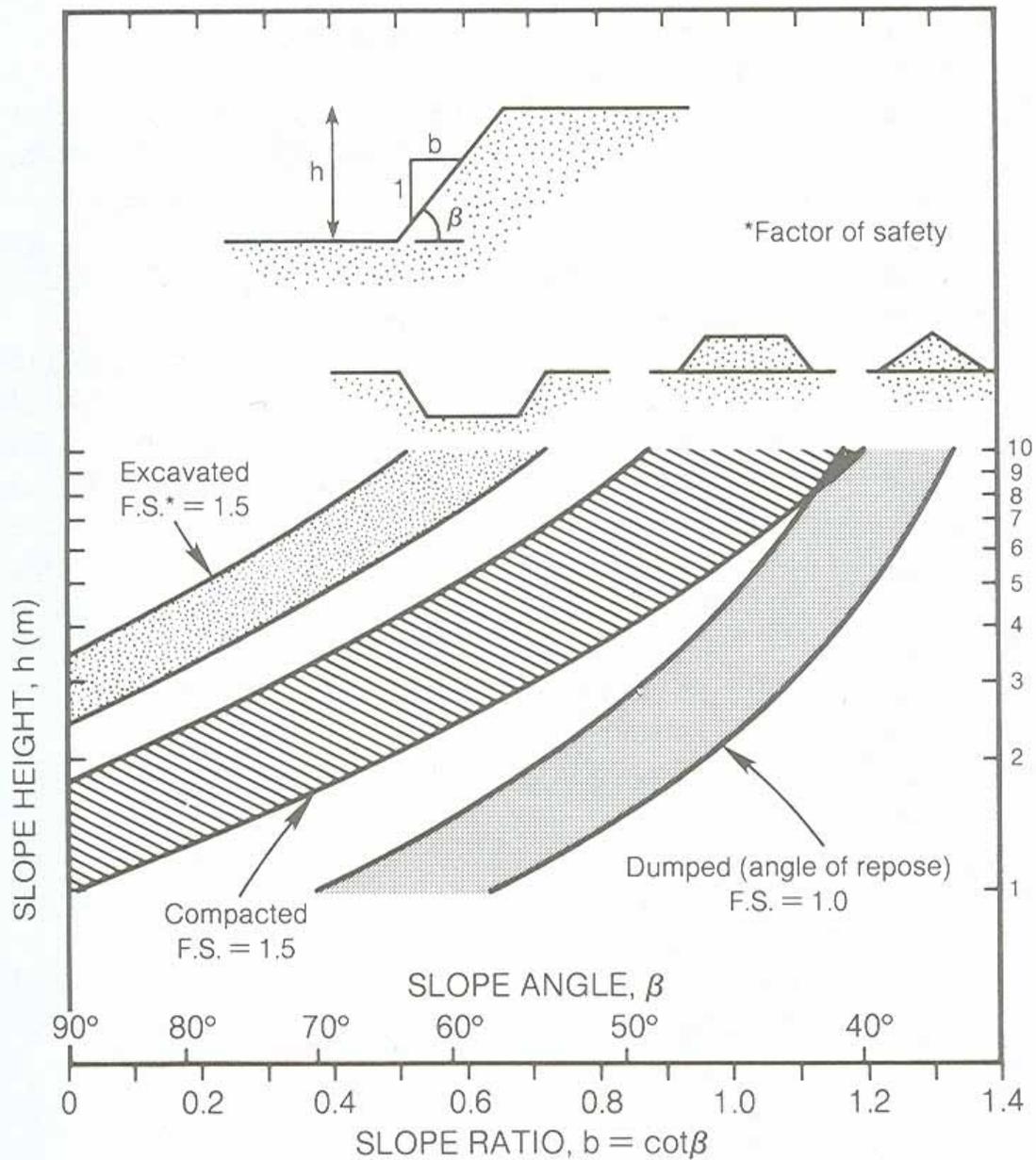
**Fig. 5:** This is a closeup of an Astronaut footprint taken on Apollo 12. It is one-half of a stereo pair. The field of view is approximately 50 mm × 50 mm. Note the cohesiveness of the lunar soil.



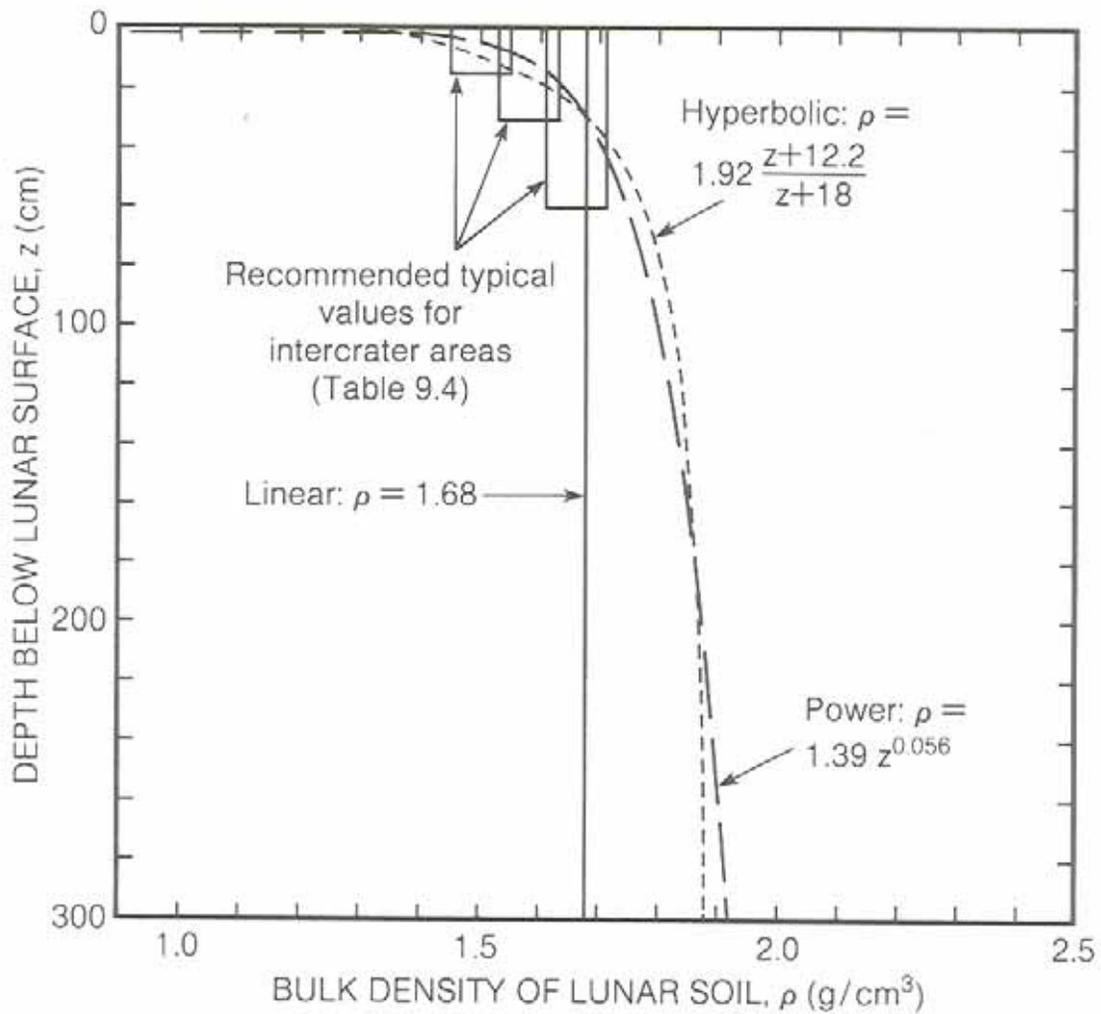
**Fig. 6:** When Surveyor III landed on the Moon, it bounced a couple of times. The fine, delicate “honeycomb” pattern on the bottom of one of the footpads was preserved in the cohesive lunar soil, as shown in the lower right-hand corner of this Apollo 12 photograph.



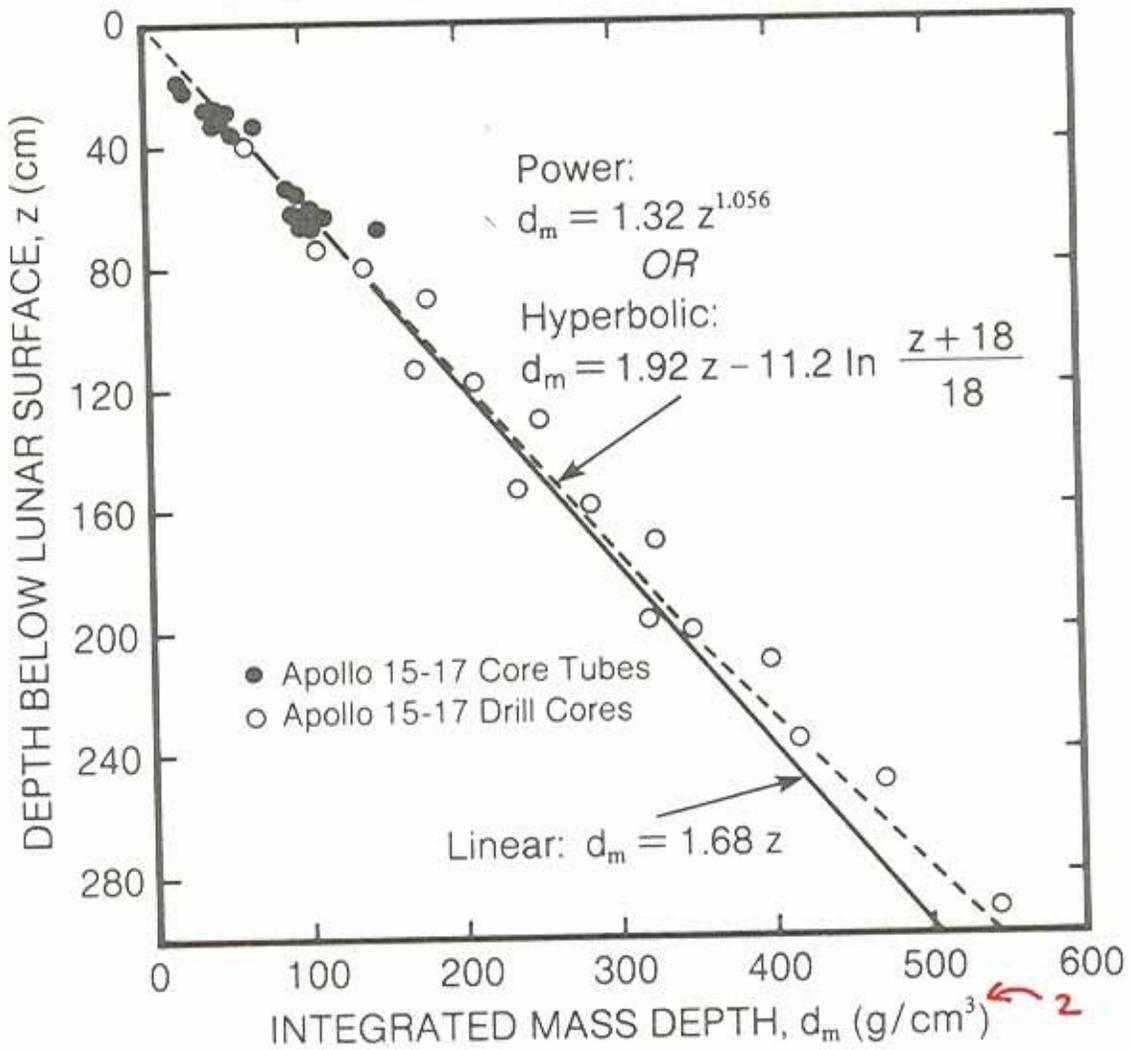
**Fig. 7:** This is a shallow trench dug by an Astronaut on Apollo 17. The smooth, nearly vertical wall is due to the cohesion and frictional shear strength of the lunar soil.



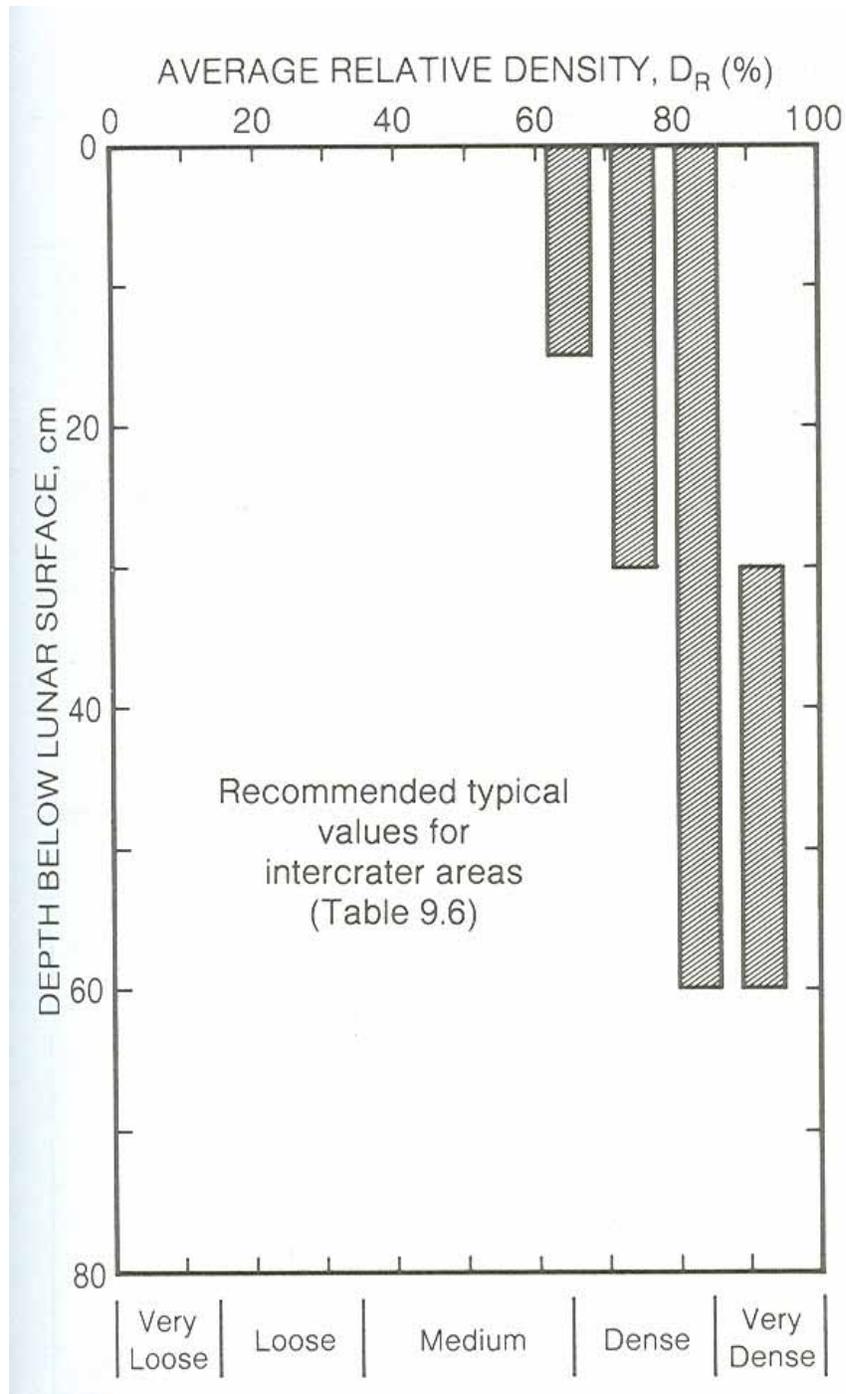
**Fig. 8:** Because of the high shear strength and low gravity, vertical trenches can be excavated in the lunar surface up to 3 m deep, with a factor of safety of 1.5. A trench with a slope of 60° can be excavated up to 10 m deep. (*Lunar Sourcebook*, p. 521)



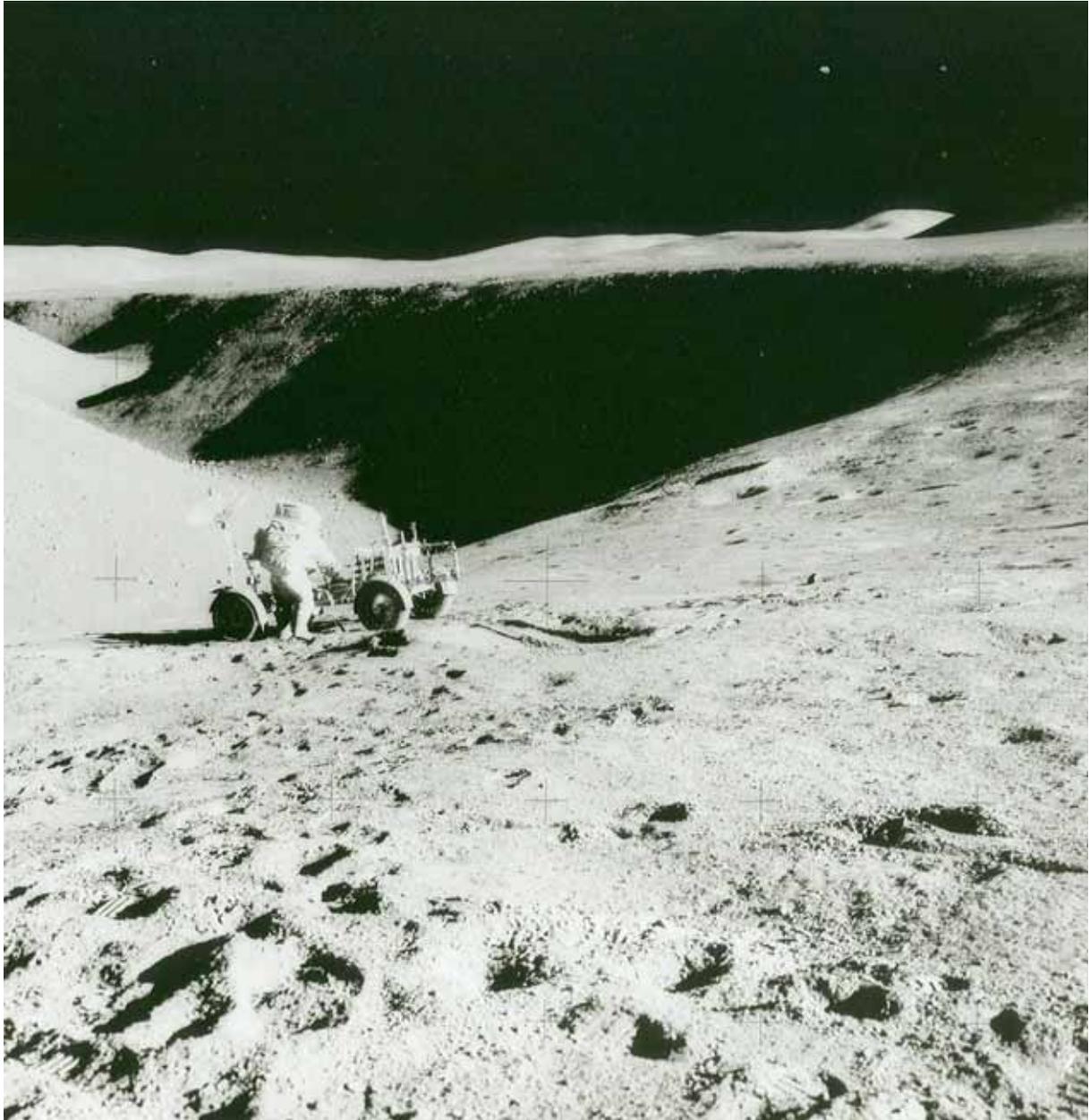
**Fig. 9:** The hyperbolic formula gives the best fit to the bulk density data from the Apollo drive core tubes and drill cores. On average, the *in situ* density is approximately  $1.30 \text{ g}/\text{cm}^3$  at the surface ( $z = 0$ ) and increases asymptotically to  $1.92 \text{ g}/\text{cm}^3$ . (*Lunar Sourcebook*, p. 494)



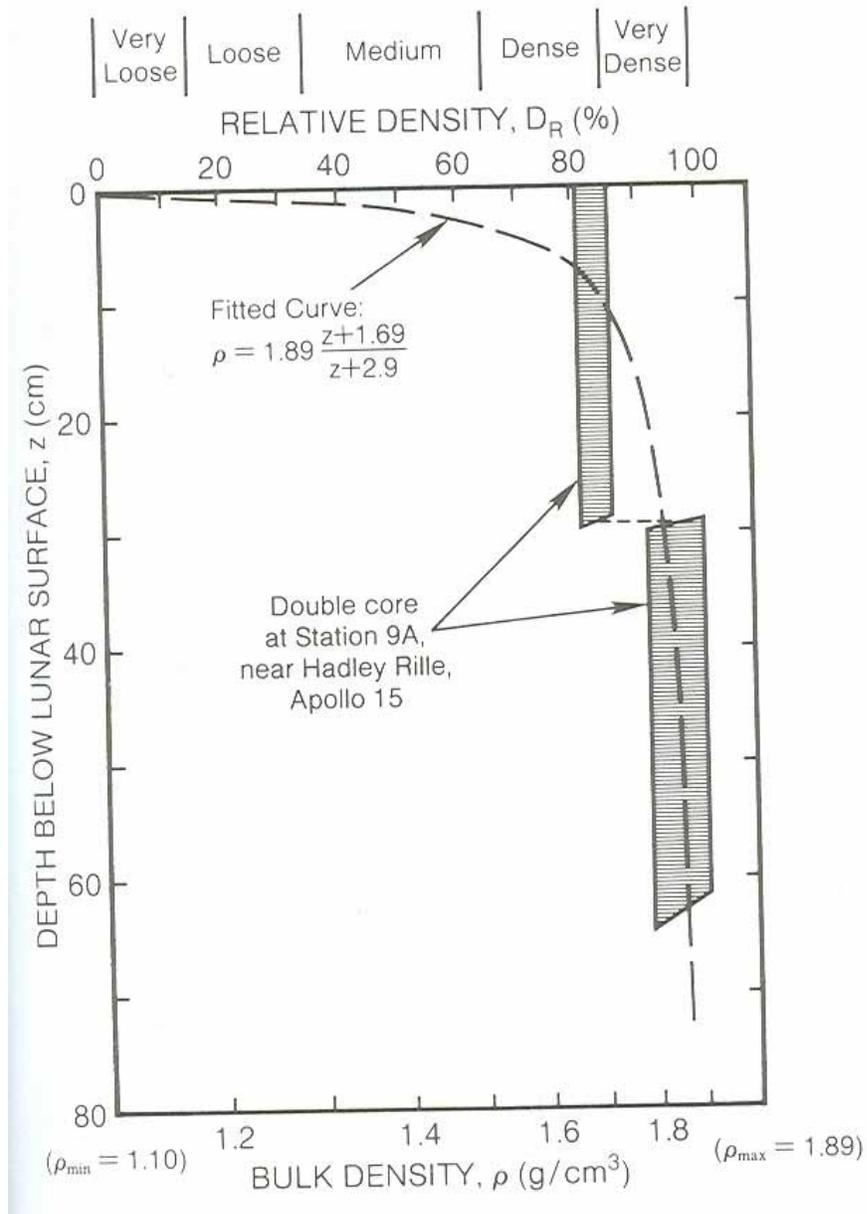
**Fig. 10:** The weighted average *in situ* bulk density of the lunar soil above a given depth,  $z$ , is equal to  $d_m / z$ . The hyperbolic formula is the best fit to the drive core tube and drill core data. (*Lunar Sourcebook*, p. 493)



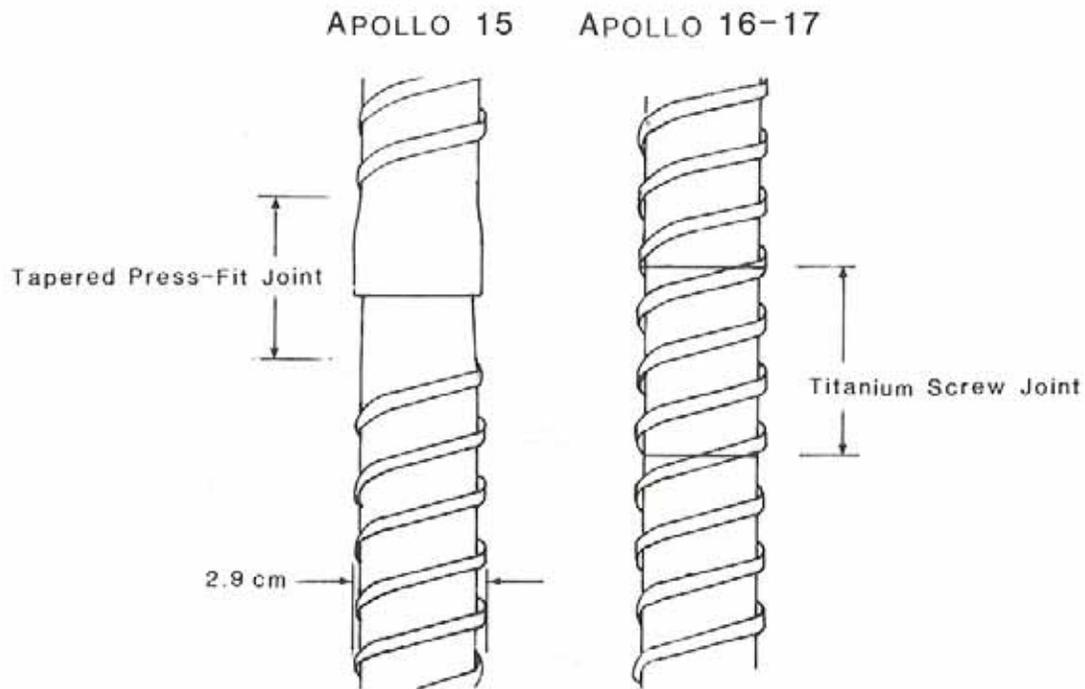
**Fig. 11:** Relative density defines how tightly soil particles are packed together geometrically. In the intercrater areas, the *in situ* lunar soil relative density is medium to dense over a depth range of 0 to 15 cm; and very dense from 30 to 60 cm. (*Lunar Sourcebook*, p. 501)



**Fig. 12:** An Apollo 15 Astronaut exploring the rim of Hadley Rille. The boulders on the bottom of the rille, in the background behind the Astronaut, are house-sized.



**Fig. 13:** Relative density versus depth near Hadley Rille on Apollo 15, based on the maximum and minimum densities measured on a nearby soil sample and the bulk densities measured in the double core tube. Even if the relative density is conservatively assumed to be 0% (very loose) at the surface, then it must increase to 75% (dense) at a depth of 5 cm; and more than 85% (very dense) below 10 cm. (*Lunar Sourcebook*, p. 499)



**Fig. 14:** The helical auger on the outside of the two bore stems used for the Apollo 15 heat flow experiment was discontinuous at the press-fit joints. As a result, the stems could only be drilled to a depth of approximately 1.5 metre: The drill cuttings could not travel up the helix past the joints and the high relative density of the surrounding soil prevented the particles from being pressed into the wall of the boring. The joints were redesigned for Apollo 16-17 and the bore stems were successfully drilled to their intended depth of 3.0 metres. (Carrier and Mitchell 1989, p. 54)