GEOTECHNICAL ENGINEERING

APOLLO SOIL MECHANICS EXPERIMENT S-200

FINAL REPORT

COVERING WORK PERFORMED UNDER
NASA CONTRACT NAS9-11266

by

J. K. Mitchell, Principal Investigator

W. N. Houston, Co-Investigator

W. D. Carrier, III, Co-Investigator

N. C. Costes, Co-Investigator

January, 1974

Submitted to the National Aeronautics
and Space Administration

SPACE SCIENCES LABORATORY SERIES 15, ISSUE 7

UNIVERSITY OF CALIFORNIA • BERKELEY

APOLLO SOIL MECHANICS EXPERIMENT S-200

FINAL REPORT

COVERING WORK PERFORMED UNDER
NASA CONTRACT NAS9-11266

by

J. K. Mitchell, Principal Investigator

W. N. Houston, Co-Investigator

W. D. Carrier, III, Co-Investigator

N. C. Costes, Co-Investigator

January, 1974

Submitted to the National Aeronautics
and Space Administration

SPACE SCIENCES LABORATORY SERIES 15, ISSUE 7

"The surface is fine and powdery. I can kick it up loosely with my toe. It does adhere in fine layers like powdered charcoal to the sole and insides of my boots. I only go in a small fraction of an inch--maybe an eighth of an inch, but I can see the footprints of my boots and the treads in the fine sandy particles."

Neil A. Armstrong
July 20, 1969

ACKNOWLEDGEMENTS

The authors wish to gratefully acknowledge the assistance of the many individuals who have contributed to the success of the Soil Mechanics Experiment. The lists of references at the end of this report indicate the active participation of those associated with the principal and co-investigators.

The basic design concept of the SRP was developed at the Geotechnical Research Laboratory of the NASA Marshall Space Flight Center Space Sciences Laboratory with the support of Teledyne-Brown Engineering Company, Huntsville, Alabama. Dr. Rolland G. Sturm, Roland H. Norton, George E. Campbell, and G. T. Cohron were instrumental in the development of this concept. The final design, construction, and qualification of the flight article were carried through by W. N. Dunaway, and W. Lyon of the NASA Manned Spacecraft Center (now Johnson Space Center) and W. Young of the General Electric Company.

Charles S. Alton and W. D. Sherborne of the NASA Manned Spacecraft Center (now Johnson Space Center) contributed greatly to the design and development of the core tubes used on Apollo 15 and subsequent missions.

Dr. H. John Hovland, Dr. Arshud Mahmood, Dr. L. I. Namiq, Dr. H. Turan Durgunoglu, C. S. Chang, Donald D. Treadwell, and Y. Moriwaki, all of the soil mechanics research staff at the University of California, were responsible for many of the simulation studies, data analyses, and computations discussed in this report.

Dr. Stewart W. Johnson, National Research Council Senior Postdoctoral Fellow from the Air Force Institute of Technology, and Richard A. Werner, Lisimaco Carrasco, and Ralf Schmidt of Lockheed Electronics Company participated in simulation studies at the Manned Spacecraft Center (now Johnson Space Center).

CONTENTS

LIST OF FIGURES

LIST OF TABLES

APOLLO SOIL MECHANICS INVESTIGATION

- FINAL REPORT -

CHAPTER 1

INTRODUCTION

Objective

Soil mechanics investigations during the Apollo Program were organized to meet the following objectives:

(1) to obtain an understanding of the compositional, textural, and mechanical properties of lunar soils and the variations of these properties with depth and among different locations on the lunar surface,

(2) to use this understanding to aid in the formulation, verification or modification of theories for lunar history and processes,

(3) to use lunar soil data to aid in the interpretation of data obtained from other lunar surface activities and experiments,

(4) to develop lunar surface models that were useful for the solution of engineering problems in subsequent Apollo missions; e.g., core tube sampling, drilling in the lunar surface, trafficability,

(5) to obtain information which can be used in planning future exploration and development of the Moon.

Thus the Soil Mechanics Experiment (S-200) was unique among the experiments assigned to the Apollo missions in that the results have both science and engineering applications. Types of problems for which an understanding of lunar soil properties is important include (1) formation and compaction of surface layers, (2) characterization of deposits of different composition, (3) slope stability, (4) downslope movement of soil and rock fragments, (5) estimation of thermal properties for heat flow studies, (6) prediction of seismic velocities, (7) characterization of dielectric properties for use in radar backscatter and electrical property studies, (8) gas diffusion through the lunar surface, (9) definition of conditions for terrestrial simulation studies, and (10) various soil-dependent engineering analyses. Some engineering applications were immediate and related to such items as redesign of new core tubes for Missions 15-17, to resolution of problems of drilling and coring for the Heat Flow Experiment, and to installation of the neutron flux probe during Apollo 17.

Organization of Investigations

Soil mechanics studies were one of the few areas of investigation to be incorporated into all of the Apollo missions, and the resulting continuity and interactions with other facets of the program proved valuable. A Team of Cognizant Scientists composed of N. C. Costes, Team Leader, NASA Marshall Space Flight Center (MSFC); W. D. Carrier, III, NASA Johnson Space Center (JSC); J. K. Mitchell, University of California, Berkeley; and R. F. Scott, California Institute of Technology, was appointed by NASA Headquarters to deduce soil mechanics information from observations, photographs, and samples obtained during Apollo 11. These same investigators were appointed Co-Investigators for the Apollo 12 Lunar Geology Experiment S-059), E. M. Shoemaker, Principal Investigator, and served as a sub-group for soil mechanics with R. F. Scott as Team Leader.

A formal Soil Mechanics Experiment was approved for Apollo Missions 14 through 17 with J. K. Mitchell as Principal Investigator and the above-named individuals as Co-Investigators. In addition L. G. Bromwell, Massachusetts Institute of Technology, was appointed as Co-Investigator beginning with Apollo 14 and W. N. Houston, University of California, Berkeley, was designated as a Co-Investigator commencing with Apollo 15.

Support for those phases of the work done at the University of California, Berkeley, was provided under NASA Contract NAS 9-11266, "Principal Investigator Support for Soil Mechanics Investigation," work at M.I.T. was carried out under subcontract to NAS 9-11266, and the effort at the California Institute of Technology was supported by NASA Contract NAS 9-11454, "Coinvestigator Support for Apollo Soil Mechanics Experiment S-200." Participation of N. C. Costes was supported by Inter-Center Agreement between MSFC and JSC, and the contributions of W. D. Carrier were provided by the Johnson Space Center.

Scope of Report

Emphasis in this report is on findings concerning the physical and mechanical properties of the unconsolidated lunar surface material or regolith, termed "soil" herein, that have been obtained as a result of the Apollo missions, on the development of the best possible model for lunar soil behavior, and on assessment of implications for lunar history and processes.

Pre-Apollo information concerning the mechanical properties of lunar soil is not reviewed herein. Such information, which was derived from visual observations, thermal measurements, photographs obtained by the U. S. Ranger and Lunar Orbiter Spacecraft and from the soft landings of the Surveyor and Soviet Luna spacecraft, is presented in detail in several of the references listed at the end of this report and in Appendix I.

The Surveyor Program deserves special note, however, because the results enabled formulation of a model for the lunar soil that has proven surprisingly accurate. In essence it was concluded (see Scott and Roberson, 1967, 1968a,b,c, 1969) that the lunar soil at the surface was slightly cohesive and composed mainly of grains ranging in size from silt to fine sand. Behavior was similar to that of terrestrial soils with a density of about 1.5 g/cm^3. A cohesion of about 0.7 kN/m^2 (0.1 psi) and a friction angle of 35° to 37° were deduced, and strength increase with depth was observed. With the results of Apollo considerable refinement of this basic model is possible, particularly as regards variability of the different properties laterally and with depth.

In the next chapter of this report sources of data useful for deduction of soil information and methods used to obtain the data are indicated. In the following chapter a physical and mechanical model for the lunar soil is developed. In particular, soil characteristics (index properties), density and porosity, strength, compressibility, and trafficability parameters are considered. The concluding chapter of the report considers the implications for lunar history and processes, a comparison of lunar and terrestrial soil behavior, and soil considerations for future exploration and development of the Moon.

Detailed procedures, analyses, and calculations are not presented, but can be found in other papers and reports prepared by the Investigators.

A complete listing of these publications is presented in Appendix I.

As a result of the studies completed to date it is concluded that present knowledge of lunar soil properties in situ to depths of several tens of centimeters is good and that predictions of behavior can be made with considerable confidence. Reasonable terrestrial simulation of lunar soil can be made; however, gravity differences preclude direct correlation between terrestrial and lunar measurements in some cases.

Much remains to be learned about the influences of such things as confining stress, stress history, and fabric on the thermal, electrical, and mechanical properties of lunar soil. Such knowledge can be of great importance in the interpretation of results from different geophysical experiments. More extensive testing of returned lunar soil samples for evaluation of these properties would aid greatly in closing the gap.

CHAPTER 2

DATA SOURCES AND ANALYSIS METHODS

INTRODUCTION

Conclusions about the nature, physical behavior, and mechanical properties of lunar soil were inferred or deduced from a variety of data sources and analysis methods. With the exception of the Self-Recording Penetrometer (SRP) used on the Apollo 15 and Apollo 16 Missions, there were no soil testing devices unique to the Soil Mechanics' Experiment that could provide quantitative data. Thus it was necessary to utilize alternative data sources and to develop special methods of analysis. These sources and methods are listed below; further details can be found in the Preliminary Science Reports for each mission and in several other of the references listed in Appendix I.

Data Sources

Observational Data

Astronaut observations, descriptions, and comments in real time and at debriefings following the EVA (ExtraVehicular Activity) periods and the missions provided much useful qualitative information on the nature and behavior of lunar soil.

Visual Data

Real time television during the EVA's and kinescopes made therefrom were studied in detail. Sequence camera photography (Missions 11 and 12) was useful, as were also photographs obtained using the Lunar Surface Closeup Camera (Apollo 11, Apollo 12, and Apollo 14). The photographs of greatest value, however, were obtained using the Hasselblad still camera with 70 mm. and 500 mm. lenses.

Spacecraft Descent Data

Analysis of LM (Lunar Module) descent profiles together with study of surface erosion under the action of the DPS (Descent Propulsion System) exhaust was made to provide information on soil conditions at the surface including particle size and cohesion.

Interaction Data

Analyses of the interactions of the LM footpads, equipment, and astronauts with the lunar surface were made. In many cases when sizes, weights and forces were known as well as depths of penetration or sinkage, approximate analyses could be made for estimation of strength and porosity. Interactions between the lunar surface and (1) astronaut boots, (2) LM footpads, (3) flagpole, and (4) the Solar Wind Composition experiment were of particular value. Observations and measurements during drilling and core tube sampling using both drive tubes and drill stems were also very useful.

Vehicle Data

A Modularized Equipment Transporter (MET), a two-wheeled, ricksha-type vehicle with pneumatic tires was used during Apollo 14 to carry instruments, tools, and photographic equipment. For Apollo Missions 15, 16 and 17, the Lunar Roving Vehicle (LRV) was used to transport both astronauts, their equipment and lunar samples. The LRV, (Fig. 2-1) is a four-wheeled surface vehicle with "tires" of thin, steel, piano-wire mesh, and 50 percent of the contact area with the lunar surface is

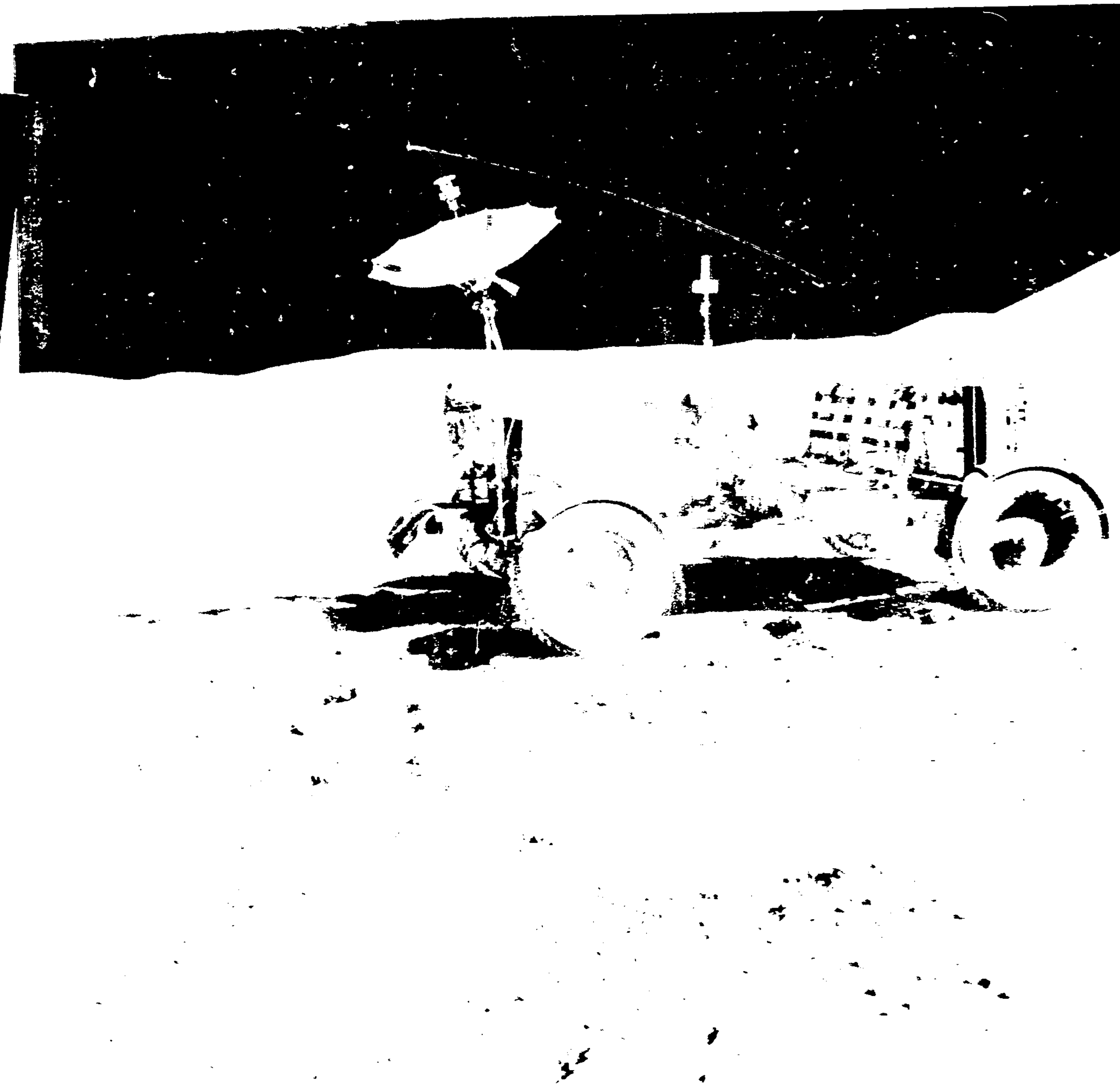


FIG. 2-1 LUNAR ROVING VEHICLE

covered with a chevron tread. Analyses of track depths, power consumption, and general observations during operation were used to deduce soil conditions and soil variability.

Penetration Tests

During deployment of the Apollo 14 lunar surface experiments package (ALSEP), the geophone/thumper anchor, also known as the Apollo Simple Penetrometer (ASP), was used to obtain three two-point penetration tests into the lunar surface. This simple tool and the depths to which it could be pushed by the astronaut using one hand are shown in Fig. 2-2.

The SRP was used on Apollo 15 and Apollo 16 to obtain continuous force vs. penetration depth data to a maximum depth of 76 cm. and maximum recordable forces of 111N and 215N for the Apollo 15 and Apollo 16 devices, respectively. This apparatus, shown in Fig. 2-3, was the main quantitative data source for the Soil Mechanics Experiment. The record of each penetration was inscribed on a recording drum contained in the upper housing assembly. The lunar surface reference plane rested on the lunar surface during a measurement and served as datum for penetration depth. A bearing plate 2.54 cm wide by 12.7 cm long and three penetrating cones, each of 30° apex angle and base areas of 1.29, 3.22, and 6.45 cm^2 were available for attachment to the penetrometer shaft.

The upper housing assembly with the recording drum were returned to earth. Data were transcribed from the recording drum and are presented in the Apollo 15 and Apollo 16 Preliminary Science Reports. The data are also on file at the National Space Sciences Data Center, and the recording drums are stored at the Johnson Space Center.

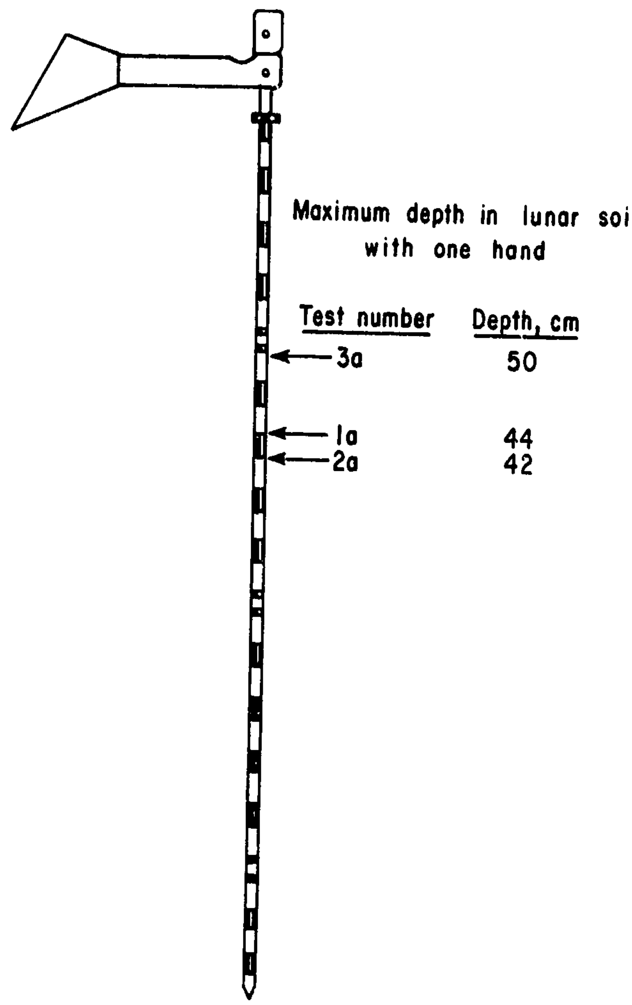


FIG. 2-2 APOLLO SIMPLE PENETROMETER

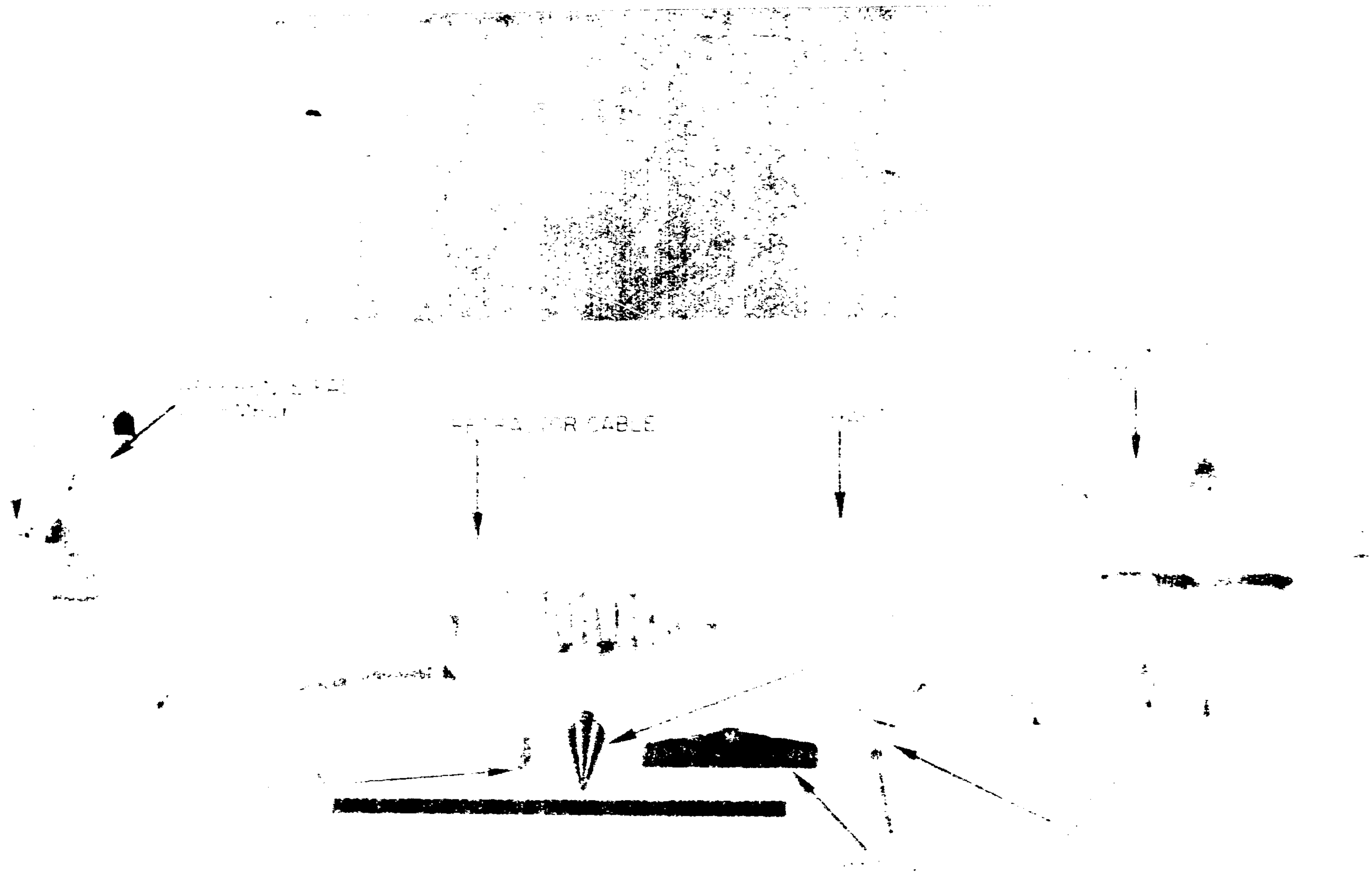


FIG. 2-3 SELF-RECORDING PENETROMETER

Soil Samples

Soil sample characteristics as determined by the Lunar Sample Preliminary Examination Team (LSPET) were considered in the evaluation of soil properties. Data on the core samples, both drive tube and drill stem, were of particular value. Limited testing of soil returned by Apollo 11 was done by members of the Soil Mechanics Team in the Lunar Receiving Laboratory (LRL), and three small samples of approximately one gram each, two from Apollo 14 and one from Apollo 15, were made available for measurements of specific gravity and density limits.

Analytical Methods

Quantitative analyses of the mechanical properties of lunar soil in situ were made using two main approaches, singly and in combination; namely, (1) simulations, wherein terrestrial measurements are made using appropriately designed lunar soil simulants, and (2) theoretical analyses to relate observed behavior to soil properties and imposed boundary conditions.

Theories of soil mechanics are reasonably well established, although the inherent variability of most soils and difficulties in determination of stresses in the ground require judgment in their application. Scott (1963) and other soil mechanics texts present these theories in detail. The theory of elasticity is used for computation of stresses and displacements, and the theory of plasticity is used to relate failure stresses and loads to soil strength parameters. The Mohr-Coulomb strength theory has been found suitable for most terrestrial soils. According to this theory the shear strength, s, can be represented by

$$s = c + \sigma \tan\phi \qquad (2\text{-}1)$$

where c is unit cohesion, σ is normal stress on the failure plane, and ϕ is the angle of internal friction. Available evidence indicates that the same approach can be applied to lunar soil behavior.

Details of the analysis methods are presented in the Preliminary Science Reports for each mission and in several of the references listed in Appendix I. Examples of the types of studies that were made using the results of simulation studies and theoretical analyses either singly or together include:

(1) Determination of density and porosity from astronaut bootprint depth

(2) Deduction of strength parameters from penetration test results

(3) Evaluation of strength parameters and density values from vehicle-soil interaction

(4) Determination of strength parameters from stability analysis of the walls of trenches dug on the lunar surface

(5) Computation of strength parameters from stability analysis of open drill and drive tube holes

(6) Evaluation of soil friction angle from boulder tracks on lunar slopes

(7) Analysis of downslope soil movements resulting from meteoroid impact.

CHAPTER 3

PHYSICAL AND MECHANICAL MODEL FOR THE LUNAR SOIL

INTRODUCTION

In this chapter a comprehensive description of the physical and mechanical properties of the lunar soil is presented. Where possible the results of all missions have been combined in an effort to produce a general model. At the same time, however, attention has been given to variability on both global and local scales, and to unique local conditions. While the model presented is believed to be as correct and comprehensive as possible on the basis of the data at hand, it should be recognized that further refinement and, in fact, even substantial changes may be required in the future when studies that integrate the results of several lunar surface experiments have been made.

Attention here is first directed at the soil characteristics and index properties. Then density and porosity are considered, followed by strength, compressibility, and trafficability parameters.

CHARACTERISTICS AND INDEX PROPERTIES

The Apollo series returned more than 380,000 g of rocks and soils, however approximately 90% of this material has received only a cursory examination and is stored in the Curatorial Facility at the Johnson Space Center for future analyses. The remainder has been distributed to numerous investigators around the world for detailed study and analysis. As the average sample size is 2 to 3 g, and many of the samples are as small as 0.05g, it has not been possible to determine the engineering properties of lunar soils according to usual soil testing procedures. However, grain size distribution, specific gravity and minimum and maximum densities on one-gram lunar samples have been measured successfully. The results of these tests and additional index property data determined by other investigators can be used to develop an understanding of the characteristics of lunar soil. The scope of this section includes lunar soil genesis, particle types, grain size distribution, grain shape distribution, specific gravity, minimum and maximum density, and relative density.

Lunar Soil Genesis

Lunar soil is formed primarily as a result of meteorite impact on the lunar surface (c.f., Oberbeck and Quaide, 1968). Meteorites that would burn up or be slowed down considerably in the earth's atmosphere are unimpeded in lunar vacuum and strike the lunar surface at velocities of 15 to 20 km/sec. The energy of impact is so great that the meteorite explodes and vaporizes, excavating a mass of material up to 1000 times that of the impacting meteorite (Gault et al., 1968). The crater thus formed is then filled in time by the action of subsequent impacts. The impacts tend to comminute the native material into finer and finer particles. Less apparent is the fact that the impacts also melt some of the rock and soil into glasses which tend to aggregate with other particles. The two processes, cc minution and aggregation, evidently reach a steady state balance because, as shown subsequently, the grain size distribution stabilizes even though the distribution of particle types varies considerably (c.f., Quaide et al., 1971 and McKay et al., 1971).

The ejected material can be thrown very long distances; the meteorites (or planetoids) that produced the craters that are visible from earth with the unaided eye probably distributed material over the entire surface of the moon. Consequently, meteorite impact is also a primary transport mechanism on the lunar surface, along with gravity, and very complex soil mixtures can be produced from distinctly different geologic formations located at varying distances and in different directions.

The lunar soil deposits are similar t terrestrial wind-blown deposits such as sand dunes in that the stratigraphy is very complex. The strata may be interrupted, tilted, non-planar and constantly changing in relative positions. Soil particles may be buried and exposed many times. Furthermore, the density varies erratically within short distances. The two types of deposits differ, however, in that meteorite impacts produce a random deposit and the wind produces a systematic deposit. Thus, the particles are well-sorted by size in a sand dune; whereas, they are well-graded in the lunar soil. Furthermore, the changes in a sand dune deposit occur far more rapidly with time than do changes in a soil on the moon.

A rain of meteorites is constantly falling on the lunar surface producing craters ranging in diameter from tenths of microns to hundreds of kilometers. Impact frequency decreases an order of magnitude for each increase in order of magnitude of the diameter of the meteorite. The flux of this bombardment appears to be generally decreasing with geologic time (c.f., Shoemaker, 1971 and Hartmann, 1972). Probably more than 100 million years of exposure at the lunar surface are required to produce a mature soil.

Primary mechanisms involved in the formation of terrestrial soils have not been active on the moon. If water and free oxygen have ever been present on the lunar surface, then it has evidently been for only short periods and in highly localized areas (c.f., Charles et al., 1971 and Gibson and Moore, 1973). Mechanical disintegration due to running water, freezing and thawing, glaciation, etc., and chemical decomposition due to oxidation and hydration are absent on the moon. Nonetheless, an incredible variety of particle types are to be found in the lunar soil.

Particle Types

Despite the similar appearance of the lunar surface at the different landing sites - dark brown to dark grey silty-sandy soil - the compositions of the returned samples are highly variable. Four general groups of particles have been identified (c.f., McKay et al., 1971, 1972):

Mineral fragments

miscellaneous glasses

agglutinates

lithic fragments

Mineral Fragments

The mineral fragments found in lunar soils include:

plagioclases

pyroxenes (augite, pigeonite, etc.)

ilmenite

olivine

potassium feldspar

quartz (extremely rare)

dozens of other minerals in small quantities

It is interesting to note that the mineral fragments are billions of years old and yet are unweathered chemically. Thus, although there are clay-sized particles, there are no clay minerals. Selected mineral fragments are shown in Fig. 3-1(a).

Miscellaneous Glasses

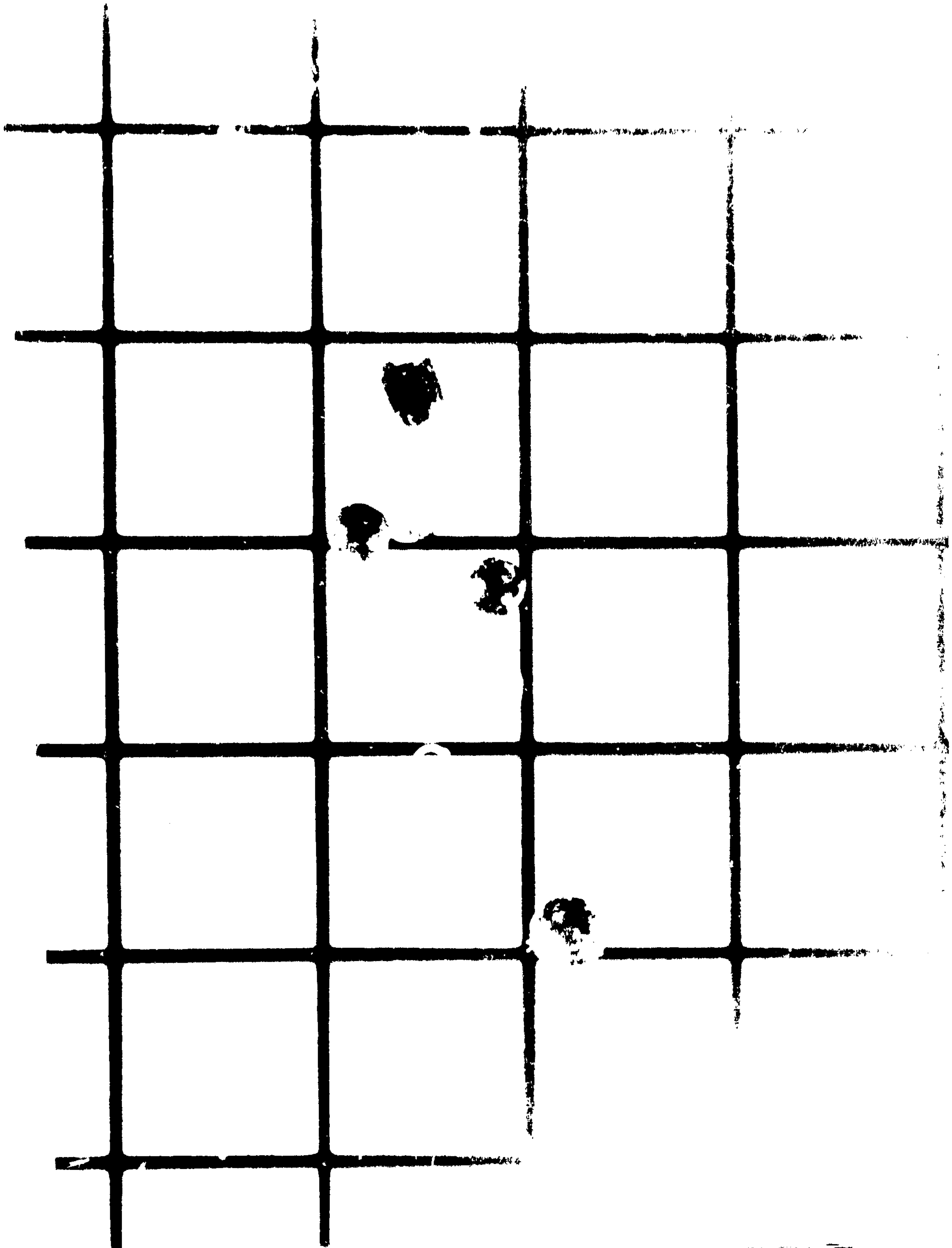
A large variety of glasses (particles without crystal structure) are present in the lunar soil, differing in form, chemical composition and color. The basic forms are angular fragments, droplets, and ropy glasses; and the different chemical compositions produce brown, red, orange, green and colorless glasses.

Glass droplets, or spherules (Fig. 3-1(b)) represent only a small percentage of the lunar soil and have little or no influence on geotechnical properties. They are formed when molten glass that is ejected by a meteorite impact has a sufficiently long time-of-flight to form droplets (due to surface tension) and then harden into beads before landing back on the surface. The diameter of these beads generally ranges from 0.005 to 1 mm (Quaide et al., 1971). Examples of typical glass fragments found in lunar soils are shown in Fig. 3-1(c).

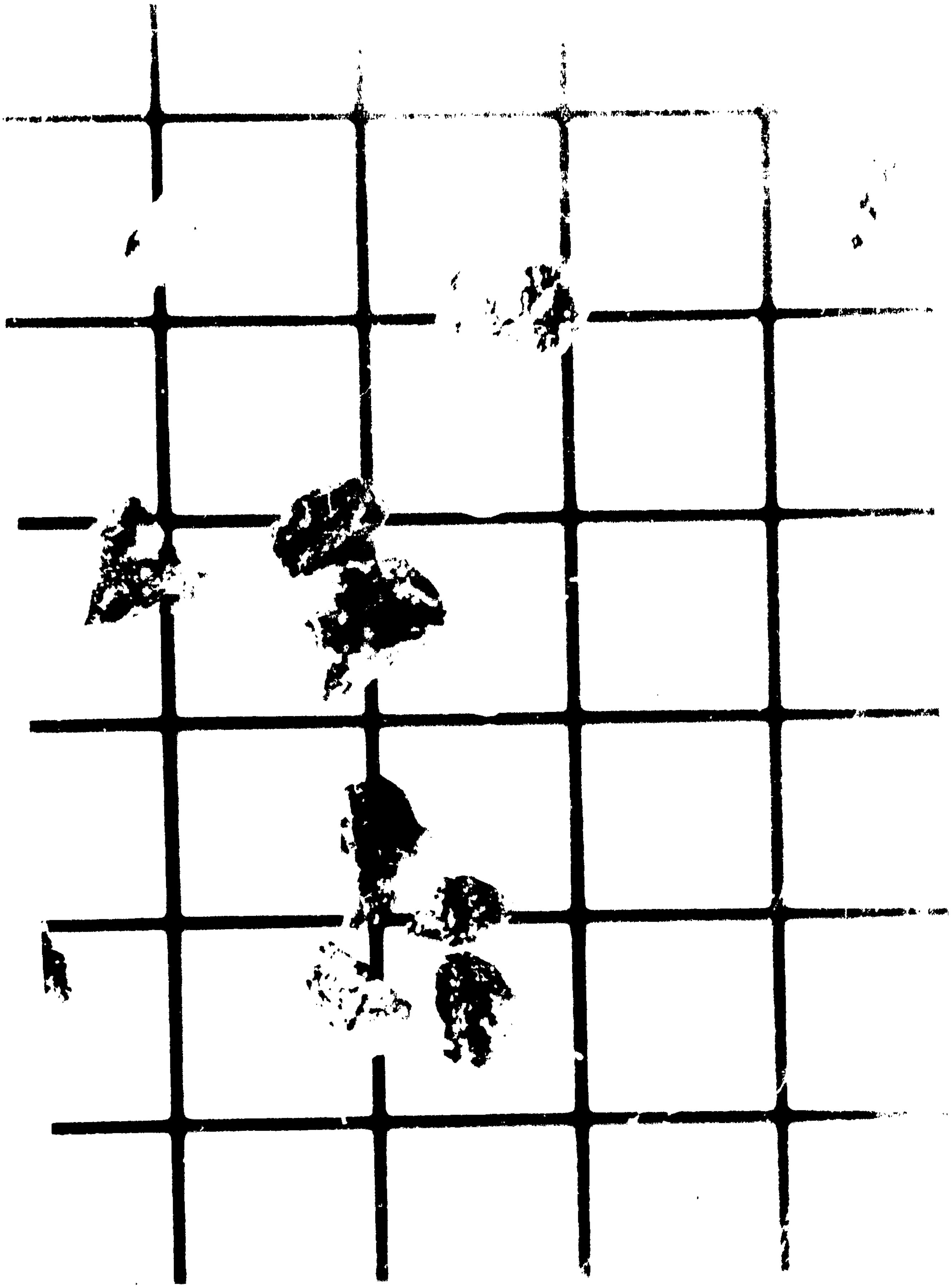
Agglutinates

Agglutinates are composed of lithic and mineral fragments and glass debris bonded together by inhomogeneous glass. Agglutinates are formed when the molten glass that was produced during an impact strikes and penetrates the lunar surface, thereby welding soil particles together. This is an important constructional process, as it creates big soil particles from small ones. However, the agglutinates tend to be quite fragile and therefore a soil containing a large amount of this material

FIG. 3-1 TYPICAL PARTICLE TYPES FOUND IN THE LUNAR SOILS
(The particles are resting on a 1 x 1 mm grid): a) MINERAL GRAINS



b) GLASS DROPLETS



c) GLASS FRAGMENTS

may show a curved Mohr-Coulomb strength envelope because of particle breakage at higher confining pressures (Carrier et al., 1973a). Examples of agglutinates are shown in Fig. 3-1(d), where their irregular, delicate form may be seen.

Lithic Fragments

Lithic fragments consist of comminuted pieces of lunar rocks and include:

basalts

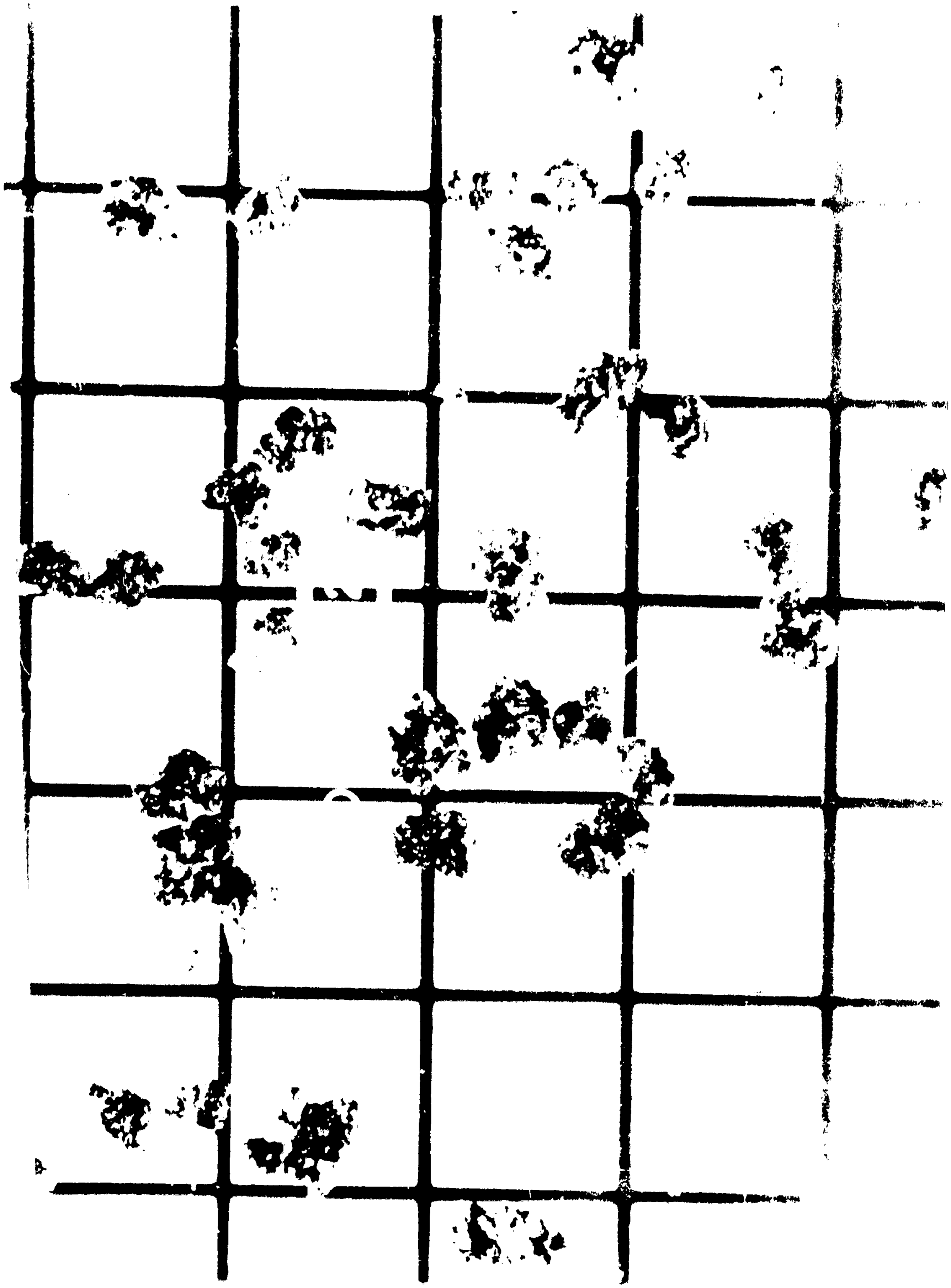
breccias

feldspathic rocks

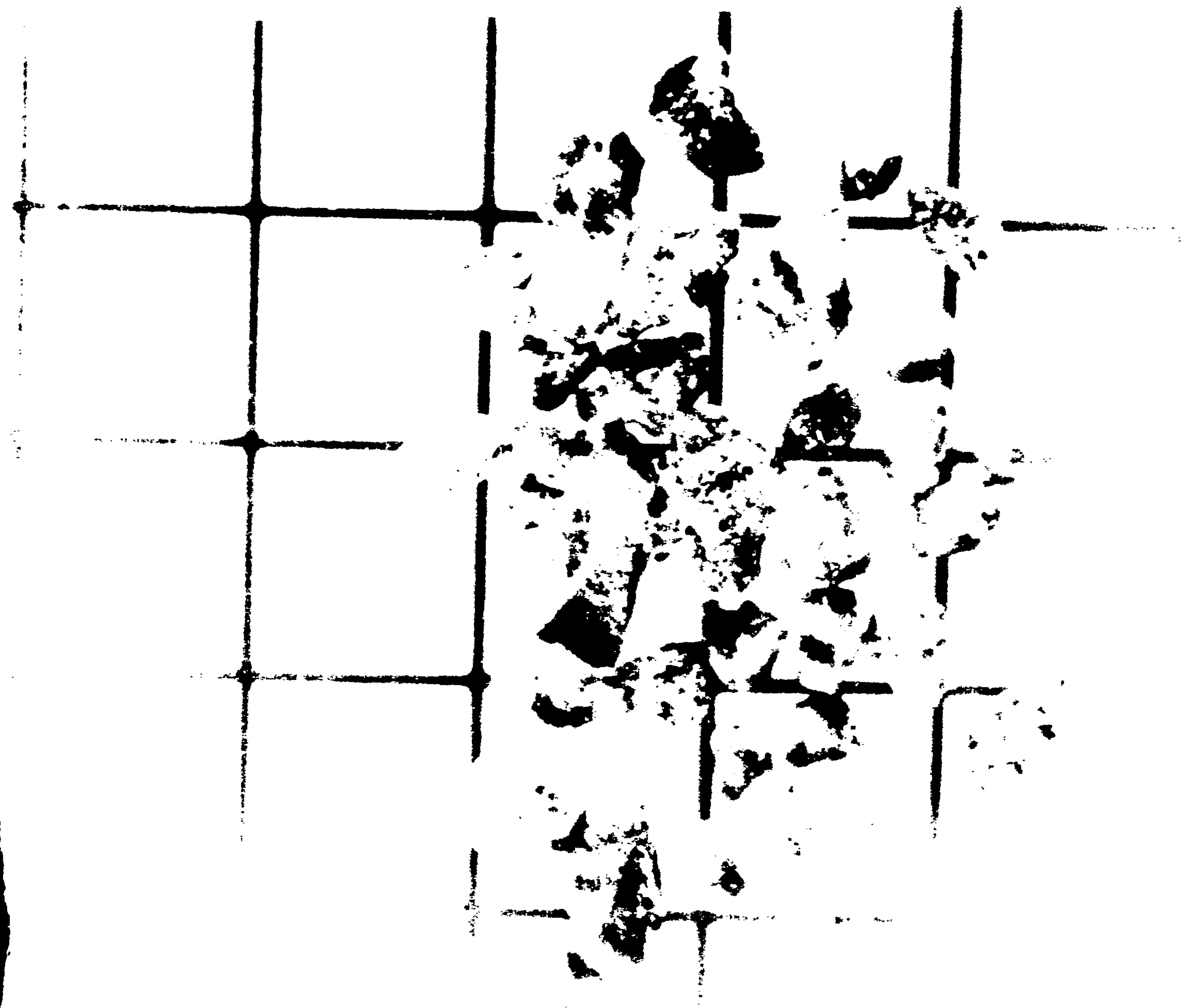
pyroxenites

Some types of breccias are similar to agglutinates in that they consist of lithic and mineral fragments and glass debris welded together either by molten glass or by glass which has been recrystallized due to thermal metamorphism (c.f., Williams, 1972). However, these breccias are formed not by the injection of molten glass into the lunar surface, but within the hot ejecta blanket of gases and fragments produced by a meteorite impact. All of the constituents of the breccia are thrown out as a mass and part of the glass melts to bond the other particles together. This is another important constructional process. Other breccias are formed when the native rocks are broken up, jumbled and then re-welded in situ but without the presence of glass. Both types of breccias are denser and more coherent than agglutinates, but not as strong as basalts. Examples of breccias and basalts are shown in Figs. 3-1(e) and 3-1(f).

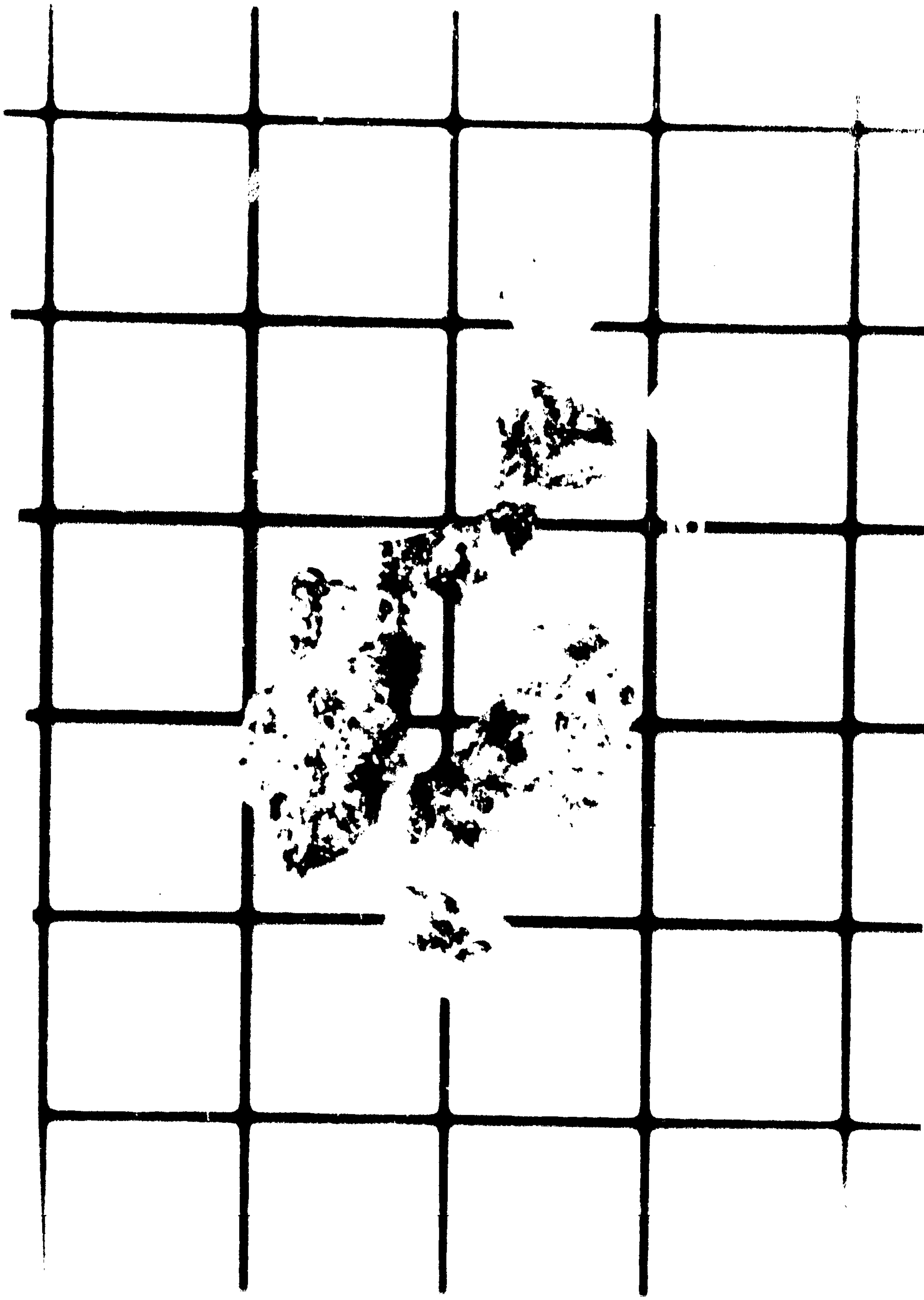
The proportions of the different particle types discussed above are variable from site to site, from sample to sample and even from size



d) AGGLUTINATES



e) RECRYSTALLIZED BRECCIA MATRICES



f) BASALT FRAGMENTS

fraction to size fraction. Table 3-1 presents particle type distribution data for lunar soils from the Apollo 12, 14 and 15 landing sites (McKay et al., 1971, 1972 and Clanton et al., 1972). The locations on the lunar surface of specific samples referred to in Table 3-1 and in subsequent tables and figures in this section are given in Table 3-2. The range of proportions can be considerable, the extreme case being the breccias in the Apollo 12 soil samples, which can comprise anywhere from 0.7% to 75% of the 0.25 to 1.00 mm size fraction.

Particle type data for one Apollo 14 sample, 14259, are separately included: of all the samples for which specific gravity and relative density measurements have been made, 14259 is the only sample to date for which the distribution of particle types is also known. Its distribution is very similar to that of the mean distribution for Apollo 14 soils. Samples 14141 and 14149, the former taken near the rim of Cone Crater and the latter from the bottom of the Soil Mechanics Trench, are considered to be exceptional samples, as evidenced by their much coarser grain size than the bulk of the samples, and are therefore not included in the mean and range for Apollo 14 soils.

All of the Apollo 15 samples in Table 3-1 were taken at different depths along a 2.4 m drill stem core and are probably representative of the plains area of the Apollo 15 landing site.

Although the percentage of particle types in the Apollo 12 soils were not determined for the same size fraction as in the Apollo 14 and 15 soils, the general trends seem to be the following: Apollo 15 soils contain the greatest proportion of mineral fragments, and Apollo 14 the least; Apollo 12 the greatest proportion of glasses, and Apollo 14 and 15 about equal; Apollo 14 the greatest proportion of agglutinates, and

TABLE 3-1

DISTRIBUTION OF PARTICLE TYPES

IN LUNAR SOILS

	Apollo 12*		Apollo 14**			Apollo 15***	
Particle Type	Mean	Range	Mean	Range	14259	Mean	Range
Mineral fragments	21%	4-48%	9%	7-14%	9%	38%	29-48%
Glasses	35%	12-75%	14%	11-18%	13%	12%	4-26
Agglutinates	15%	0.5-30%	52%	48.57%	52%	33%	20-51%
Lithic fragments							
Basalts	11%	3-45%	1%	0-2%	1%	6%	2-14%
Breccias	16%	0.7-75%	23%	14-29%	25%	10%	4-14%

*Apollo 12: 0.25 to 1.00 mm size fraction for nine samples (McKay et al., 1971)

**Apollo 14: 0.09 to 0.15 mm size fraction for six samples, excluding samples 14141 and 14149 (McKay et al., 1972)

***Apollo 15: 0.09 to 0.15 mm size fraction for 12 drill stem samples (Clanton et al., 19 ?)

†See Table 3-2 for location of sample

TABLE 3-2 -- LUNAR SAMPLE LOCATION

Mission	Sample	Location/Station	Reference
Apollo 11: Mare Tranquillitatis (Tranquillity Base)	10004	Core tube sample near LM	Shoemaker et al. (1970)
	10005	" " " " "	" " " "
	10084	Bulk sample near LM	" " " "
Apollo 12: Oceanus Procellarum (Surveyor III)	12001	Near LM	
	12029	Surveyor III scoop	Shoemaker et al. (1970)
	12057	Mixture of fines from bottom of sample return container	Jaffe (1972)
	un-numbered	Fines removed from packing material in the same container as 12057	
Apollo 14: Fra Mauro	14141	Station C', near rim of Cone Crater	Swann et al. (1971)
	14149	Station G, 200 m E of LM	" " " "
	14163	Bulk sample, near LM	" " " "
	14259	Comprehensive sample, 150 m W of LM	" " " "
	14321	Station C1, near rim of Cone Crater	" " " "
Apollo 15: Hadley Rille-Appenine Front	15001-15006	Drill stem, Station 8,	Swann et al. (1971)
	15031	Bottom of Soil Mechanics Trench, Station 8, 100 m NW of LM	" " " "
	15101	Station 2, on the flank of St. George Crater (Appenine Front)	" " " "
	15601	Station 9A, at rim of Hadley Rille	" " " "

Apollo 12 the least; Apollo 12 the greatest proportion of basalts, and Apollo 14 the least; and Apollo 14 the greatest proportion of breccias and Apollo 15 the least.

<u>Grain Size Distribution</u>

The grain size distribution for the >1 mm fraction of many lunar soil samples was determined by the Lunar Sample Preliminary Examination Team (LSPET) in the Lunar Receiving Laboratory by dry sieving nearly the entire sample, usually amounting to several hundred grams. Small sub-samples of the <1 mm fraction, typically 0.1 to 0.5g, were then selected and distributed to different investigators for further analysis. The grain size distributions determined by these investigators are generally quite repeatable and reproducible, in spite of the small sample size and slight differences in sieving techniques. Despite the variety of lunar soil compositions, the grain size distributions for the bulk of the returned samples fall within a remarkably narrow band, and are classified as well-graded silty sands to sandy silts: SW-SM to ML in the Unified Soil Classification System. The results from a recent compilation of data from a number of sources (Carrier, 1973a) are shown in Fig. 3-2. The average particle size by weight for all samples is 0.07 mm, with a range in the average size of any sample from 0.04 to 0.13 mm. The grain size parameters are summarized in Table 3-3. These samples have been exposed at the lunar surface for 100 million years or more (determined by counting the number of nuclear particle tracks per square centimeter: c.f. Arrhenius et al., 1971 and Crozaz et al., 1971, 1972); whereas, the few exceptionally coarse samples that have been found have exposure ages of only 15 to 40 million years. Consequently, 100 million years seems to be the minimum time required to produce a "steady state" soil. After that

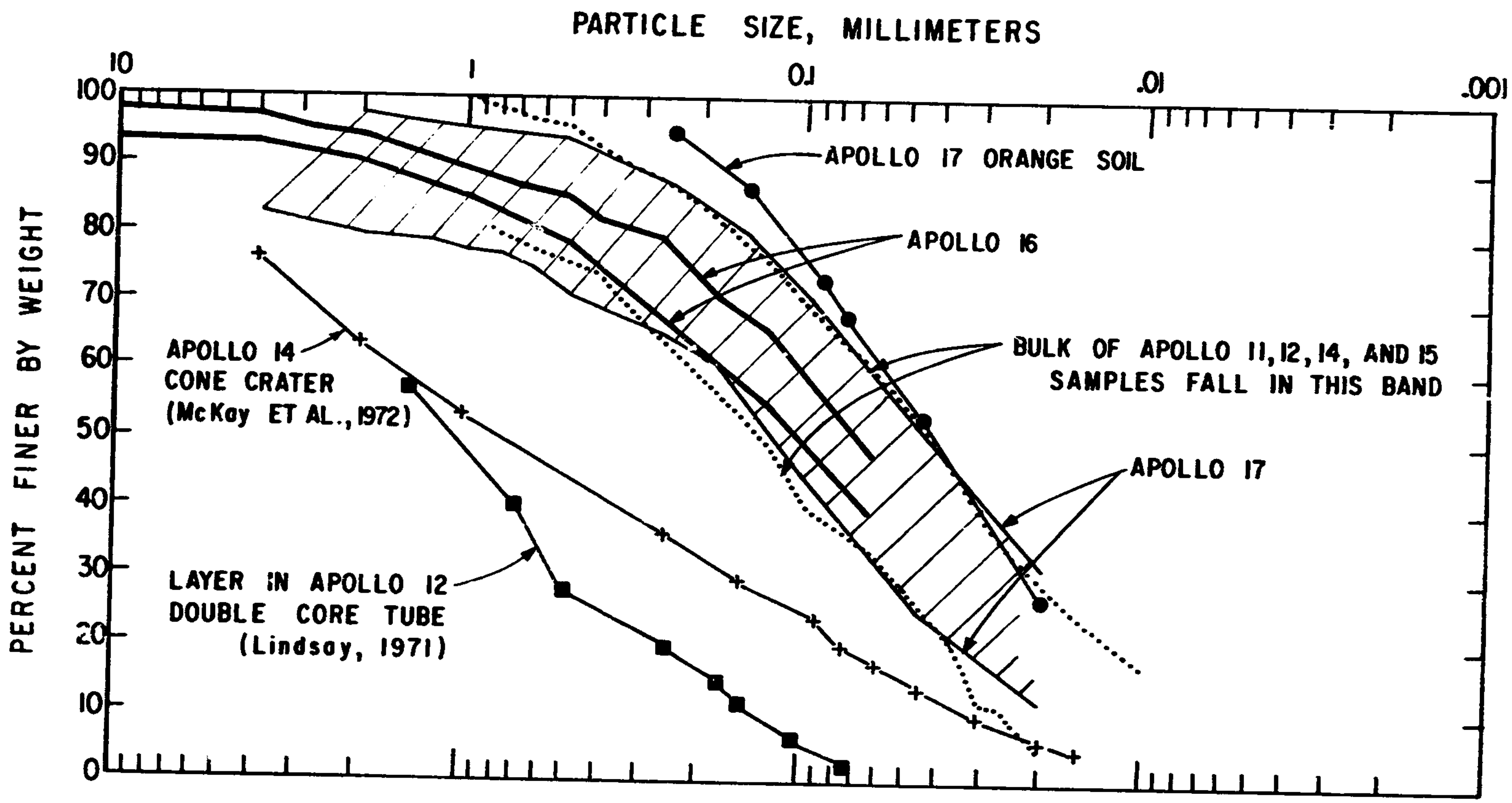


FIG. 3-2 GRAIN SIZE DISTRIBUTIONS OF LUNAR SOIL

TABLE 3-3

LUNAR SOIL GRAIN SIZE PARAMETERS: APOLLO 11-15

The grain size distributions of the bulk of the returned lunar soil samples fall within a relatively narrow band defined by the coarse and fine boundaries indicated below and shown in Fig. 3-2.

Parameter	Coarse boundary of band	14163†	14259†	15601†	Fine boundary of band
Percent finer than 1 mm	82%	90.5%	95.1%	88.4%	100%
D_{80} (mm)	.72	.34	.26	.45	.163
D_{60} "	.21	.094	.103	.155	.060
D_{50} "	.128	.057	.071	.104	.042
D_{30} "	.054			.048	.021
D_{20} "	.036				.013
D_{10} "	.026				~.006
$*C_u = \frac{D_{60}}{D_{10}}$	8				~10
$**C_c = \frac{(D_{30})^2}{D_{60} x D_{10}}$	.5				~1.2

†See Table 3-2 for location of samples

*Coefficient of uniformity

**Coefficient of curvature

period, the aggregation processes balance the comminution processes, and while the composition may continue to change, the grain size distribution will evidently only vary back and forth within the band shown in Fig. 3-2.

The authors have also determined the grain size distributions for three, one-gram submillimeter samples: 14163, 14259 and 15601 (see Table 3-2). The samples were wet-sieved in freon. These distributions are in close agreement with the results obtained by other investigators for other subsamples of the same parent samples. The distributions for these three samples, as shown in Fig. 3-2 and Table 3-3, have been corrected for the >1 mm size fractions; the distributions for the <1 mm fractions are even closer together.

Grain Shapes

The shapes of the individual particles in lunar soil range from perfectly spherical to extremely angular, as shown in Fig. 3-1. Many (in some cases, most) of the particles are not compact, but exhibit very irregular shapes and surface textures, including re-entrant surfaces. The standard shape parameters that have been developed by various investigators (c.f. Wadell, 1935, Krumbein, 1941, Aschenbrenner, 1956, Lucks, 1970) are inadequate to describe accurately the shapes of these irregular lunar soil particles. Nonetheless, some shape measurements have been made, and the results are summarized here.

Heywood (1971) has determined seven shape coefficients for 30 particles of 0.7 mm diameter from an Apollo 12 sample, 12057. These coefficients are: elongation, flatness, area ratio, volume coefficient, rugosity coefficient, specific circularity of profile, and specific circularity including the effect of rugosity. One of these, volume coefficient, was also measured for separate size fractions and it was found that the intermediate-size fractions of this particular lunar sample are more nearly equi-dimensional than the coarser and finer fractions.

Görz et al. (1971, 1972) have determined aspect ratios for samples from Apollo 12, 14 and 15. The aspect ratio of a particle is defined as the ratio of the minor and major axes of an ellipse which has been fitted to the particle by a least squares approximation. Measured aspect ratios range from 1.0 (equant) to 0.1 (very elongate), with most values falling in the range 0.8 to 0.3 (slightly to medium elongated) and an average ratio of 0.6. Because the majority of particles are somewhat elongated, it is possible that preferred particle orientations may exist in the lunar soil in situ. If so, then anisotropic properties may be anticipated. These possibilities have been under study and are reported separately.

Cadenhead et al. (1972) and Cadenhead and Jones (1972) have measured the specific surface area of an Apollo 14 sample, 14153, and that of an Apollo 15 sample, 15101, by means of nitrogen gas adsorption and obtained values of 0.21 m^2/g and 0.65 m^2/g, respectively, which are typical for silty soils.

Specific Gravity

Unfortunately, specific gravity has received very little attention in the lunar samples program. The density of none of the rock samples has been accurately determined thus far, and specific gravity measurements have been made on only a few soils. The former is due to difficulties involved in measuring the volume of a rock without immersing it in a liquid. The latter is due to an understandable unwillingness to commit the relatively large soil samples necessary for standard tests: at least 30 g for an air comparison pycnometer and 50 g for a conventional 500 cm^3 water pycnometer. Other methods have now been developed, however, which require much smaller samples. In particular, we have obtained good results on three, one-gram submillimeter samples using 3 and 5 cm^3 volumetric flasks. The average specific gravity of the particles in each samples was determined using conventional water immersion micropycnometry techniques. The miniaturization required for the small lunar samples was found to be practical and to give reproducible results.

Specific gravity values are summarized in Table 3-4 and range from 2.9 to greater than 3.2. These values are high by terrestrial standards, even for ground basalts which have specific gravities of 2.9. The first specific gravity test was on an Apollo 11 sample obtained from the combined splits of the two core tube samples. An air comparison pycnometer was utilized for this test. The value of 3.1 that was obtained indicated that the lunar soil was significantly different from typical terrestrial soils, and it was later found that the Apollo 11 soil was enriched in titanium oxide. A large range of specific gravities for the individual particle types has been found. By suspending the soil particles in a density gradient, produced by varying the proportions of a mixture of methylene iodide and dimethyl formamide, Duke et al. (1970a) found the following values of specific gravity:

agglutinate and glass particles:	1.0 to > 3.32
basalt particles:	> 3.32
breccia particles:	2.9 to 3.1

TABLE 3-4

SPECIFIC GRAVITY OF LUNAR SOILS

Mission	Sample Number†	Sample Weight (g)	Specific Gravity G	Test Technique	Reference
Apollo 11	10004 10005	49.1	3.1*	Nitrogen pycnometry	Costes et al. (1970)
	10084	1.5	3.01	Suspension in a density gradient	Duke et al. (1970a)
Apollo 12	unnumbered	56.9	3.1*	Air pycnometry	Carrier (1970)
Apollo 14	14163	0.65	2.9 ± .1	Helium pycnometry	Cadenhead et al. (1972)
	14163	0.97	2.90 ± .05	Water micro-pycnometery	This report
	14259	1.26	2.93 ± .05	Water micro-pycnometery	This report
Apollo 15	15101		3.1 ± .1	Helium pycnometry	Cadenhead and Jones (1972)
	15601	0.96	3.24 ± .05	Water micro-pycnometery	This report

†See Table 3-2 for location of samples

*Total sample; all others were performed on -1 mm size fraction

The wide variation in chemical composition of the glasses, as evidenced by the many different colors, is partly responsible for the broad range of specific gravities. The very low values approaching 1.0 result from enclosed voids within the glasses.

An Apollo 12 samples was also tested with an air comparison pycnometer, and the same specific gravity as for Apollo 11, 3.1, was obtained. This type of test technique was not authorized for use on lunar samples from subsequent missions.

Cadenhead et al. measured a value of 2.9 ± 0.1 in helium as part of their gas adsorption studies. Our value of 2.90 ± 0.05 for another sub-sample of the same parent sample, 14163, agrees exactly. The slightly higher value of 2.93 ± .05 for sample 14259 probably indicates a small difference in soil composition. Cadenhead et al. also measured the specific gravity of a fragment from a breccia rock, 14321, and obtained a value of 3.2 ± .1.

In the section on Particle Types, it was seen that the Apollo 14 (Fra Mauro region) soils contain a higher proportion of agglutinates and breccias and fewer mineral fragments and basalts than the Apollo 12 and 15 soils. The significantly lower specific gravities of the Apollo 14 soils undoubtedly reflect these differences in composition.

A specific gravity of 3.1 ± .1 has been measured by Cadenhead and Jones for one Apollo 15 soil sample, 15101, and the writers obtained a value of 3.24 ± .05 for another, 15601. The latter is a remarkably high value: preliminary, unpublished data obtained by the Apollo 15 LSPET suggests that this particular sample contains more basalts and mineral fragments, about the same proportion of agglutinates, and fewer glasses and breccias than the median Apollo 15 drill stem samples in Table 3-1.

As more data are accumulated, it is very likely that a correlation can be developed between the proportion of the various particle types and the average specific gravity. It may be that a reasonable estimate of specific gravity can be calculated given the percentage of agglutinates, basalts, breccias, etc. This would permit calculation of the porosity of undisturbed core tube samples for which the specific gravity is not known directly.

Minimum and Maximum Density

The few minimum and maximum density measurements that have been made for lunar soils have been by a variety of methods. It is well known that the maximum density is dependent on the method, and therefore the values reported by different investigators cannot be compared directly. The method developed by the authors, while arbitrary, does provide a well-defined, repeatable approach that can be used with very small samples (1 g). Small graduated cylinders of 1.0 and 1.5 cm^3 capacity were used to measure sample volumes after placement in loose and dense states. The loosest condition was obtained by pouring the sample from a small height in a single, continuous operation. To obtain the maximum density the cylinders were filled with soil and tapped 90 times by dropping 4 to 5 cm (1-1/2 to 2 in) in nearly free fall onto a table. It was found that the maximum densification that could be obtained was reached by 90 taps of the sample.

The effect of compactive effort (number of taps) on maximum density was studied using 0.5 gram samples of crushed basalt simulant. It was found that a compactive effort in excess of 90 taps did not make any measurable difference in the density obtained; thus 90 taps were used to obtain dense samples. The effects of number of layers (1 to 5) and cylinder diameter (9 mm) was used, and the loose sample (deposited in one layer) was densified by tapping it 90 times.

Results of standard A.S.T.M. tests on crushed basalt simulant are compared with small sample test results in Table 3-5. The data show that small samples can be prepared to lower minimum densities (higher void ratios) than large samples. This can be interpreted as due to smaller body forces (self-weight) causing compression in the small samples, and possibly due to the influence of side wall friction in the small graduated cylinder. Conversely, the small samples can be prepared to a higher maximum density (lower void ratio) than the large samples. This probably reflects the fact that standard A.S.T.M. test for maximum density does not provide complete densification of soils of silty fine sand gradation. The variability in results was much greater when small samples were used. It should be noted, however, that no special equipment is needed for these tests and no ultra-precise measuring techniques are required.

Table 3-5: Maximum and Minimum Densities of Crushed Basalt Simulant

Sample		Density, g/cm^3 Best Value	Density, g/cm^3 Range of Percent Variation
Standard A.S.T.M.	Maximum Density	1.82	±0.3%
	Minimum Density	1.36	±0.4%
Small Sample (0.5 gram)	Maximum Density	1.94	±2.0%
	Minimum Density	1.24	±4.0%

The minimum and maximum densities for several samples are presented in Table 3-6; in cases where the specific gravity is known, the maximum and minimum void ratios have also been calculated. The Apollo 11 densities reported by Costes et al. (1970) were determined as part of a study of penetration resistance. Cremers et al. (1970), Cremers and Birkebak (1971), Cremers (1972) and Cremers and Hsia (1973) found minimum densities for Apollo 11, 12, 14 and 15 samples as part of an investigation of thermal conductivity and noticed that it was not possible to place the Apollo 11 and 12 samples at as low an absolute density as the Apollo 14 sample. The densities determined by Jaffe (1972) were for a sample returned inside the scoop of the Surveyor III spacecraft and were part of a study on penetration resistance. The densities of Luna XVI samples were determined by Gromov et al. (1971) as part of their penetrometer, oedometer, and direct shear tests. Their sample represented approximately two percent of the entire Luna XVI returned sample.

The higher minimum and maximum densities of the Apollo 15 soil compared with the Apollo 14 samples studied by the authors is obviously partly due to the higher specific gravity of the Apollo 15 soil. This cannot be the entire explanation, however, otherwise the maximum and minimum void ratios would be comparable, and the Apollo 14 soils have greater void ratios than the Apollo 15 soil. The submillimeter grain size distributions for the three samples are all quite similar, so the explanation for the difference in void ratios must lie elsewhere. One possibility is that the higher proportion of agglutinates and breccias in the Apollo 14 soils contributes more re-entrant, intra-granular voids than the Apollo 15 soil. If it is assumed that the Apollo 15 soil has no re-entrant voids, which is probably not true, then based on the minimum void ratios, the Apollo 14 soils would have a re-entrant component of void ratio of about

TABLE 3-6

MINIMUM AND MAXIMUM DENSITY OF LUNAR SOILS

Mission	Sample Number[†]	Sample* Weight (g)	Density, ρ: ρ_{min} (g/cm^3)	Density, ρ: ρ_{max} (g/cm^3)	Specific gravity G (Table 3-4)	Void ratio, e**: e_{max}	Void ratio, e**: e_{min}	Reference
Apollo 11	10084	565	1.36	1.80	3.01	1.21	0.67	Costes et al. (1970)
	10084	5	1.26		3.01	1.39		Cremers et al. (1970)
Apollo 12	12001	6	1.30					Cremers and Birkebak (1971)
	12029	1.3	1.15	1.93				Jaffe (1972)
Apollo 14	14163	5	1.10		2.90	1.64		Cremers (1972)
	14163	0.97	0.89±.03	1.55±.03	2.90	2.26	0.87	This paper
	14259	1.26	0.87±.03	1.51±.03	2.93	2.37	0.94	This paper
Apollo 15	15031	5	<1.30					Cremers and Hsia (1973)
	15601	0.96	1.10±.03	1.89±.03	3.24	1.94	0.71	This paper
Luna XVI	-	10	1.12	1.79				Gromov et al. (1971)

[†]See Table 3-2 for location of samples.
*All tests performed on -1 mm size fraction
**Void ratio = porosity/1-porosity

.91 - .71 = 0.2, which is a significant amount. Even so, this cannot be the entire explanation, since the difference in maximum void ratios is even higher: 2.32 - 1.94 = 0.4.

It appears, therefore, that other factors such as particle shape, surface texture and grain arrangement must also be important. In fact, the maximum and minimum void ratios of a ground basalt simulant with the same grain size distribution as the lunar soils are significantly less than even the Apollo 15 soil. It is imperative to make minimum and maximum density tests on a variety of lunar soils, because with these values and the in situ density known it is possible to calculate the relative density. Relative density is important in both engineering and geological considerations, as discussed in more detail later.

Summary

Lunar soil is produced primarily by meteorite impacts on the lunar surface; the usual terrestrial agents of soil formation are absent on the moon. These impacts cause both comminution and aggregation of particles and the soils consist of complex mixtures of mineral fragments, miscellaneous glasses, agglutinates, and lithic fragments (primarily basalts and breccias). Although the proportions of the various particle types are extremely variable, the grain size distributions for soils which have been exposed to meteorite re-working for 100 million years or more fall within a relatively narrow band and are classified as well-graded silty sands to sandy silts (SW-SM to ML in the USCS). The average particle size by weight generally varies from 0.04 to 0.13 mm. Grain shapes range from perfectly spherical to extremely irregular, including some particles with re-entrant surfaces.

The specific gravity of submillimeter lunar soil samples varies from 2.90 to 3.24; and individual particles range from 1.0 to >3.32. The minimum and maximum bulk densities of submillimeter one-gram samples vary from 0.87 to 1.10 g/cm^3 and from 1.51 to 1.89 g/cm^3, respectively. The ranges in the minimum and maximum densities are due to the differences in the specific gravity, intra-granular porosity, particle shape, surface texture, and grain arrangements.

DENSITY AND POROSITY

Data Sources

Data sources used specifically for infering lunar soil density or porosity are listed in Table 3-7. These data sources were listed and discussed briefly in Chapter 2. Shown also in Table 3-7 are parameters which have been measured directly or deduced from correlations with simulants, as opposed to those parameters which must be calculated. The last column in Table 3-7 shows the approximate range in depth from which density data has been obtained by each of these methods.

The relationships between all of the parameters in Table 3-7 are shown by the following set of equations.

$$\text{bulk density, } \rho = \frac{G_s \rho_\omega}{1 + e} = G_s \rho_\omega (1 - n) \tag{3-1}$$

where porosity, n is in decimal and density of water, ρ_ω, is 1 gm/cm³ at 4°C and G_s = specific gravity of solids.

$$\text{porosity, } n = \frac{e}{1 + e} \tag{3-2}$$

$$\text{void ratio, } e = \frac{n}{1 - n} \tag{3-3}$$

$$\text{relative density, } D_r = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100\%$$

$$= \frac{(1-n_{min})}{(1-n)} \frac{(n_{max}-n)}{(n_{max}-n_{min})} \times 100\%$$

$$= \frac{\rho_{max}}{\rho} \frac{(\rho-\rho_{min})}{(\rho_{max}-\rho_{min})} \times 100\% \tag{3-4}$$

TABLE 3-7 -- DATA SOURCES FOR INFERRING LUNAR SOIL DENSITY OR POROSITY

Source	Bulk density, ρ	Void ratio, e	Porosity, n	Relative density, D_r	Depth Range cm
Core Tube Samples	Measured directly - but corrections for disturbance during sampling must be made	<u>Calculated</u> Requires specific gravity of solids, G_s	<u>Calculated</u> Requires G_s	<u>Calculated</u> Requires ρ_{max} and ρ_{min}	0-60
Lunar Drill Samples	Measured directly - but correction for disturbance during drilling must be made	"	"	"	0-300
Astronaut Footprints	<u>Calculated</u> Requires e_{max}, e_{min}, and G_s for simulant and lunar soil	<u>Calculated</u> Requires e_{max} and e_{min} for lunar soil and simulant	<u>Calculated</u> Requires e_{max} and e_{min} for lunar soil and simulant	Obtained by direct correlation with simulant, but effect of gravity must be assessed	0-15
LRV and MET Tracks	"	"	"	Obtained by direct correlation with simulant, but effect of gravity must be assessed	0-15
Boulder Tracks	"	"	"	Obtained by direct correlation with friction angle - which in turn requires assessment of gravity effects	0-300 or 400
Penetration Resistance	"	"	"	"	0-60

where e_{max}, n_{max} and ρ_{min} = maximum void ratio, maximum porosity, and minimum density when deposited by a standard procedure designed to minimize density

e_{min}, n_{min} and ρ_{max} = minimum void ratio, minimum porosity, and maximum density when deposited by a standard procedure designed to maximize density.

As illustration of the use of these equations, if e is known, then n is also known by Equation (3-2). If G_s is also known, then ρ can be computed precisely by Equation (3-1). Likewise if e_{min} is known, then n_{min} is obtained by Equation (3-2). If G_s is also known, then ρ_{max} can be computed by Equation (3-1).

Thus conversion from one density parameter to another may be readily accomplished if sufficient data are available. Unfortunately, however, sufficient data have rarely been available to allow these conversions with a high degree of confidence. Particularly scarce have been data on lunar soil specific gravity and maximum and minimum density values. Therefore it has usually been necessary to widely extrapolate the few values of specific gravity and maximum and minimum density which have become available.

From the beginning of the study of lunar soil mechanical properties it was recognized that lunar soils and various lunar soil simulants are best compared after densities have been normalized by conversion to relative density. That is, as a first approximation it may be assumed that granular soils of similar gradations exhibit similar property values when compared at the same relative density. However, data became available progressively, and in the early stages of study simplifying assumptions had to be made in the absence of hard data.

Prior to the Apollo lunar landings, it was necessary to assume that the actual lunar soil and basaltic lunar soil simulants which had similar gradations had the same values of G_s, e_{max}, and e_{min}. With this assumption it followed that lunar soil and lunar soil simulants would be expected to exhibit the same properties when their bulk densities were the same.

After values of $G_s = 3.1$ were measured for Apollo 11 and 12 samples it became apparent that the simulant G_s value, 2.9,was not the same and that simulants and lunar soil should be compared on a porosity (or void ratio) basis to insure that relative densities were the same. However it was still necessary at that time to assume that e_{max} and e_{min} were the same for simulants and lunar soil of similar gradation. Thus most of the results of analyses which in some way involved simulants were reported in terms of porosity or void ratio as late as the Apollo 16 Preliminary Science Report.

When relative density test results became available for 1 gram samples of Apollo 14 and 15 soil it became apparent that equivalence of e_{max} and e_{min} for simulants and lunar soil was not a good assumption and that they should be compared directly on a relative density basis only.

Thus additional measurements of e_{max}, e_{min}, and G_s on lunar soil samples are needed to make maximum utilization of available density data with minimum error.

However, it should be noted that comparison of granular soils on a relative density basis is simply the most practical way of minimizing errors of extrapolation, but it does not eliminate them entirely. Cases have been observed in which granular soils of similar gradation have exhibited somewhat different properties at the same relative density, due probably to differences in surface texture, grain shape, and mineralogy. Results from each of the Table 3-7 data sources will be summarized in the following sections, but most of the details of the related analyses will be omitted and referenced elsewhere.

Core Tube Samples

The thin-walled drive tubes used on Apollos 15, 16, and 17 provided the first accurate direct measurements of lunar soil density in situ. The various estimates that were made prior to Apollo 15 were based on ambiguous data, including the densities measured in the Apollo 11, 12, and 14 thick-walled drive tubes. A summary of the early estimates of density are presented in Mitchell et al. (1972a).

The Apollo 15-17 drive tubes indicated that the average density of the top 30 cm of the lunar soil is typically 1.58 g/cm^3; from a depth of 30 cm to 60 cm, the average density is typically 1.74 g/cm^3, based on statistical averages of core tube densities. The drive tube data from these three missions are summarized graphically in Fig. 3-3. The exceptional sample is the double core through the orange soil at Station 4 on Apollo 17. The densities in the upper and lower sections are approximately 0.5 g/cm^3 greater than the average values. The higher density has been assumed (Mitchell et al., 1973a) to be due to a significantly higher specific gravity, and consequently different composition than the other lunar soils.

The importance of relative density or degree of compaction has been noted earlier in this chapter in the section on characteristics and index properties. The specific gravity of lunar soils has been found to be quite variable, ranging from 2.9 to greater than 3.2, depending on the proportions of the various particle types, such as agglutinates, basalts, breccias, and glasses.

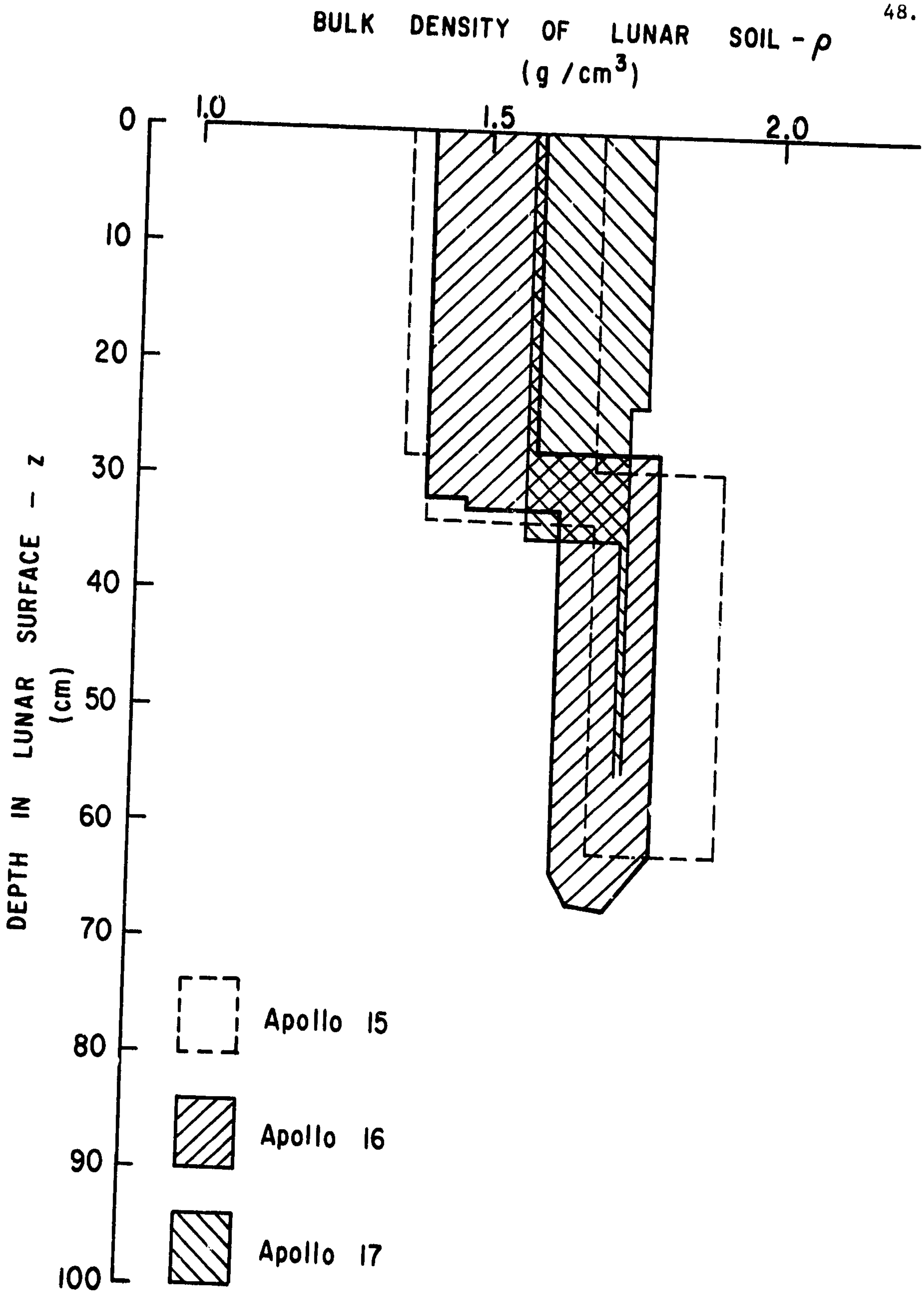


FIG. 3-3 VARIATION OF DRIVE (CORE) TUBE DENSITIES WITH DEPTH

Since the absolute density of a given soil is directly proportional to its specific gravity, absolute density is not sufficient to quantify the degree of compactness of the soil. Instead, it is necessary to determine the relative density of the soil (see Eq. 3-4). Physical properties such as thermal conductivity, sonic velocity, penetration resistance, shear strength, compressibility, and dielectric constant are extremely dependent on the in situ relative density; some soil properties may vary several orders of magnitude between a relative density of 0% and 100%.

Minimum and maximum density determinations have thus far been performed on only one sample associated with a drive tube sample from Apollo 15-17. The sample, 15601,82, was taken at Station 9A at the rim of Hadley Rille, less than 10 meters from a double core tube sample: 15011/15010. Although no index properties are available for the core sample itself, since it has not yet been opened, nor is it known how these properties might vary with depth, the 15601,82 data can be used to estimate relative density vs. depth at this one location on the lunar surface.

The minimum and maximum densities of 15601,82 are shown graphically in Fig. 3-4 along with the average densities in the double core tube samples. The corresponding average relative densities are 87% and 94%, respectively. While these values are somewhat arbitrary, they do indicate a high relative density at this location. This had previously been predicted by Mitchell et al. (1972a) on the basis of the high number of hammer blows required to drive the core tube and the fact that the soil surface surrounding the tube heaved slightly during driving.

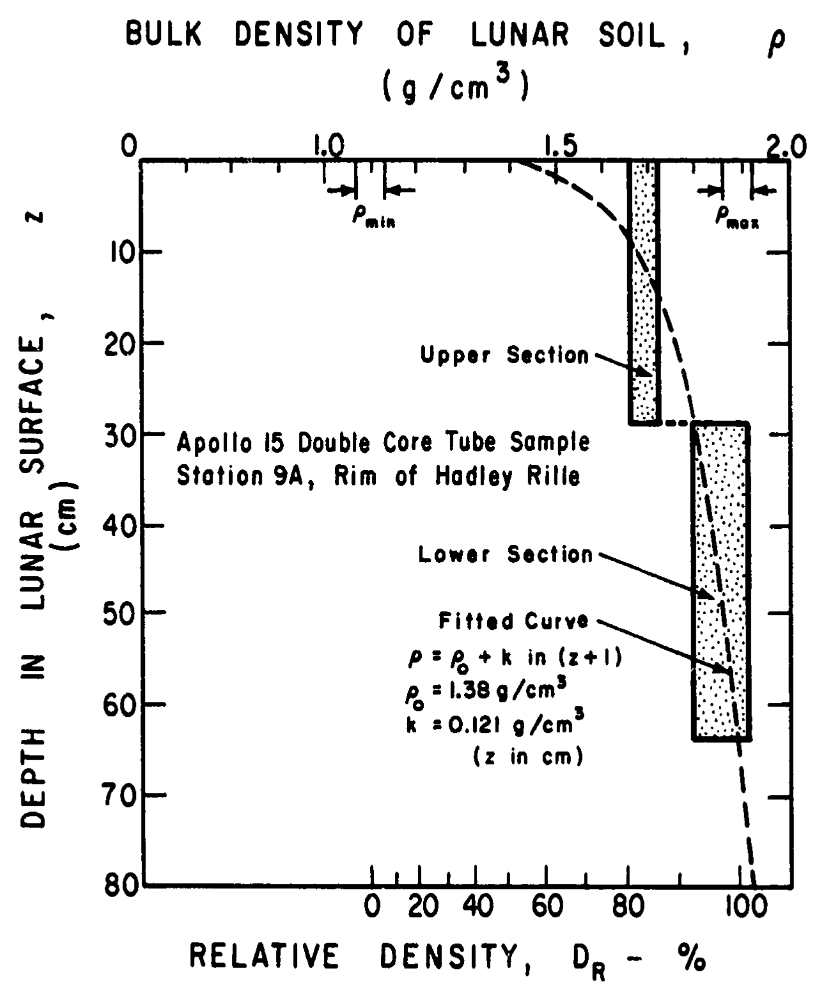


FIG. 3-4 PROPOSED VARIATION OF DENSITY WITH DEPTH FOR APOLLO 15 STATION 9A

An idealized density profile is also shown in Fig. 3-4 which was calculated by assuming that the density increases logarithmically with depth, z, from a finite value, ρ_o, at the surface. The form of the expression is:

$$\rho = \rho_o + k\ln(z+1) \qquad [z \text{ in cm}] \qquad (3\text{-}5)$$

The parameters ρ_o and k can be determined explicitly from the given data. The calculated density increases rapidly for the first 10 to 20 cm and then slowly thereafter. The relative density is 48% at the surface, 82% at 10 cm, 93% at 30 cm, and 99% at 60 cm.

An idealized density profile may also be fitted to the average density values obtained from core tube samples from Apollo 15, 16, and 17 missions. Average core tube densities were computed for the top 30 cm and for the next 30 cm and are shown as the first two entries in Table 3-8. The corresponding values of relative density were computed using average values of specific gravity and maximum and minimum void ratios as shown. When Equation (3-5) was fitted to these averages, $\rho_o = 1.27$ g/cm^3 and $k = 0.121$ were obtained. These constants, together with Equation (3-5), were used to evaluate the corresponding average density in the top 15 cm as shown in Table 3-8 for subsequent comparison with values from astronaut footprint and LRV and MET track analyses.

It is important to note that if a density-depth relationship is arbitrarily chosen such that $\rho_o = \rho_{min}$, that is, the surface is at 0% relative density, the effect is to have even higher relative densities at shallower depths than given by the idealized profile. Consequently, one is led to the inescapable conclusion that while the surface may be at a low to medium relative density, the soil just 10 to 20 cm down is typically at a very high relative density, much higher than would be

TABLE 3-8 -- PROPOSED VARIATION OF AVERAGE DENSITY WITH DEPTH

Average Bulk Density for Apollo 15, 16 and 17 Core Tubes - g/cm^3	Depth Range - cm	Relative Density, D_R, in percent for average values of $G_s = 3.1$, $e_{max} = 1.7$, and $e_{min} = 0.7$	Values of ρ_o and k in $\rho = \rho_o + k \ln (z+1)$
1.58	0-30	74	$\rho_o = 1.27$ g/cm^3 $k = 0.121$
1.74	30-60	92	
1.50	0-15	64	$\rho_o = 1.27$ $k = 0.121$

required to support the very small overburden stress in the low lunar gravity.

Lunar Drill Samples

The rotary-percussion drill cores used on Apollos 15, 16, and 17 have also been extremely important in determining lunar soil density in situ. Fig. 3-5 presents density vs. depth in the drill stems; the densities for the Apollo 16 and 17 stems have been corrected for disturbance suffered during earth-return (Carrier, 1973b). The densities are comparable to those measured in the drive tubes; however, the distributions of density are considerably more complex. The lunar soil density does not increase monotonically with depth; in fact, the density in the Apollo 17 core decreases from an initially high value of 2 g/cm^3. The three distributions suggest distinctly differend depositional histories for each of the sites.

The average density in the 30-60 cm depth range is about the same as was obtained with the core tubes (1.77 vs 1.74 g/cm^3 for the core tubes), but the density in the 0-30 cm range appears to be somewhat higher for the lunar drill samples than for the core tubes (1.69 vs 1.58 g/cm^3). However this difference is not considered to be statistically significant because only three lunar drill values are available and the near-surface density values appear to be slightly skewed due to the one unusually high value.

Astronaut Footprints

Statistical variation in lunar soil relative density has been assessed (Houston et al. (1972), Mitchell et al. (1973b) through analyses of astronaut footprints. A total of 776 footprints were analyzed and the

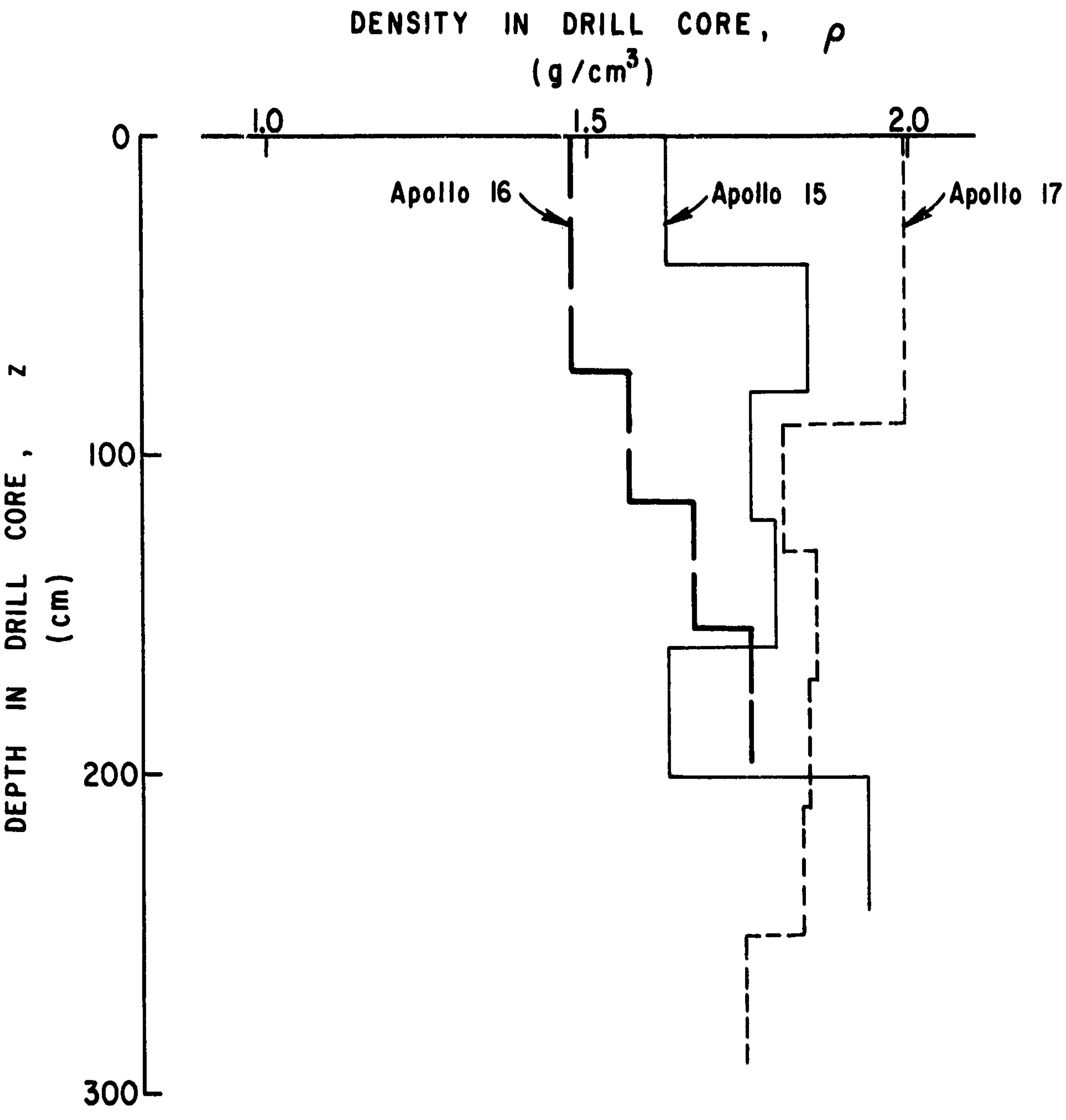


FIG. 3-5 VARIATION OF DENSITY WITH DEPTH FOR LUNAR DRILL STEM SAMPLES

results for all six Apollo landings are summarized in Table 3-9.

As indicated by Table 3-7, the most reliable values from footprint analyses are the relative density values. Computation of the porosity values shown required on assumption for n_{max} and n_{min}. The assumed values of 58.3% and 31% in Table 3-9 are the values for Lunar Soil Simulant No. 2 (Houston, et al. (1973), Houston and Namiq (1971)) and these values were assumed for all previously published footprint-derived porosity data as well.

The results summarized in Table 3-9 support the following conclusions--derived in part from previous studies.

(1) The average porosity for the top 15 cm in intercrater areas is essentially the same for all six Apollo landing sites, although the observed average porosity for Apollo 16 was about 1 to 1.5 percentage points higher than for the other five sites.

(2) The standard deviation of porosities for intercrater areas is about the same for all Apollo sites. The arithmetic average for all sites is about 2.55 percentage points.

(3) The average porosity on crater rims for all Apollo sites is about 2.5 percentage points higher than for intercrater areas. The standard deviation for crater rims is also greater than for intercrater areas - 4.3 rather than 2.55.

(4) A total of 687 observations of footprint depth indicate that the average relative density for intercrater areas for all Apollo landing sites is about 65 to 66%. If the average values of maximum and minimum porosities for lunar soil were 58.3% and 31%, the corresponding value of average porosity would be 43.5% - as indicated in Table 3-9. Measured

TABLE 3-9

SUMMARY OF RESULTS OF STATISTICAL ANALYSIS OF POROSITIES DEDUCED FROM FOOTPRINT DEPTHS

Location	No. of Observations	Mean Porosity,◇ Percent	Standard Deviation	Mean Relative Density Percent
Intercrater areas, Apollo 11	30	43.3	1.8	67
Intercrater areas, Apollo 12	88	42.8	3.1	68
Intercrater areas, Apollo 14	38	43.3	2.2	67
Intercrater areas, Apollo 15	117	43.4	2.9	67
Intercrater areas, Apollo 16	273	45.0	2.8	61.5
Intercrater areas, Apollo 17	141	43.4	2.4	67
Intercrater areas, Apollo 11, 12, 14, and 15	273	43.2†	2.8†	67
Crater rims, all Apollo sites	89	46.5†	4.3†	55.5
Intercrater areas, all Apollo sites	687	44.0†	2.75†	65
Intercrater areas, all Apollo sites	687	43.5Γ	2.55Γ	66

◇Based on assumption that n_{max} = 58.3% and n_{min} = 31%, for which e_{max} = 1.4 and e_{min} = 0.45.

†Weighted average

ΓEach Apollo site given equal weight regardless of no. of observations values of n_{max} and n_{min} on three one-gram samples of returned lunar soil cited earlier in this chapter indicate that the values for lunar soil generally may be considerably higher, however. If so, it may be necessary to adjust the best estimate of average porosity upward, perhaps as much as 7 or 8 percentage points.

(5) Although the average porosity, measured on a regional scale, appears to be about the same for all the soil-covered lunar surface, very significant local variations are found to exist on a small scale of one or a few meters. Core tube densities and penetrometer measurements have indicated that these small scale variations exist vertically as well as laterally.

(6) The relative density values of 65 to 66% obtained from the astronaut footprint studies (Table 3-9) agree very well with the value of 64% for the same depth range, 0-15 cm, obtained in Table 3-8 for average core tube densities. This close agreement could be only apparent, however, because the values of C_s and e_{max} and e_{min} used in Table 3-9 were averages for only a very few tests and significant deviations from the average are known to occur.

LRV and MET Tracks

LRV (15, 16, and 17 missions) and MET (14 mission) tracks as well as tracks developed by the unmanned vehicle Lunokhod 1 have been analyzed. The results are reported by Costes (1973), Mitchell et al. (1972a,b and 1973a). The results of these analyses indicate that, at least for the Apollo 14 through 17 and Luna 17 landing sites, the surficial lunar soil appears to possess similar average mechanical properties at all intercrater locations regardless of initial origin, geologic history, or gross chemical composition and local environmental conditions. Significant local variations from the average were frequent, however. The procedure used to deduce relative density data from vehicle track data is briefly as follows.

a) Use vehicle and wheel geometry and loading conditions together with track depths to get dimensionless soil mobility numbers (Green and Melzer, 1971).

b) Use correlations between mobility numbers and penetration resistance gradient (the slope of the stress vs penetration curve) for granular soils to obtain values of penetration resistance gradient for the lunar surface - denoted G_L.

c) Adjust G_L values for effect of gravity to find corresponding values for the earth's environment - denoted G_E.

d) Use correlations between G_E and relative density for terrestrial granular soils to get relative density - denoted D_R.

e) Assume that response to vehicular load is controlled entirely by relative density, when gravity effect has been accounted for and soil gradations are similar, and that the lunar soil relative density values are therefore the same as those obtained in step d.

Using this procedure the results shown in Table 3-10 were obtained. The values for soft soil are heavily weighted by track depths for soft crater rims. Therefore the values for firmer intercrater areas should be compared with corresponding values from core tube samples and footprint analyses.

Although the upper limit of D_R = 63% compares very well with the footprint analyses results, it appears that the vehicle track data

TABLE 3-10

AVERAGE MATERIAL PROPERTIES OF SURFICIAL LUNAR SOIL

AT APOLLO 14-17 AND LUNA 17 LANDING SITES

Soil Consistency	G_L N/cm^3	D_r %	ϕ_{TR} deg
Soft	0.15	30	38
Firm	0.76-1.35	48-63	39.5-42

G_L = Penetration resistance gradient for lunar surface

D_r = Relative density = $(e_{max} - e)/(e_{max} - e_{min})$, based on standard ASTM methods

ϕ_{TR} = Angle of internal friction, based on triaxial compression tests.

yield somewhat lower relative density values on the average.

Another basis for comparison may be used, however. The values of G_L from Table 3-10 may be used directly with the correlation derived by Houston and Namiq (1971), to obtain values of void ratio, e, and relative density therefrom (using $e_{max} = 1.4$ and $e_{min} = 1.45$ for LSS No. 2 as in previous analyses). Using this procedure the values of $G_L = 0.76$ to $1.35\ N/cm^3$ correspond to a range in relative density of 62% to 71% - which agrees very closely with the core tube and footprint analyses values.

Complete resolution of the differences between the two procedures would probably require additional laboratory and field testing, but it appears that much of the apparent discrepancy may be caused by the use of two different procedures for determining the maximum void ratios of the two different lunar soil simulants involved.

In summary it may be concluded that relative density data derived from vehicle tracks are consistent with results from footprint analyses in that the average relative density was essentially the same for all lunar sites studied and significant variations from the average occurred on a small scale. Furthermore, the numerical values of average relative density may be found to be consistent as well, pending further study.

Boulder Tracks

Theoretical analyses (Hovland and Mitchell, 1972; Hovland, 1970) of the deformation mechanism associated with rolling boulders have led to the development of a relationship between the boulder track geometry and the mechanical properties of the soil, including porosity, through correlation. Sixty-nine lunar boulder tracks from 19 different locations on the moon were examined using lunar orbiter photography. Measurements of the track widths show that some boulders sank considerably deeper than others.

Using bearing capacity theory and an average value of cohesion of 0.5 kN/m^2, the average friction angle, ϕ, of the lunar soil was estimated for each of the 69 boulder tracks.

The relationship between ϕ and porosity (and D_R therefrom) for LSS No. 2 as reported by Mitchell et al. (1972c) was used to obtain relative density values. The mean and standard deviation for the 69 boulder tracks analyzed were 65% and about 20% respectively in terms of relative density. The mean value is the same as was obtained from the footprints described in a preceding section, but the standard deviation is considerably higher--suggesting that soil porosity is more variable on slopes and crater walls than on generally level intercrater areas.

The apparent agreement between the mean values for the boulder track and footprint data may be misleading. Due to the large size of the boulders, the relative density estimates obtained represent averages for the upper few meters, whereas the footprint data represent average values for the upper 15 cm. It has been shown that density generally decreases with depth (preceding section on core tube samples, Mitchell et al., 1972c; Houston and Namiq, 1971), although local exceptions occur. Therefore, agreement between the average values for boulder track and footprint data implies that the average relative density of the top 15 cm of the boulder track slopes must be lower than the value obtained from the footprints for level intercrater areas, but it is difficult to estimate precisely how much lower.

Penetration Resistance

In Chapter 2 it was noted that several types of devices have been used to penetrate the lunar surface and that the results of these tests have been used to obtain density and strength variations with depth.

In a subsequent section devoted specifically to penetration resistance these results are presented. This presentation includes a collection of envelopes of stress vs. penetration curves for Apollos 14, 15, and 17 and Lunokhod 1. The slopes of these stress vs. penetration curves, G_L, vary widely from about 1 to 6.6 N/cm³ with an average value of about 3.8 N/cm³. This average slope value, together with the correlation developed by Houston and Namiq, (1971) and values of e_{max} = 1.4 and e_{min} = 0.45 for LSS No. 2, corresponds to an average relative density value of about 83% to 84%. The range in G_L values corresponds to a range in relative density values from about 63% to 95%.

By comparison with the average value of D_R = 66% for the footprint analysis the average penetration resistance relative density value of 83% to 84% appears considerably higher. However, the footprint analyses results pertain to the top 15 cm whereas the penetration resistance values pertain to the 0-60 cm depth range (see Table 3-7). From Table 3-8 the average relative density obtained for the upper 60 cm from core tube samples is about 83% which is in excellent agreement with the value from the penetration resistance tests.

In making these comparisons it must be noted, however, that the average relative density values from penetration resistance tests are based on only about 9 tests and are therefore not highly significant statistically.

Summary and Conclusions - Density and Porosity Studies

The results from each of the studies discussed in this section are summarized in Table 3-11. The results in Table 3-11 and the discussions in the preceding sections may be used to conclude the following:

(1) The average relative density and porosity for the upper 15 cm in intercrater areas is essentially the same for all six Apollo landing sites and perhaps for all soil-covered locations on the lunar surface--if areas are considered on a scale of a few hundred meters.

(2) The best estimates for the average bulk densities for the lunar surface are as follows:

Depth Range, cm	Bulk Density, ρ - g/cm^3
0-15	1.50 ± .05
0-30	1.58 ± .05
30-60	1.74 ± .05
0-60	1.66 ± .05

(3) The variation of average bulk density, ρ, with depth can be described by

$$\rho = \rho_o + k \ln (z+1)$$

where z = depth in cm

ρ_o = 1.27 g/cm^3

k = 0.121

but deviations from the general pattern of density increase with depth may be very frequent and pronounced.

(4) The best estimates for the average relative density for the lunar surface are as follows:

TABLE 3-11

SUMMARY OF RESULTS FROM DENSITY AND

POROSITY STUDIES

Source	Depth Range, cm	Bulk Density or Absolute Density g/cm^3	Relative Density %	Standard Deviation for Relative Density
Core tube samples	0-15	1.50 ± .05	64*	
	0-30	1.58 ± .05	74*	
	30-60	1.74 ± .05	92*	
	0-60	1.66 ± .05	83*	
Lunar drill samples	0-30	1.69 ± .08		
	30-60	1.77 .08		
Astronaut footprint analyses	0-15		65-66	≃10
LRV and MET tracks	0-15		48-63 by 1st procedure	
	0-15		62-71 by 2nd procedure (see text)	
Boulder tracks	0-300 or 400		65	≃20
Penetration resistance	0-60		83-84	≥10?

*Calculated, based on average G_s = 3.1, e_{max} = 1.7 and e_{min} = 0.7.

Depth Range, cm	Relative Density, D_R - %
0-15	65 ± 3
0-30	74 ± 3
30-60	92 ± 3
0-60	83 ± 3

(5) Statistical studies of footprints, LRV and MET tracks, and boulder tracks show that relative density varies considerably on a scale of 1 or 2 meters laterally and indicate that a best estimate of the standard deviation is about 15 percentage points for relative density. Histograms (Houston, et al. 1972) of density data indicate an essentially normal distribution with a slight skewness toward the high density side.

(6) Average values of absolute and relative density for the lunar surface cannot at this time be confidently converted to values of porosity or void ratio because of insufficient data on values of G_s and e_{max} and e_{min} for lunar soil. Based on a very small number of tests--too small to give statistically significant averages--the following averages have been tentatively proposed and used in this and other sections of this report.

G_s	e_{max}	e_{min}
3.1	1.7	0.7

If these values were indeed valid as averages for the lunar surface, the "best estimate" average values of ρ = 1.50 g/cm^3 and D_R = 65% for the uppermost 15 cm given in conclusions 2 and 4 would correspond to a void ratio of 1.05 and a porosity of 51%.

(7) The average relative density on crater rims for all Apollo sites is about 10 to 12 percentage points lower than for intercrater areas. The standard deviation for crater rim density is also greater than for intercrater areas.

(8) In consideration of the depth ranges to which each of the methods in Table 3-11 apply, the boulder track data indicate that average relative density on slopes and crater walls where boulder tracks were generally observed is lesser and more variable than for level intercrater areas. This observation is consistent with the hypothesis that downslope movements may loosen lunar soil somewhat.

(9) The apparent mechanism controlling the relative density of lunar soil in the plains areas seems to be that the constant meteorite and micrometeorite bombardment maintains a loose, stirred up surface; but directly beneath the surface, the vibrations due to innumerable shock waves shake and densify the soil to a very high relative density. The sub-surface soil may even be overconsolidated at some locations; i.e., the soil may have been densified under a greater confining stress at some time in the past than is presently applied to it by the overlying soil.

PENETRATION RESISTANCE

As noted in Chapter 2 a variety of types of penetration tests has been used to probe the lunar surface, ranging from the pushing and driving of flag poles and core tubes to quantitative measurements using the Self-Recording Penetrometer. The results of these tests have been used to infer details of variability and stratigraphy as well as a basis for quantitative estimates of density, porosity, and strength parameters.

An appreciation for the local and regional variabilities in soil conditions is important for at least two reasons:

(1) Some insight is provided into the complexity of lunar surface history and processes.

(2) Some assessment can be made of the probable variations in the numerical values of soil properties that may be expected for a lunar soil model with specified average values.

Mitchell et al. (1972b, 1973b) have shown how the penetration test data obtained during the Apollo 16 mission could be used to deduce details of the near-surface soils at the Descartes landing site. Fig. 3-6 shows good correlation between the penetration resistance vs. depth data at a point on Stone Mountain and the stratigraphy shown in an adjacent double core tube sample. Treadwell (1974) has shown that penetrometer tests can be a sensitive indicator of layering in soil deposits of a type similar to those on the Moon. Previously Houston and Namiq (1971) had shown that penetration test results could be used to assess the suitability of a lunar soil simulant to characterize actual lunar soil behavior.

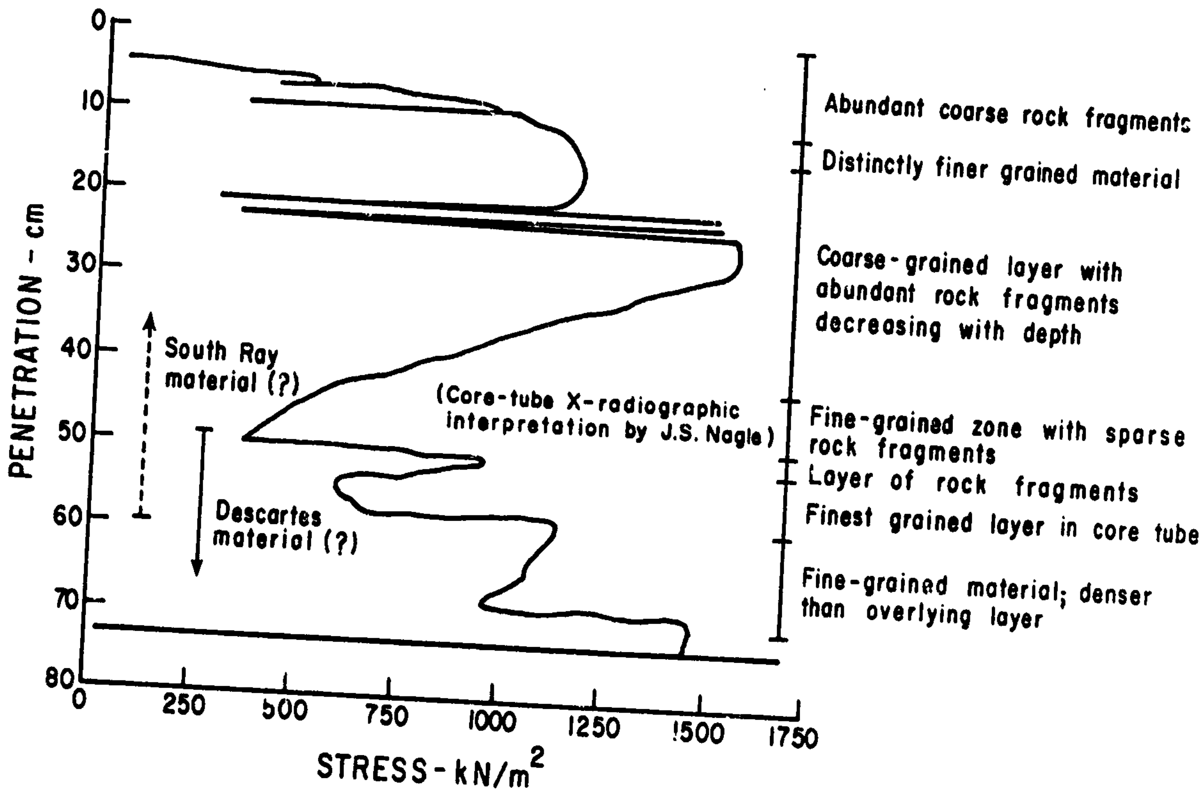


FIG. 3-6 CORRELATION OF APOLLO 16 STATION 4 DOUBLE-CORE-TUBE STRATIGRAPHY WITH SRP TEST 4

An approximate soil profile between the Station 10 double core tube site and the deep drill site in the ALSEP area of Apollo 16 is shown in Fig. 3-7. Penetration test data in conjunction with X-radiographs of the drill-core stem and the Station 10 core sample were used to develop this profile. These examples, as well as the discussion of strength in the next section and the analyses of porosity and density presented previously, provide evidence of the usefulness of penetration testing for evaluation of soil properties in situ. Because such tests are simple and rapid and apparatus of extreme sophistication is not required, they offer much potential for the exploration of extraterrestrial bodies in the future.

All penetration data obtained on the lunar surface available to the authors are included in Fig. 3-8, where the characteristics of the penetrometers used are also indicated. The zones shown encompass data obtained using the SRP, the Apollo Simple Penetrometer, and the Soviet Lunokhod I; additional data were obtained on Lunokhod II but have not been published.

From Fig. 3-8 it may be seen that:

(1) A considerable variation exists between the results of different penetration tests.

(2) Although the 327 Lunokhod I test results all fell within a rather narrow band, the depth investigated was small.

(3) On Apollo 16 greater soil variability was encountered on the slopes of Stone Mountain (Station 4) than in the Plains area (Station 10).

(4) The average penetration resistance on the Plains is greater than on Stone Mountain.

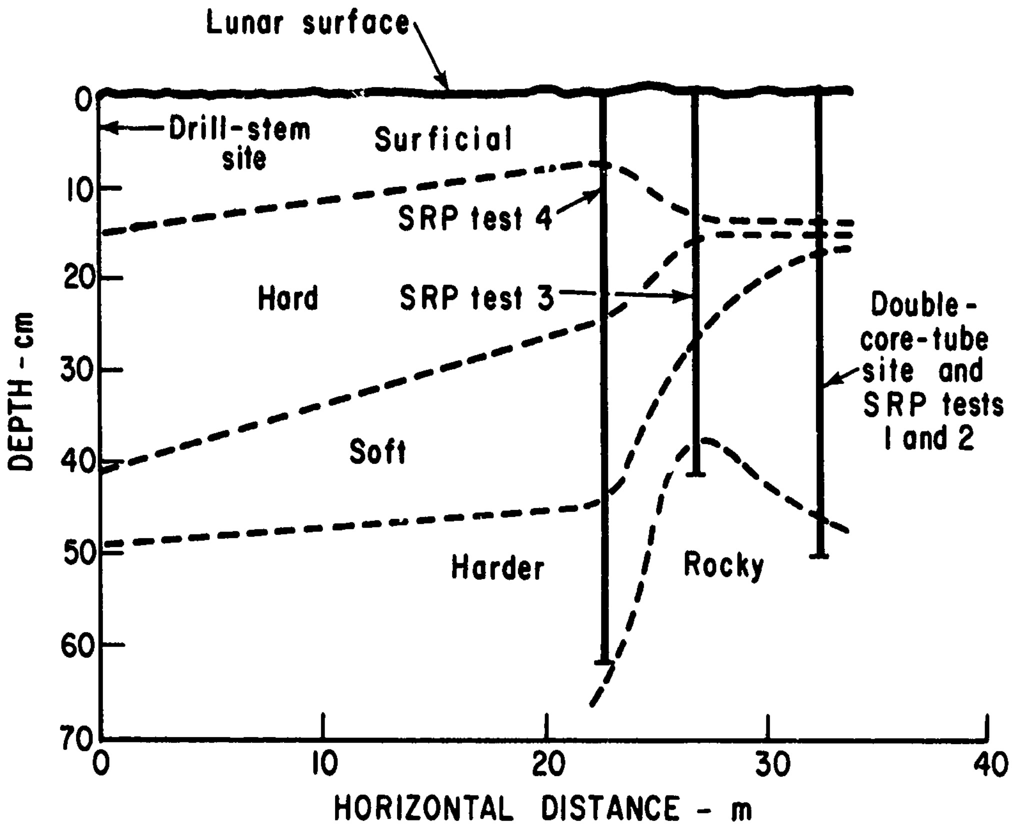
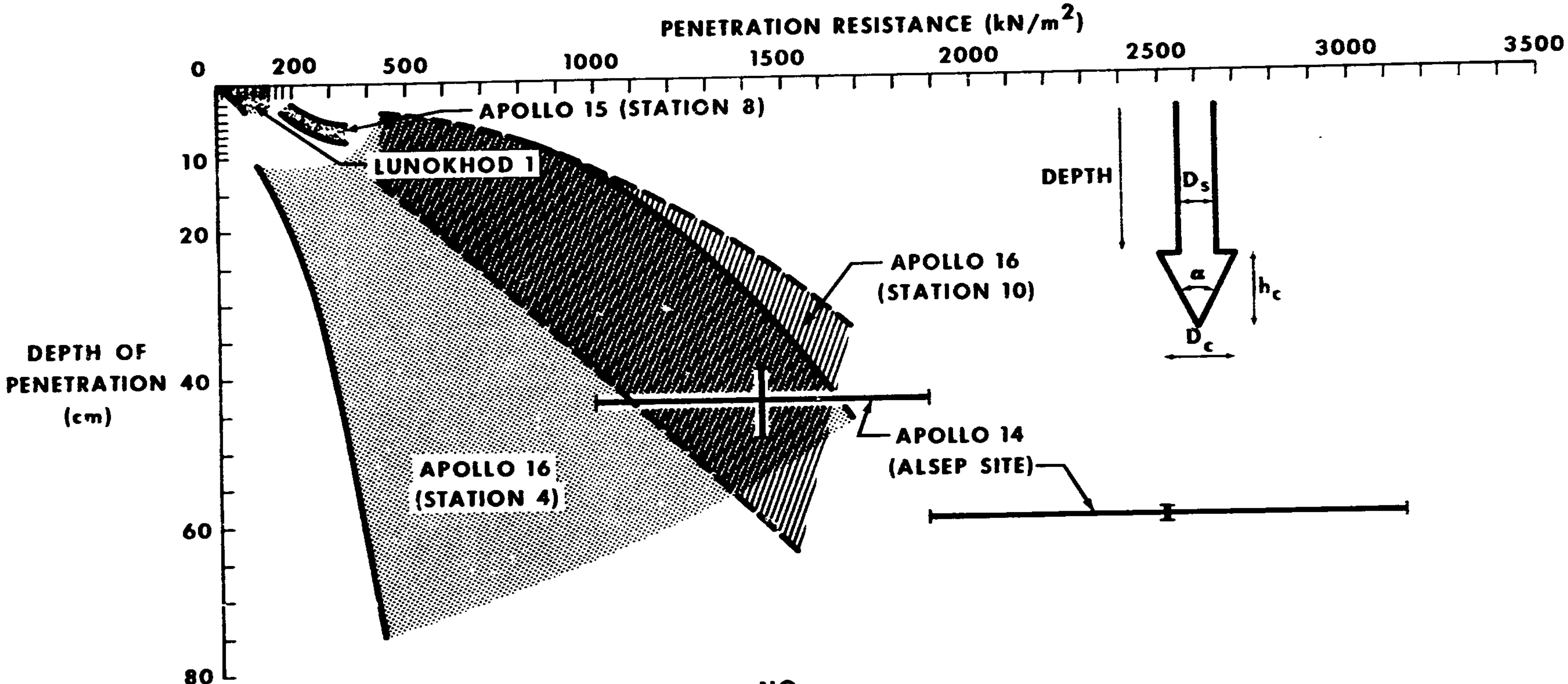


FIG. 3-7 APPROXIMATE SOIL PROFILE BETWEEN APOLLO 16 STATION 10 DOUBLE-CORE-TUBE SITE AND DEEP-DRILL-STEM SITE IN ALSEP AREA

NASA-S-72-3934-V



MISSION	NO. OF TESTS	D_c (cm)	α	h_c (cm)	D_s (cm)
APOLLO 14	3	0.95	30°	1.78	0.95
LUNOKHOD 1	327	5.0	60°	4.4	-
APOLLO 15	2	2.03	30°	3.78	0.94
APOLLO 16 (STATION 4)	1	2.03	30°	3.78	0.94
	3	1.28	30°	2.39	0.94
APOLLO 16 (STATION 10)	1	2.03	30°	3.78	0.94
	3	1.28	30°	2.39	0.94

FIG. 3-8 PENETRATION RESISTANCE OF THE LUNAR SURFACE AT DIFFERENT LOCATIONS

In addition observations have indicated that penetration resistance at Station 4 on Stone Mountain bears little relationship to local slope or surface appearance. Thus generalizations concerning the strength of soils on sloping terrain are not possible.

DEFORMABILITY AND STRENGTH

Introduction

A variety of methods has been used for deduction of the strength of lunar soils as indicated in Chapter 2. Most approaches have resulted in estimates of cohesion and friction angle (Eqn. 2-1) and have been based on analyses of failure conditions. Like terrestrial soils of comparable gradation, the evidence indicates clearly that the cohesion and friction angle of lunar soils depend strongly on porosity and relative density. Variations in friction angle and cohesion with porosity for a crushed basalt lunar soil simulant are shown in Figs. 3-9 and 3-10, respectively.

Information on the deformability of lunar soils at sub-failure stresses is very limited. No stress-strain data has been obtained for tests on undisturbed soils either in situ or in the laboratory. Although moduli of deformation might be estimated from seismic wave velocity data, the values obtained can be expected to pertain to behavior at only very low strains.

A number of estimates of cohesion and friction angle were developed from data obtained prior to the Apollo missions. These values are summarized in Table 3-12. The fact that a considerable variation exists between the estimated values is not surprising in view of the

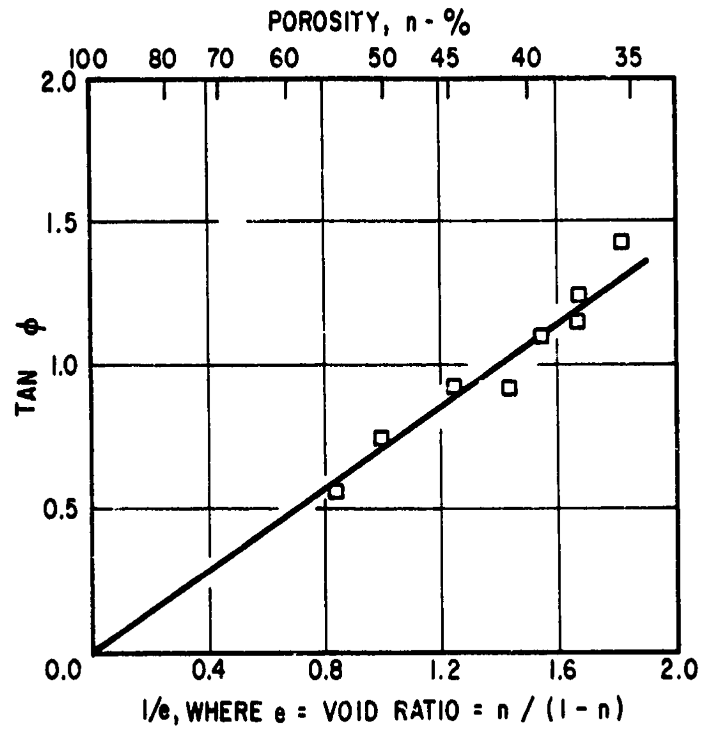


FIG. 3-9 FRICTION ANGLE AS A FUNCTION OF POROSITY FOR LUNAR SOIL SIMULANT NO. 2 (GROUND BASALT)

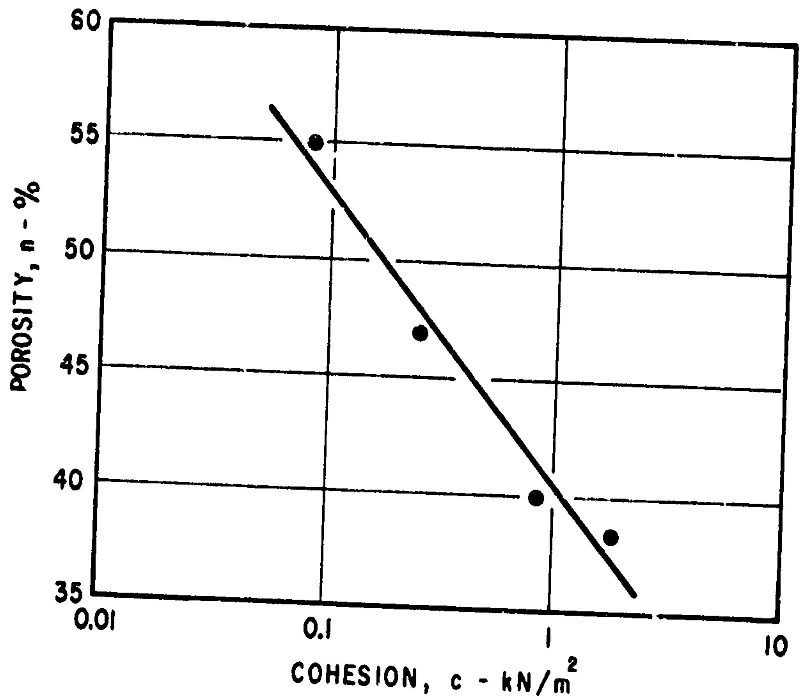


FIG. 3-10 COHESION AS A FUNCTION OF POROSITY FOR LUNAR SOIL SIMULANT NO. 2 (GROUND BASALT)

TABLE 3-12

ESTIMATES OF LUNAR SOIL COHESION AND FRICTION ANGLE

BASED ON PRE-APOLLO DATA

Basis	Cohesion c (kN/m^2)	Friction angle ϕ (deg)	Reference
(1) Boulder track analysis--Orbiter data	0.35	33	Nordmeyer (1967)
(2) Surveyor I strain gage and TV data	0.15-15	55	Jaffe (1967)
(3) Surveyor I	0.13-0.4	30-40	Christensen et al. (1967)
(4) Surveyor III, soil mechanics surface samples		>35	Scott and Roberson (1968a,b)
(5) Surveyor III, landing data	0 for 10 for	45-60 0	Christensen et al. (1968a)
(6) Surveyor VI, vernier engine firing	>0.07 for	35	Christensen et al. (1968b)
(7) Surveyor VI, attitude control jets	0.5-1.7		
(8) Surveyor III and VII, soil mechanics surface samples	0.35-0.70	35-37	Scott and Roberson (1969)
(9) Lunar Orbiter boulder track records	0.1	10-30	Moore (1970)
(10) Lunar Orbiter boulder track records	0.5*	21-55 39†	Hovland and Mitchell (1971)

*Assumed.

†Mean of 69 values.

assumptions and uncertainties in the analyses. It is important also to note that the results of subsequent analyses have shown that such variations can be real, arising mainly as a consequence of variations in density.

Summary of Strength Parameter Evaluations

During the last and the first three Apollo missions, no force or deformation measuring devices were used to determine directly the in-place mechanical properties of lunar soil. Consequently, inferences on these properties were made from (a) observed deformations resulting from the interaction of the soil with objects of known geometry and weight including the MET, the LRV, and Astronauts boot; (b) assumptions on the ranges of loads applied by the astronauts in pushing shafts, poles, and tubes into the ground; (c) slope stability analyses applied to natural crater slopes, incipient slope failures in soft-rimmed craters due to loads imposed by walking astronauts, the collapse of the soil mechanics trench during Apollo 15 and Apollo 16; (d) LM landing dynamics and soil erosion by the LM engine exhaust; (e) penetration tests on loose and densely compacted Apollo 11 bulk sample; (f) analysis of open hole stability; (g) boulder track analysis (Apollo 17); and (h) studies on simulated lunar soil. Quantitative data obtained using the Self-Recording Penetrometer were used to deduce strength parameter values for locations at the Apollo 15 and Apollo 16 landing sites. Direct strength measurements have been made using one 200g sample of soil returned by Apollo 12 mission (Carrier et al., 1972, 1973).

A summary of the strength estimates made using these methods is given in Table 3-13. Details of the analyses can be found in the indicated references.

The penetration resistance curves obtained during Apollo 16 using the SRP indicated that the soil is not homogeneous with depth at the points tested in the Descartes region, and variations in lateral directions are sufficiently great to preclude direct comparison of penetration resistance curves for cones of two sizes. As a result a unique solution for c and ϕ is possible only in special cases, such as seen the soil is homogeneous with depth. One such case was for a test at Station 4 uphill from the LRV. For this case the values of $c = 0.6\ kN/m^2$ and $\phi = 46.5°$ (Table 3-13) were obtained. In most cases, however, the results are best expressed in terms of cohesion as a function of friction angle required to give the measured penetration resistance for a given penetration depth. This has been done for the remainder of the SRP results from Apollo 16.

Fig. 3-11 shows combinations of c and ϕ that would account for the measured values of penetration resistance for three additional tests at Station 4, Apollo 16. Relationships are shown for values of the ratio of depth to cone-base diameter (D/B) of 10, 20, and 30, which correspond to actual depths of 12.8, 25.6, and 37.4 cm. A point is also shown on Figs. 3-11(a) and 3-11(b) to show the strength given in Table 3-13.

It is clear from Fig. 3-11 that a large difference exists in soil strength within the localized area of Station 4. Low and high strength areas at depth are not readily discernible by observation of the surface or even on the basis of bootprints.

Fig. 3-12 shows the c-ϕ relationships for a point near the double core tube site at Station 10, Apollo 16. The curves indicate that soil

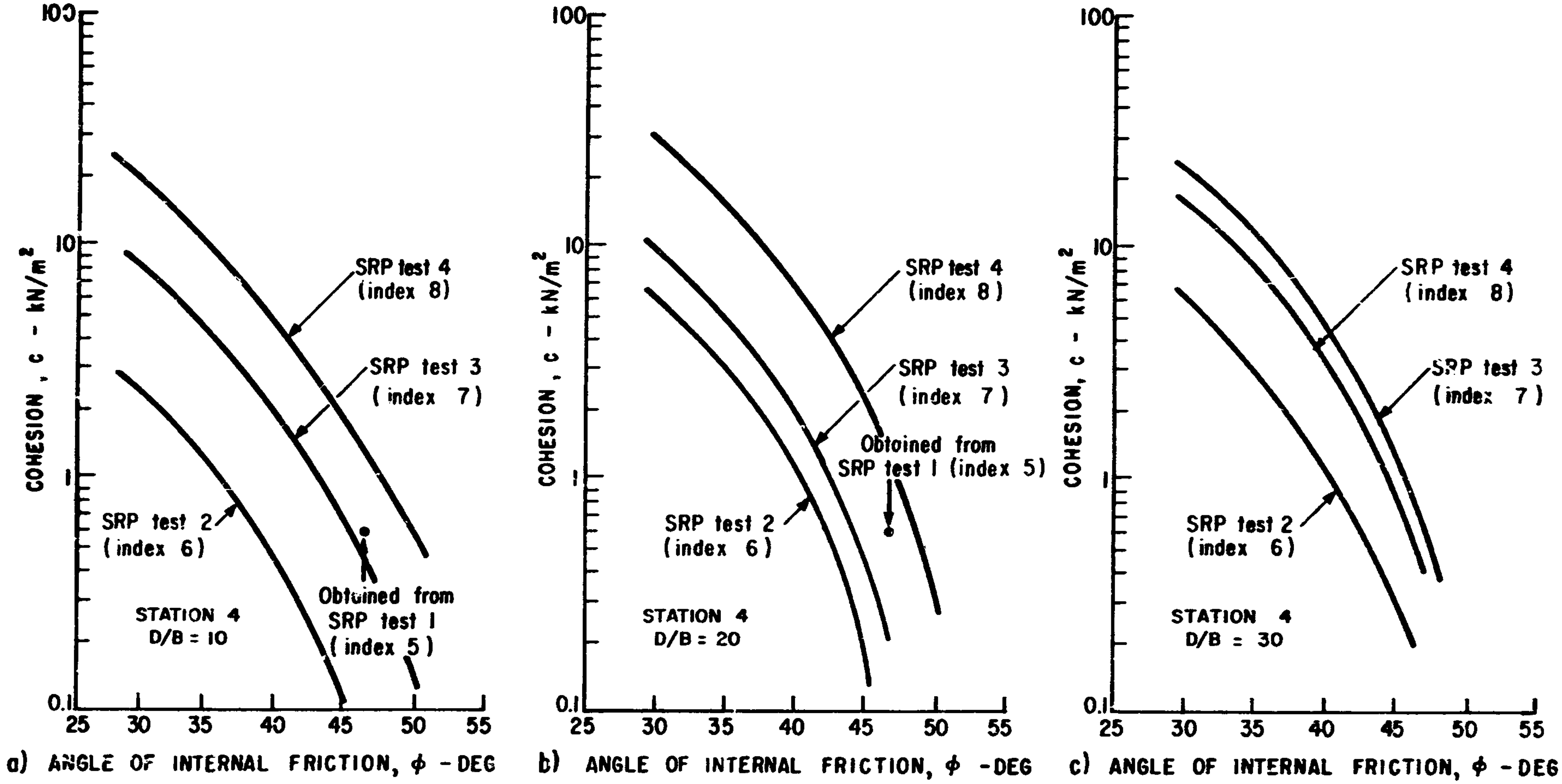


FIG. 3-11 RELATIONSHIPS OF COHESION AS A FUNCTION OF FRICTION ANGLE REQUIRED TO DEVELOP MEASURED PENETRATION RESISTANCES AT APOLLO 16 STATION 4.
(a) DEPTH OF 12.8 CM (b) DEPTH OF 25.6 CM (c) DEPTH OF 37.4 CM

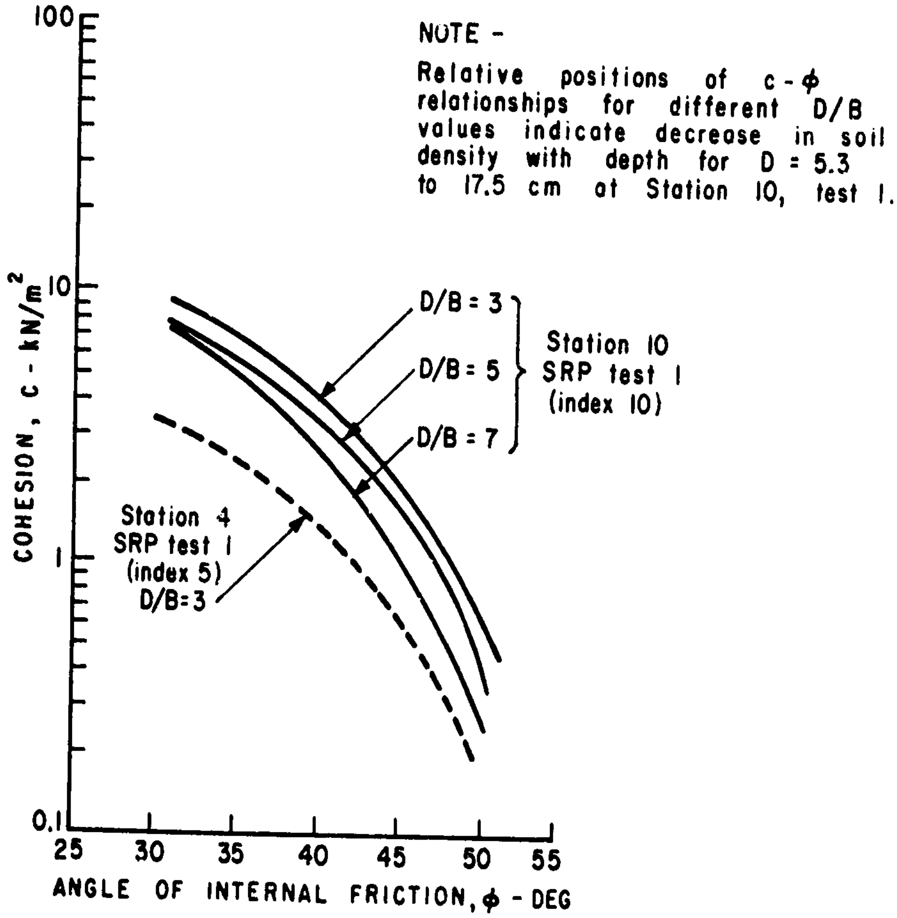


FIG. 3-12 RELATIONSHIPS OF COHESION AS A FUNCTION OF FRICTION ANGLE REQUIRED TO DEVELOP MEASURED PENETRATION RESISTANCES AT APOLLO 16 STATION 10, TEST 1.

TABLE 3-13

LUNAR SOIL COHESION AND FRICTION ANGLE VALUES

Mission	Location or sample	Density (g/cm^3)	Porosity (%)	Cohesion, c (kN/m^2)	Friction Angle, ϕ (degrees)	Basis	Reference
11	Several Sites	1.6-2.0		Consistent with Soil Model Based on Surveyor data		Footprints, LM landing, Crater slope stability	Costes et al. (1969)
11	Bulk Soil Sample	1.36-1.80	56-42	0.3-1.4	35-45	Penetrometer tests in LRL	Costes et al. (1970)
11	LM-ALSEP area			0.8-2.1	37-45	Core tube, flag pole, SWC shaft penetration	Costes et al. (1971)
12	Several Sites	1.6-2.0		Consistent with Soil Model Based on Surveyor data		Footprints, LM landing, Crater slope stability	Scott et al. (1970)
12	Several Sites			0.6-0.8	38-44	Core tube, flag pole, SWC shaft penetration	Costes et al. (1971)
14	Station G	1.9*		<0.03-0.3	35-45	Soil Mechanics Trench	Mitchell et al. (1972c)
14	ALSEP Area	1.5*		Equal to or greater than that of Soil Model based on Surveyor data		Apollo Simple Penetrometer	Mitchell et al. (1972c)
14	Traverse Area	1.8-1.9**			37-47	MET Tracks	Mitchell et al. (1971a)

Continued

TABLE 3-13 (con't.)

Mission	Location or sample	Density (g/cm^3)	Porosity (%)	Cohesion, c (kN/m^2)	Friction Angle, ϕ (degrees)	Basis	Reference
15	Station 8 near ALSEP	1.9-2.0**	38-35†		47.5-51.5	SRP data and simulation studies	Mitchell et al. (1972a)
15	Station 8 near ALSEP	2.0**	36.5†	1.0	50	SRP data and Mechanics Trench	Mitchell et al. (1972a)
16	Station 4, up-hill from LRV, 10-20 cm.depth	1.9**		0.6	46.5	SRP data	Mitchell et al. (1972b)
16	Station 10, near core tube site	1.96**		0.37	49.5	SRP data	Mitchell et al. (1972b)
16	Station 10, 7m. SW of core tube site	1.93**		0.25-0.60	50-47	SRP data	Mitchell et al. (1972b)
16	ALSEP area, drill stem hole	1.75		1.3	46.5*	Open drill hole	Mitchell et al. (1973a)
17	ALSEP area-Neutron flux probe site	1.8		1.1-1.8	50-30	Open hole stability	Mitchell et al. (1972b)
17	North, East & South Massifs	1.6**		1*	26-50 37.3 (Mean)	Boulder Track Analysis	Mitchell et al. (1973a)
17	Traverse areas			0.17	35	LRV performance analysis	Mitchell et al. (1973a)

*Assumed.

**Deduced by analysis using G_s = 3.1 (not measured).

†Computed using n_{max} = 58.3% and n_{min} = 31%--see section on density and porosity earlier in this chapter.

strength (and therefore probably density) decrease with depth, which is the opposite of what would be expected if the soil deposit were homogeneous. Fig. 3-12 shows also that at a depth of 6 cm, the soil at Station 10 was stronger than that for one test at Station 4.

The results of two SRP tests in the Station 10 area suggested that the soil was sufficiently homogeneous that specific solution for c and ϕ could be made based on the penetration resistance values at two depths (12.8 and 25.6 cm.). These results are also listed in Table 3-13.

Discussion

From the information summarized in Table 3-13, as well as consideration of all other observations of lunar soil behavior as related to penetration resistance and strength, the following general picture has evolved:

1. The strength of lunar soils results from both frictional (stress-dependent) and cohesive components.

2. The friction angle in most cases appears to be within the range of 35 to 50°, with the higher values associated with lower porosities and higher densities.

3. The cohesion is in the range of 0.1 to 1.0 kN/m^2 (.015-0.15 psi), again with the higher values associated with high density and low porosity. Terrestrial soils of comparable gradation do not generally exhibit a cohesion of such a large magnitude. A detailed study of the mechanism of cohesion development in lunar soil is in progress.

4. On the average, strength increases with depth, which is consistent with the finding that in general density increases with depth, as shown earlier.

5. Substantial variations in strength may exist between points only a few cm. apart. This is not surprising, however, in view of the substantial differences in density and possibly gradation that may also exist between the same points.

6. Although the evidence is not extensive or conclusive, strength variability appears to be less on plains than on slopes.

7. Local slope and surface appearance provide little indication of whether the strength of the underlying soil is high or low.

8. Insufficient data are available or have been analyzed as yet to provide strong correlations between relative density and strength parameters for lunar soils of the same or similar gradation. Such correlations are expected to exist, however, and additional study is recommended.

9. Although not yet shown specifically, there should be some dependence of strength on composition as particle sizes, shapes, and durability are controlled by their mineralogy.

Strength of Returned Lunar Soil

To our knowledge the only direct measurements of the strength of returned lunar soil samples were those of Gromov et al. (1971) and Carrier et al. (1972, 1973). In the latter case, three direct shear tests were done using Sample No. 12001, 119 from Apollo 12. The sample was returned to the LRL at a pressure of 10^{-2} torr and then stored at 10^{-9} torr for more than a year before testing. Test specimens were prepared at a pressure less than 2×10^{-6} torr and tested at less than 5×10^{-8} torr.

The three tests were insufficient to allow independent determination of c and ϕ. The cohesion was probably in the range of 0 to 0.7 kN/m^2. Although this order of magnitude is consistent with the values of cohesion deduced on the lunar surface (0.1 to 1.0 kN/m^2), the friction angles, 28° for a loose sample and 34-35° for medium dense samples, were somewhat less than indicated in Table 3-13 for the soil in-situ. These values of ϕ are also less than has been found for ground basalt of comparable gradation.

Carrier et al. (1972, 1973) suggest that while the exact cause for the lower strength of the lunar soil than the simulant is not known, it may be a result of particle composition differences. The ground basalt consists of strong, coherent rock fragments; whereas, the lunar sample contained many breccias, agglutinates, and other weakly cemented particles which could break down during shear. As it has been established that reduction of particle size in simulants leads to a decrease in friction angle, the same may have been true for the lunar sample.

If this interpretation is correct concerning the relative strengths of the sample and the simulant, it still remains to account for the low values of ϕ for the sample as compared to the in-situ values listed in Table 3-13. Exposure to an atmospheric pressure of 10^{-2} torr during earth return with consequent contamination of particle surfaces is one possibility. Alternatively, or additionally, particle breakdown during compression and shear may have been a factor.

Reference to Carrier et al.'s data indicates that the samples were subjected to vertical normal stresses of 30 to 70 kN/m^2 prior to shear. Stresses of these magnitudes would correspond to pressures at depths of

9 to 21 meters on the lunar surface, assuming a density of 2.0 gm/cm^3. The values in Table 3-13 are for soil at depths generally less than a few tens of cm, where the confining pressures are an order of magnitude less. Thus the compressive stresses in the laboratory tests may have been well into the range where particle breakdown becomes important; whereas, on the lunar surface the strength was not influenced by this effect. More study of these questions is needed.

COMPRESSIBILITY

The compressibility characteristics of lunar soil have been derived primarily from the following two sources:

a) Laboratory tests on lunar soil simulants whose other properties have been found to be similar to lunar soil

b) Compression data obtained as a part of a direct shear test program on returned Apollo 12 soil (Carrier, et al., 1972, 1973).

An additional source of data for derivation of compressibility characteristics of lunar soil is the collection of measured astronaut footprint depths. A method for utilizing this footprint data will be outlined.

In addition, a procedure for making immediate use of the footprint depth measurements to compute moduli of subgrade reaction will be discussed.

Lunar Soil Simulants

Particularly during the period before lunar soil samples became available, lunar soil simulants were used to infer the compressibility of lunar soils. Many simulants were developed and studied at the University of California, Berkeley (UCB), MSC, MSFC, and Waterways Experiment Station (WES). The simulant which appears to match the "average" actual lunar soil best, particularly from among those developed at UCB, is designated Lunar Soil Simulant No. 2 (LSS No. 2).

Compressibility characteristics of LSS No. 2 are shown in Figure 3-13 in terms of the void ratio-log pressure relationship for various initial densities.

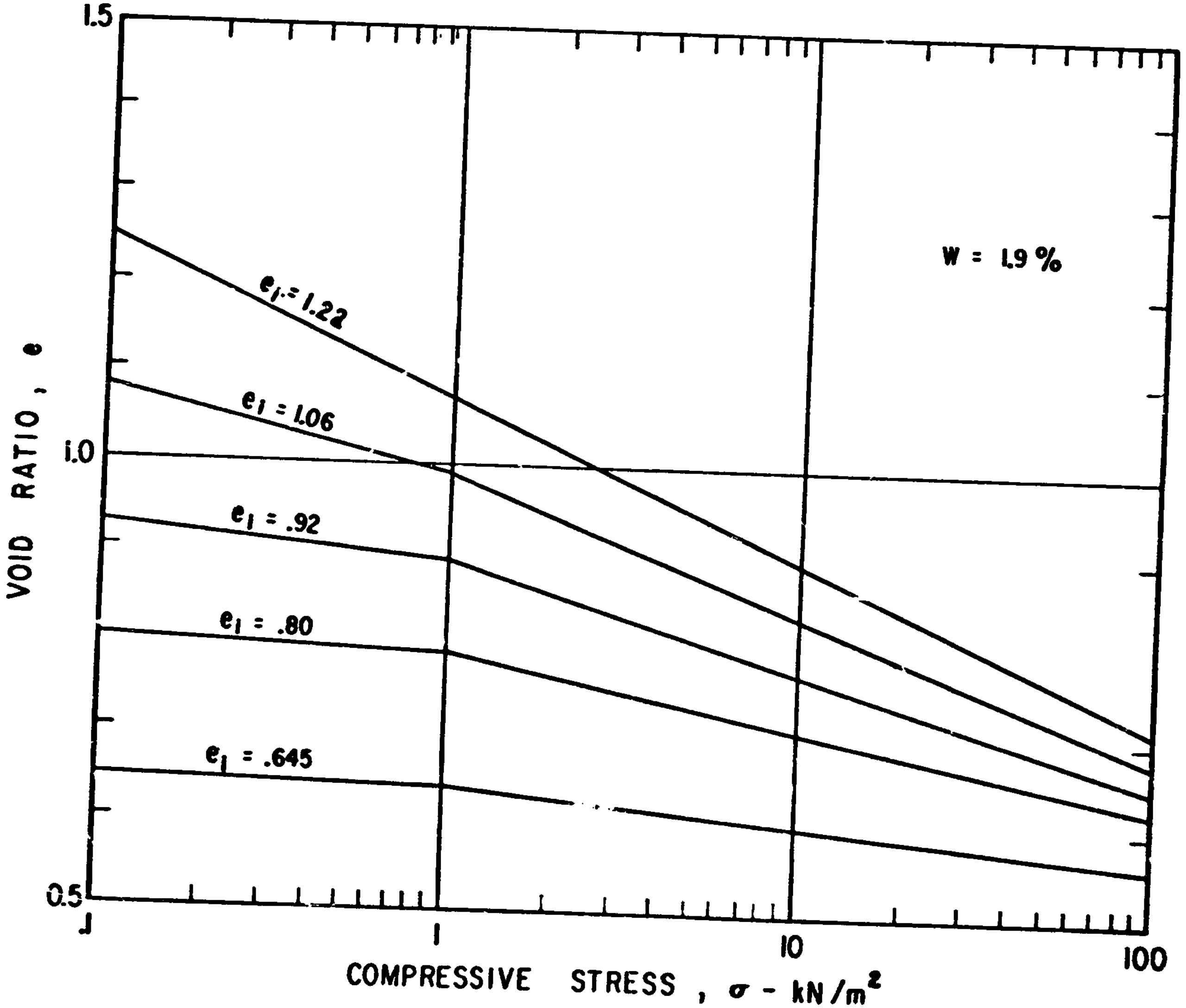


FIG. 3-13 ONE-DIMENSIONAL COMPRESSION CURVES FOR LSS NO. 2 AT 1.9 % WATER CONTENT

The compression curves were slightly curved, but the straight lines drawn in Fig. 3-13 are very good approximations of the raw data. Straight lines were drawn so that simple two-parameter equations could be written for the relationship (Mitchell, et al. 1971b).

Gravity stresses on the test samples in the laboratory are negligible compared to the applied stresses. Therefore differences in terrestrial and lunar gravity should not serve to invalidate the relationships in Figs. 3-13 for application to the lunar surface.

LSS No. 2 has a gradation similar to the average for most lunar soils (see Fig. 3-2 and Mitchell et al., 1971b).

The compressibility data in Fig. 3-13 were used to estimate the probable variation in soil density with depth for lunar soil, assuming the soil were deposited at the surface in thin layers of one or two centimeters thickness and subsequently compressed under the weight of new soil deposited on top, without stirring or mixing (Mitchell and Houston, 1973). The results of these computations for lunar gravity are shown in Fig. 3-14.

It should be emphacized that the profiles shown in Fig. 3-14 apply only to cases where soil mixing and disruption are absent. It is believed that meteroid impact causes sufficient mixing to make uniform profiles, as shown in Fig. 3-14, very rare on the lunar surface. The penetration resistance vs. depth relationships obtained using the SRP provided strong evidence that non-uniform variations of density with depth was more the rule than the exception.

It is more probable that segments of the Fig. 3-14 profiles are frequently interbedded, with the denser layers sometimes overlying looser layers, although density increase with depth is probably much more common.

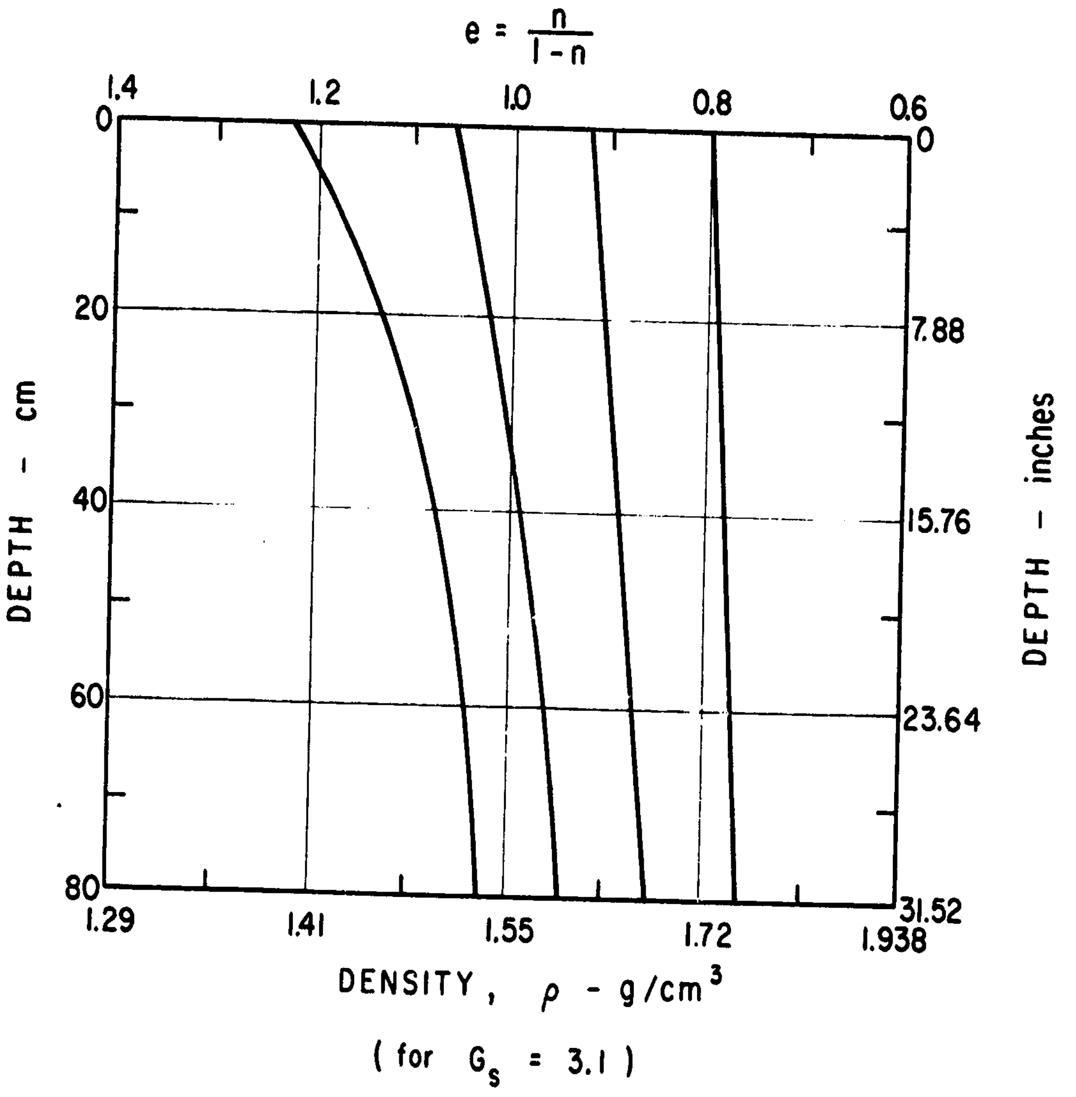


FIG. 3-14 PREDICTED VARIATION OF VOID RATIO WITH DEPTH FOR ACTUAL LUNAR SOIL UNDER LUNAR GRAVITY

It is also believed that micrometeroid impacts have effectively loosened the upper few cm. of surface material and that deeper material may have been densified by shock vibration from medium to large meteroids. Thus the actual rate of density increase with depth, on the average, is believed to be somewhat higher than that indicated by Fig. 3-14 (see section on Density and Porosity).

Compression data from direct shear test program

A limited number of one-dimensional compression and direct shear tests were performed by Carrier et al. (1973a) on just over 200 g of soil from Apollo 12 (Sample No. 12001,119) under a vacuum of less than 1×10^{-7} torr.

Test specimens were compressed one-dimensionally prior to shearing and the compression data obtained has been plotted in Fig. 3-15 for comparison with curves obtained for LSS No. 2. This comparison indicates that LSS No. 2 has comparable compressibility at low initial void ratio but slightly higher compressibility at higher initial void ratio.

However, compressibilities of two granular soils are best compared when the densities have been normalized by comparing the soils at the same relative density. A comparison of the Apollo 12 lunar soil with LSS No. 2 on a relative density basis is difficult because of lack of data on the maximum and minimum density values for the lunar soil.

Houston et al. (1973) chose values of 1.7 and 0.7 for e_{max} and e_{min} for "average" lunar soil, but the deviations from the average are known to be large. If the values $\rho_{min} = 1.15$ g/cm^3 and $\rho_{max} = 1.93$ g/cm^3 obtained by Jaffe (1972) for an Apollo 12 sample are used together with an assumed value of $G_s = 3.1$, values of 1.7 and 0.6 are obtained for

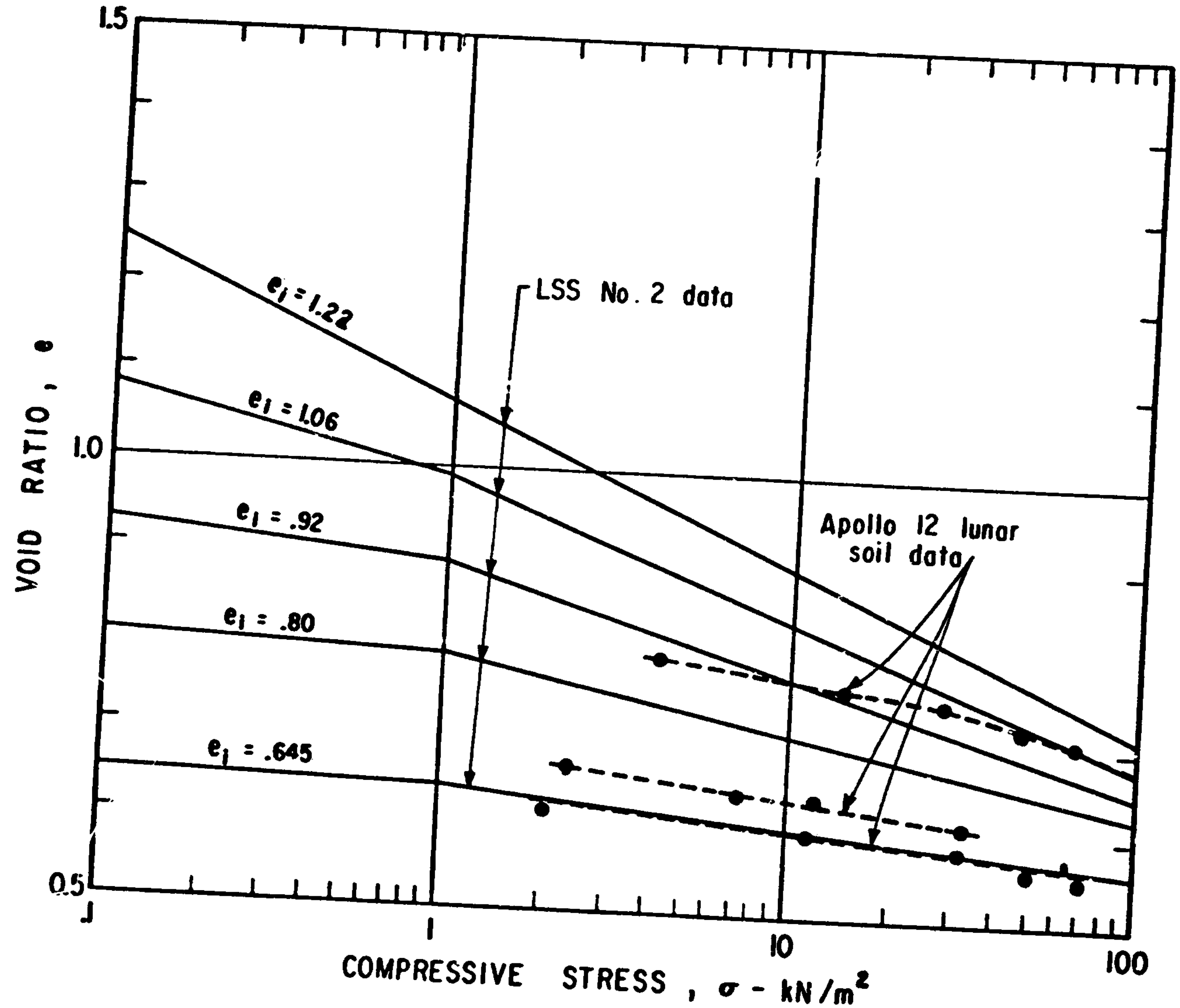


FIG. 3-15 COMPARISON OF ONE-DIMENSIONAL COMPRESSION CURVES FOR APOLLO 12 LUNAR SOIL AND LSS NO. 2

e_{max} and e_{min}. Jaffe's values, together with $e_{max} = 1.4$ and $e_{min} = .45$ for LSS No. 2, were used to compare the compressibility of LSS No. 2 and the Apollo 12 sample on a relative density basis in Fig. 3-16. The compressibilities compare quite closely with LSS No. 2 appearing very slightly less compressible when compared this way.

These comparisons suggest that simulants, and LSS No. 2 in particular, may reasonably be used to estimate lunar soil compressibility, at least until additional data become available.

Astronaut Footprints--Extensive astronaut footprint depth studies have been performed for the Apollo lunar landing missions and are reported in Houston et al. (1972), Mitchell et al. (1972b) and Mitchell et al. (1973a). Astronaut footprints were modelled as plate load tests as a part of an extensive lunar soil simulation study using LSS No. 2. The study included laboratory testing, with plate load model tests and theoretical analyses using finite element solutions to model reduced gravity. One of the findings of this study was that, for very loose soil deposits, the deformation mechanism was essentially one of compression (densification)--with a very small fraction of the settlement arising from deformation at constant volume (shear distortion).

Thus as a first approximation it may be assumed that the footprints formed in very loose lunar soil constitute a field compression test, and compression data can be derived using this assumption.

Although the contact stress with an astronaut's lunar weight on a single boot is known to be about 7 kN/m^2 ($\approx$ 1 psi), a difficulty arises from the fact that the applied stress and compression strain dissipate with depth--making it difficult to associate an average strain value with the surface settlement. However, a trial and error solution may

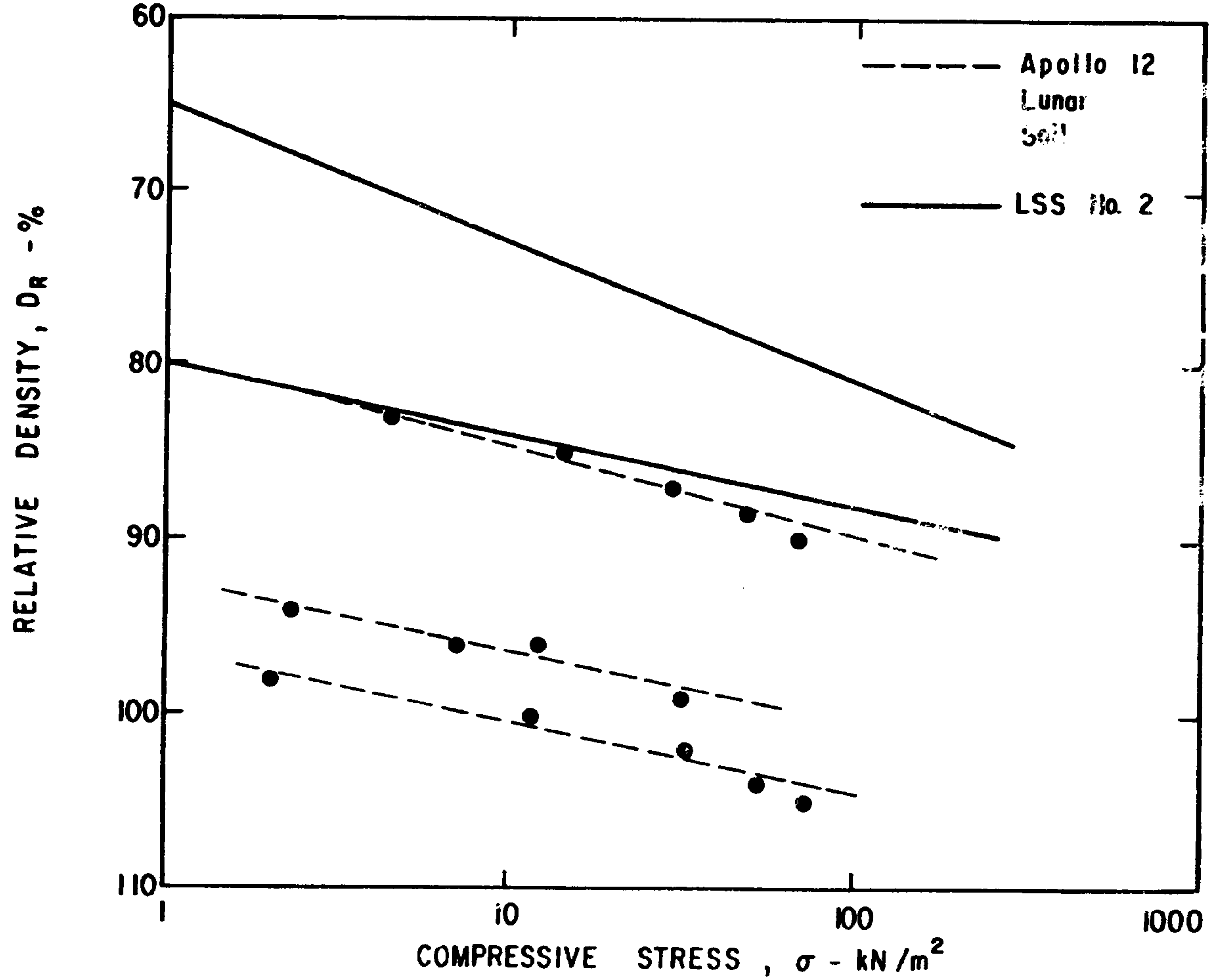


FIG. 3-16 COMPARISON OF COMPRESSION CHARACTERISTICS FOR APOLLO 12 LUNAR SOIL AND LSS NO. 2 ON RELATIVE DENSITY BASIS

be obtained as follows:

a) Use the results of the plane strain finite element solutions for very loose deposits to estimate the stress distribution with depth, with appropriate correction for the difference in the shape of the boot and the shape required for plane strain.

b) Assume a compression pattern for the loose lunar soil, similar to AB or AC in Fig. 3-17.

c) Using the compression pattern from b) and the stress distribution with depth from a), estimate the vertical strain magnitude at successively greater depths until it becomes negligibly small.

d) Integrate the strain with respect to depth to obtain a surface settlement and compare with the observed settlement.

e) Repeat b) through d) using new assumed compression patterns until satisfactory convergence is obtained.

The preceding procedure is suggested as a method for further study of lunar soil compressibility and as a basis for testing current and future models of compressibility which may be developed.

MODULUS OF SUBGRADE REACTION FOR THE LUNAR SURFACE

The results of footprint depth studies have shown that the porosity and relative density of the lunar surface are extremely variable from point to point on a scale of a meter or less. These bootprint studies suggest a means of estimating the statistical variation of the modulus of subgrade reaction of the lunar surface and thereby of predicting the probabilistic settlement of structures.

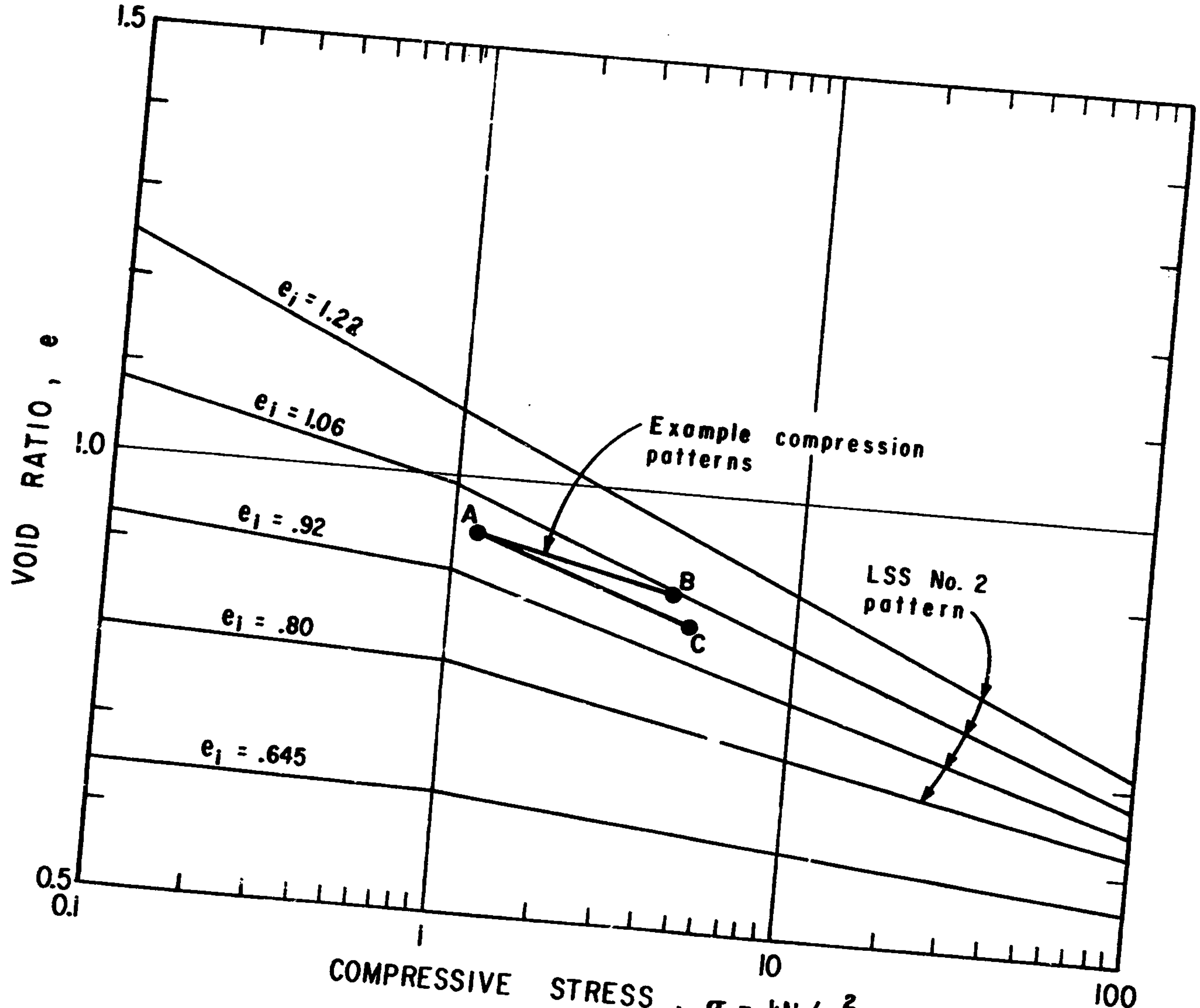


FIG. 3-17 EXAMPLE ASSUMED COMPRESSION PATTERNS FOR LUNAR SOIL

As the astronaut walks across the lunar landscape, he is also performing a series of simple plate bearing tests. The modulus of subgrade reaction may then be calculated from the following relationship:

$$k = \frac{F}{dA} \tag{3-6}$$

where k = modulus of subgrade reaction, in $kN/m^2/m$

F = applied load, in kN

A = area of applied load, in m^2

d = depth of bootprint, in m

Since F/A for a bootprint is 7 kN/m^2, Equation (3-6) may be simplified to:

$$k = \frac{7}{d} \tag{3-7}$$

The statistical variation of d from the bootprint studies is then used to estimate the statistical variation of k. In Fig. 3-18, two histograms of the percentage of occurrence of the modulus of subgrade reaction are shown, based on 776 bootprints from Apollo 11-17. The first histogram was determined simply by averaging all of the measurements. The second histogram was determined by first calculating the percentage of occurrence of k separately from each mission and then averaging the individual distributions without weighting. It can be seen that there is very little difference between the two averaging procedures. Consequently, these bootprints constitute a statistically representative set for the lunar surface.

It can be seen in Fig. 3-18 that the mean and median value of k falls in the range of 800 to 1600 $kN/m^2/m$. For most structures, a value of 1000 $kN/m^2/m$ will be satisfactory for design of the foundation dimensions.

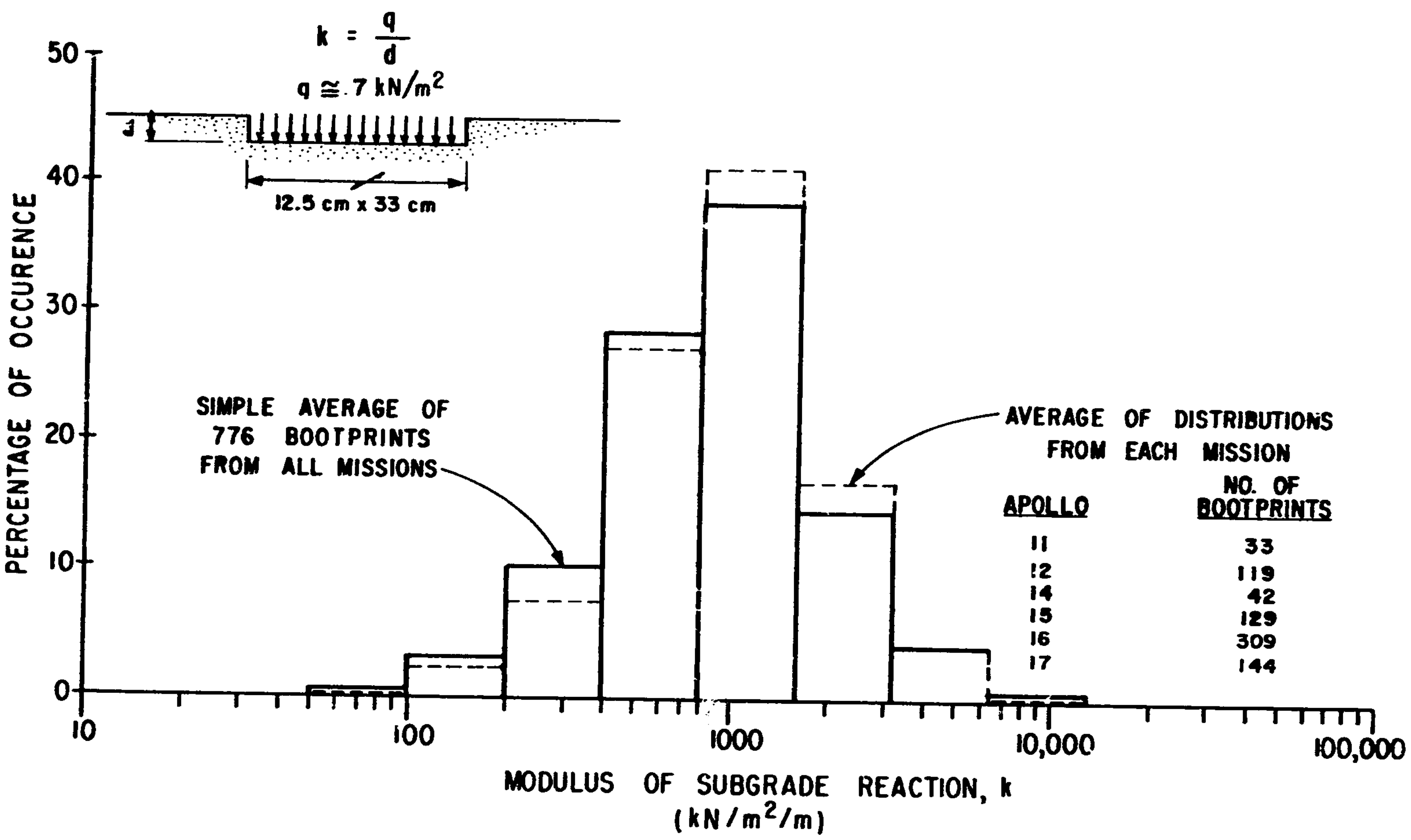


FIG. 3-18 DEPTH OF ASTRONAUT BOOTPRINTS USED TO DETERMINE MODULUS OF SUBGRADE REACTION FOR THE LUNAR SURFACE

For example, consider a load, F, equal to 10 kN; it is required that the settlement, on the average, be less than 0.02 m. Then, re-arranging Equation (3-6),

$$A = \frac{F}{kd} \tag{3-8}$$

it can be calculated that the area of the footing should be greater than or equal to 0.5 m^2. On the other hand, very sensitive structures, such as telescopes, may have very stringent requirements. For example, it might be required that the settlement be less than 0.01 m with a probability of about 95%. Referring again to Fig. 3-18, more than 95% of the values of k are greater than 200 $kN/m^2/m$. Using this value, the area of the footing would have to be 5 m^2.

This approach to estimating settlements on the lunar surface is of course limited to applied pressures relatively similar to that applied by the astronaut boot, or 7 kN/m^2. Furthermore it should be noted that no consideration has been given to the dependence of modulus of subgrade reaction, as defined by Equation (3-6), on footing size. An additional refinement could be made by using the results obtained by Namiq (1971) for lunar soil simulants for which it was found that modulus of subgrade reaction was proportional to B^{-n_p}, where B is the footing size in the same units used for settlement and n_p varies from 0.27 for very loose soil to about 0.46 for medium and dense soil. These constants were obtained for footings in the 2 to 12 cm range. Applying this refinement, values of k obtained from Equation (3-7) would be considered applicable for a 12.5 cm footing (the astronaut boot width) and would be multiplied by the factor $(12.5/B)^{n_p}$ for adjustment to other footings of size B. Additional refinements would be required to account for effects of footing shape.

It should also be noted that the compactness of the lunar soil has been observed to increase with depth, so that burying a footing would reduce the settlement. Alternatively, the construction site could be compacted beforehand which would also reduce settlements.

TRAFFICABILITY

General Performance of LRV

Information on the interaction of the Lunar Roving Vehicle with the lunar surface has been derived from (1) crew descriptions; (2) photographic coverage of the EVA activities; and (3) real-time read outs from the Rover amp-hour integrators and navigation system components.

On the basis of crew observations and close examination of photographs of Rover tracks obtained during Apollo 15, 16, and 17 missions, it appears that the vehicle developed excellent flotation and the interaction between the wheels and the soil did not extend to any appreciable depth below the lunar surface. The depth of wheel tracks was on the average of about 1-1/4 cm and varied from an imperceptible amount to about 5 cm, with the high wheel sinkage developed at the rims of small fresh craters. The 50 percent Chevron-covered, wire-mesh wheels of the Rover developed excellent traction with the lunar surficial material. In most cases, a sharp imprint of the Chevron tread was clearly discernible, indicating that the surficial soil possessed some cohesion and that the amount of wheel slip was minimal. The latter observation is also corroborated by the fact that the maximum position error of the LRV navigation system, which was biased with a constant wheel slip of only 2.3 percent, was of the order of only 100 m in each of the three Apollo 17 EVA's. Similar corroboration was obtained from the Apollo 15 and 16 missions.

On the basis of crew debriefings and photographic coverage it appears that the Rover was operated on slopes ranging from 0° to 12° on Apollo 15, from 0° to 18° on Apollo 16, and from 0° to 20° on Apollo 17. Thus the full slope-climbing capacity was not utilized on Apollo 15, but it was the impression of the Apollo 16 and 17 crews that the LRV was approaching the limit of its slope-climbing ability on the 16 and 17 missions. On the basis of extensive wheel-soil interaction tests performed with prototype LRV wheels on crushed-basalt lunar soil simulants (Green and Melzer, 1971, Melzer, 1971), the maximum slope climbing capability of the Rover was estimated to be within the slope angle range of 19° to 23°. Thus it appears that these simulation conditions were quite valid for this purpose.

Maneuvering on slopes did not present any serious operational problems from a wheel-soil interaction point of view, and the soil behavior appeared to reflect local deformation conditions and not any deep-seated mechanical action. In general, the vehicle could be controlled more easily upslope than downslope. Parking the vehicle on steep slopes posed some problems because of its tendency to slide down slope.

Under nominal driving conditions, no perceptible amount of soil appeared to be collected inside the wire-mesh wheels. Under the action of centrifugal forces generated during the rotating motion of the LRV wheels, it appears that fine-grained material collected inside the wheels was constantly ejected outward, ricocheting at the fenders and filling the space between the inside surface of the fenders and the outside surface of the wire-mesh tires. When the brakes of the vehicle were applied, this loose mass of fine-grained material fell out. These observations are in agreement with observations made on the behavior of the lunar soil simulant used in terrestrial LRV wheel-soil interaction tests.

At high vehicle accelerations a rooster tail was developed by soil ejected from the wheels. During the performance of the wheel-soil interaction test (Apollo 15 Grand Priz), the maximum height of the trajectory of the ejected material was estimated to be about 4.5 m.

The dust generated by the wheels without fenders or without any of the fender extensions was intolerable. Not only was the Apollo 17 crew covered with dust, but also all mechanical components which were not sealed, resulting in various malfunctions.

Trafficability Parameters

On the basis of LRV track depth, shape, and texture, there are no discernible variations in the average consistency of the surficial soil throughout the regions traversed during the Apollo 15, 16, and 17 missions. Similar observations were made on the consistency of the surficial material at the Fra-Mauro site of the Apollo 14 mission, based on wheel-soil interaction with the lunar surface of the Modularized Equipment Transporter (MET) (Mitchell et al., 1972).

LRV tracks and tracks developed by the unmanned vehicle Lunokhod 1 at the Mare Imbrium landing site of the Soviet spacecraft Luna 17, (Vinogradov et al., 1973) were analyzed by Costes (1973). The analysis followed the general procedure for MET tracks outlined in Mitchell et al., (1972), but it was modified to account for the wheel characteristics and mode of operation of the powered LRV and Lunokhod vehicles.

The results of this analysis indicate that at least for the Apollo 14 through 17 and Luna 17 landing sites, the surficial lunar soil appears to possess similar mechanical properties regardless of initial origin, geologic history, or gross chemical composition and local environmental conditions. These findings, which are in accord with the results of footprint and boulder track analyses, are also corroborated by calculations on the LRV energy consumption at the Apollo 15, Apollo 16, and Apollo 17 sites, shown in Fig. 3-19. These calculations were made on the basis of one soil model which for the Apollo 15 mission yielded the least Root-Mean Square deviation from the measured energy consumption for all three EVA's (Costes et al, 1972).

As shown in Fig. 3-19, the same soil model, which had been based on Surveyor data for soil near the surface (Scott and Roberson, 1968c), yields results that are in close agreement with the measured LRV energy consumption at both the Apollo 16 and the Apollo 17 sites.

The parameters characterizing this soil model, designated as Soil Model "B", are shown in Fig. 3-19. The symbols ϕ and c designate respectively the soil friction angle and cohesion, k is a normalizing constant conditioning the amount of shear strength, hence, thrust mobilized by the soil at a given wheel slip, and k_ϕ, k_c, and n describe the pressure-sinkage characteristics of the soil under wheel loads according to the expression developed by Bekker (1969)

$$p = \frac{k_c}{b} + k_\phi \, z^n \tag{1}$$

in which p = wheel contact pressure, N/cm^2

b = wheel footprint width, cm

z = wheel sinkage, cm

If for a given wheel the pressure-sinkage relationship is linear (n = 1), the coefficients k_c and k_ϕ are analogous to the soil's penetration resistance gradient G.

From these parameters pull vs. slip and torque vs. slip relationships were calculated using analytical expressions developed by Bekker and co-workers (1969) which were then used as computer input data, along

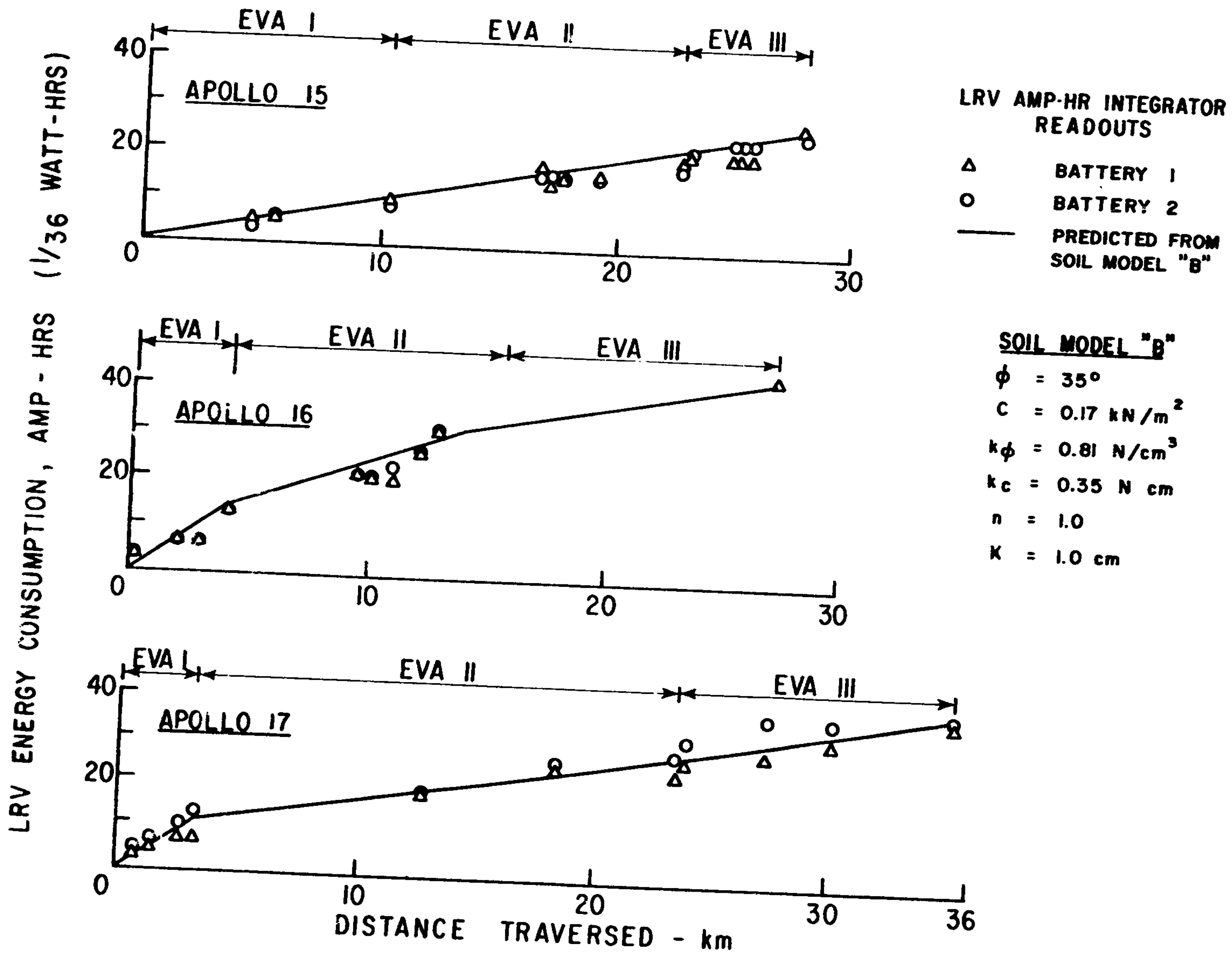


FIG. 3-19 MEASURED ENERGY CONSUMPTION OF THE ROVER IN RELATION TO THE PREDICTED VALUES BASED ON THE SOIL PROPERTIES INDICATED.

with other information relating to the mission, terrain and vehicle characteristics, to calculate the LRV energy consumption at each site (Costes, et al., 1972).

Because of the small amount of wheel sinkage, the LRV wheel-soil interaction with the lunar surface involved predominantly surface shear. Accordingly, a value of $\phi = 35°$, which characterizes the friction angle of Soil Model "B", is consistent with average friction angle values deduced from the analysis of LRV tracks (see Apollo 17, PSR) on the basis of in-place plate shear tests performed on the lunar soil simulant used for these studies (Green and Melzer, 1971, Melzer, 1971). Also, because the exponent n in equation (1) is equal to one for Soil Model "B", the values of coefficients k_c and k are consistent with the average G values deduced from LRV tracks (Apollo 17 PSR).

In general the soil-Rover interaction data support the conclusion that the surficial lunar soil is less compact, more deformable and compressible, and possesses lower strength than the subsurface material. These data also indicate that the average consistency of the surficial soil does not vary significantly over the lunar surface, although very significant local variations are common. The fact that the trafficability parameters for Soil Model "B" were so consistent with LRV energy consumptions for all three of the Rover missions indicate that these parameters represent a good "first estimate" for use in planning any future vehicular explorations of the lunar surface. It must be noted, however, that when the surficial soil is moderately firm in comparison to the wheel loads applied, as is the case for the LRV on the lunar surface, the major factors contributing to energy consumption are terrain characteristics, particularly the steepness of the slopes to be traversed.

CHAPTER 4

CONCLUSIONS

INTRODUCTION

From the results of the Apollo Soil Mechanics Experiment (S-200) much has been learned about the nature and behavior of lunar soil. In this final chapter the results of the work are summarized in terms of (1) the nature of lunar soil, (2) lunar history and processes, (3) engineering applications and implications for future lunar exploration, and (4) recommendations for further study using Apollo data.

THE NATURE AND BEHAVIOR OF LUNAR SOIL

Lunar soil is produced primarily by meteorite impacts on the lunar surface; usual terrestrial agents of soil formation are absent on the moon. These impacts cause both comminution and aggregation of particles, and the soils consist of complex mixtures of mineral fragments, miscellaneous glasses, agglutinates, and basaltic and brecciated lithic fragments. Although the proportions of the different particle types are variable, the grain size distributions for soils exposed to meteorite reworking for 100,000,000 years or more fall within a relatively narrow band and are classified as well-graded silty sands to sandy silts. The average particle size by weight generally varies from 0.04 mm to 0.13 mm. Grain shapes range from perfectly spherical to extremely irregular, including some particles with reentrant surfaces.

The specific gravity of samples containing submillimeter sized particles varies from 2.90 to 3.24, with individual particles having values from 1.0 to more than 3.32.

The results of density and porosity studies using data from a variety of sources indicate that the average relative density and porosity for the upper 15 cm in intercrater areas is essentially the same for all six Apollo landing sites and perhaps for all soil-covered locations on the lunar surface--if areas are considered on a scale of a few hundred meters. It was concluded that the absolute bulk density and the relative density are relatively low at the surface and increase rapidly with depth--more rapidly than was originally assumed in early lunar soil profile studies. The following relationship appears to describe variation of lunar soil average bulk density, ρ, with depth, z, very well:

$$\rho = \rho_o + k \ln (z+1)$$

where $\rho_o = 1.27 \text{ g/cm}^3$

$k = 0.121$

The best estimates for the average bulk densities and relative densities for the lunar surface are:

Depth Range - cm	Average Density, ρ - g/cm³	Relative Density, D_R - %
0-15	1.50 ± .05	65 ± 3
0-30	1.58 ± .05	74 ± 3
30-60	1.74 ± .05	92 ± 3
0-60	1.66 ± .05	83 ± 3

Statistical studies of footprints, LRV and MET tracks, and boulder tracks show that relative density varies considerably on a scale of 1 or 2 meters laterally and indicate that a best estimate of the standard deviation is about 15 percentage points for relative density. Histograms of density data indicate an essentially normal distribution with a slight skewness toward the high density side.

Average values of absolute and relative density for the lunar surface cannot at this time be confidently converted to values of porosity or void ratio because of insufficient data on values of G_s and e_{max} and e_{min} for lunar soil. Based on a very small number of tests--two small to give statistically significant averages--the following averages have been tentatively proposed and used in this report.

G_s	e_{max}	e_{min}
3.1	1.7	0.7

If these values were indeed valid as averages for the lunar surface, the "best estimate" average values of $\rho = 1.50\ g/cm^3$ and $D_R = 65\%$ for the uppermost 15 cm given above would correspond to a void ratio of 1.05 and a porosity of 51%.

The average relative density on crater rims for all Apollo sites is about 10 to 12% percentage points lower than for intercrater areas. The standard deviation for crater rim density is also greater than for intercrater areas.

Based on the small amount of lunar soil compressibility data available it was concluded that lunar soil is not highly unusual in its compressibility characteristics when compared with terrestrial soils of similar gradation. In fact it appears that compressibility parameters developed from UCB Lunar Soil Simulant No. 2 are reasonably appropriate for lunar soil and may be used until more test results become available.

The strength of lunar soil results from frictional (stress-dependent) and cohesive components. The friction angle falls in the range of 35 to 50°

with the higher values associated with the higher densities. Cohesion is in the range of 0.1 to 1.0 kN/m^2, again with the high values associated with the high densities. On the average, strength increases with depth. Substantial variations in strength may exist between points only a few cm apart. Limited evidence suggests that strength variability may be less on plains than on slopes. Local slope and surface appearance provide little indication of whether the strength of the underlying soil is high or low.

The important effect of confining stress on the compressibility, stress-strain, and strength behavior of lunar soil must be borne in mind. Any models developed for the interpretation of behavior; e.g. seismic velocities and deformation moduli, must take the dependence on, as well as local variations in, density into account.

Trafficability data were derived primarily from LRV energy consumption and interactions between the LRV, the MET, and the lunar surface. These data show that the LRV developed excellent flotation and traction and interaction with the soil was confined to the upper few centimeters. It appears that the full slope-climbing capacity of the LRV was not utilized on Apollo 15 but that it was approaching its limit on the 16 and 17 missions where slopes up to about 20 degrees were traversed.

Maneuvering on slopes did not present any serious operational problems and in general the vehicle could be controlled more easily up slope than down slope. Dust generated by the wheels without fenders or without any of the fender extensions was intolerable.

A single set of trafficability soil parameters was found to yield excellent estimates of the LRV energy consumption for Apollo missions 15, 16, and 17. These parameters, designated Soil Model "B" in the text of this report, therefore represent a good "first estimate" for use in planning any future vehicular lunar explorations.

LUNAR HISTORY AND PROCESSES

Soil mechanics data from all sources support the general conclusion that processes affecting the entire lunar surface, such as meteroid impact and solar wind, control the average properties such as grain size distribution and relative density, which are nearly the same at all sites. On the average the soil on slopes is less dense than the soil on level areas because of the effects of downslope movement. Local geology and topography on a small scale and specific cratering events appear to control the variation about the average to the extent that the standard deviation can be relatively large.

Mass movement of soil on the moon appears to have occurred mainly as a result of impact events, with large impacts responsible for the transport of large masses thrown from craters carried long distances. Large scale movement downslope as a result only of impact-or moonquake-induced shaking does not appear probable unless gas liquefaction was induced during slope failure. Slow downslope movement of the surface material as a result of creep induced by shear and/or thermal stresses appears plausible, as evidenced by the presence of fillets on the uphill side of rocks.

The apparent mechanism controlling the relative density of lunar soil in the plains areas seems to be that the constant meteorite and micro-meteorite bombardment maintains a loose, stirred up surface; but directly beneath the surface, the vibrations due to innumerable shock waves shake and densify the soil to a very high relative density. The sub-surface soil may even be overconsolidated at some locations; i.e., the soil may have been densified under a greater confining stress at some time in the past than is presently applied to it by the overlying soil.

ENGINEERING CONSIDERATIONS

Soil mechanics results were utilized during Apollo for problem solving in connection with other experiments and lunar surface activities. Examples include design of the LRV and prediction of its performance, redesign of the core tubes for Missions 15 through 17, development of simulants for drilling studies, prediction of open hole stability for configuration of the Neutron Flux Probe experiment, and slope stability under static and dynamic loadings.

Information obtained should prove invaluable when man again returns to the moon. Enough is known (quantitatively) about the properties to do preliminary planning and design for almost any location. For most structures that might be proposed shallow foundations (footings or mats) could be used with a design based on conservative average properties. Because of the extreme variability of the soil deposits, however, a more detailed investigation would be required for precision installations; e.g., observations where severe settlement limitations would be required.

The facts that excavations can be made without blasting or ripping, the soil can stand unsupported on slopes, and that it can be compacted will all influence the techniques adopted. Although vehicles have yet to traverse truly mountainous terrain on the moon, trafficability has been shown to be no problem in terms of soil properties and design performance predictions can be made with some confidence.

As a result of the Soil Mechanics Experiment it has been possible to develop good lunar soil simulants and analytical techniques that make possible terrestrial testing and analysis for study of future problems.

RECOMMENDATIONS FOR FURTHER STUDY

Although active exploration of the moon as represented by the Apollo Program is now at an end, much remains to be done to extend and refine the information thus far obtained. Of utmost immediate importance is the integration of the results of all Apollo experiments that provided data on or used assumptions about the lunar soil. Of interest here in addition to Soil Mechanics are the Passive and Active Seismic Experiments, Heat Flow Experiment, Surface Electrical Properties Experiment, Traverse Gravimeter Experiment. Field Geology, Lunar Neutron Probe, and Bistatic Radar, among others. A comprehensive physical-mathematical model of the lunar soil over its full depth is needed that is consistent with observations and data from all sources. A proposal for further studies in this area has been submitted which will emphasize in particular development of a model that is consistent with composition, mechanical properties, thermal properties, electrical properties, and seismic properties.

REFERENCES

Arrhenius, G., Liang, S., Macdougall, D., Wilkening, L., Bhandari, N., Bhat, S., Lal, D., Rajagopalan, G., Tamhane, A. S. and Venkatavaradan, V. S. (1971) "The Exposure History of the Apollo 12 Rigolith," Proc. Second Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 2, Vol. 3, pp. 2583-2598, MIT Press.

Aschenbrenner, B. C. (1956) "A New Method of Expressing Particle Sphericity," Journal of Sedimentary Petrology, Vol. 26, pp. 15-31.

Bekker, M. G. (1969): Introduction to Terrain-Vehicle Systems. The University of Michigan Press, Ann Arbor.

Cadenhead, D. A. and Jones, B. R. (1972) "The Adsorption of Atomic Hydrogen on 15101,68," The Apollo 15 Lunar Samples, ed. by J. W. Chamberlain and C. Watkins, Lunar Science Institute, Houston, Texas, pp. 272-274.

Cadenhead, D. A., Wagner, N. J., Jones, B. R., Stetter, J. R. (1972) "Some Surface Characteristics and Gas Interactions of Apollo 14 Fines and Rock Fragments," Proc. Third Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 3, Vol. 3, pp. 2243-2257, MIT Press.

Carrier, W. D., III (1970) "Lunar Soil Mechanics on the Apollo Missions," Spring Meeting of the Texas Section, ASCE, Galveston, Texas.

Carrier, W. D. III, Johnson, S. W., Werner, R. A., and Schmidt, R. (1971) "Disturbance in Samples Recovered with the Apollo Core Tubes," Proc. Second Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 2, Vol. 3, pp. 1959-1972, MIT Press.

Carrier, W. D., III, Johnson, S. W., Carrasco, L. H., and Schmidt, R. (1972) "Core Sample Depth Relationships: Apollo 14 and 15," Proc. Third Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 3, Vol. 3, pp. 3213-3221, MIT Press.

Carrier, W. D., III (1973b) "Apollo Drill Core Depth Relationships Submitted to the Moon," April.

Carrier, Bromwell, Martin (1972, 1973) "Strength and Compressibility of Returned Lunar Soil," Proc. 3rd Lunar Science Conference, Supplement 3, Geochimica et Cosmochimica Acta, V. 3, pp. 3223-3234, MIT Press.

Carrier, W. D., III, Bromwell, L. G. and Martin, R. T. (1973a) "Behavior of Returned Lunar Soil in Vacuum," Journal of the Soil Mechanics and Foundations Divisions, ASCE, V. 99, No. SM11, November, pp. 979-996.

Carrier, W. D., III, Mitchell, J. K. and Mahmood A. (1973b) "The Relative Density of Lunar Soil," Lunar Science IV, J. W. Chamberlain and C. Watkins, ed., pp. 118-120.

Carrier, W. D., III (1973a) "Lunar Soil Grain Size Distribution," The Moon, Vol. 6, No. 314, in press.

Charles, R. W., Hewitt, D. A. and Wones, D. R. (1971) "H_2O in Lunar Processes: The Stability of Hydrous Phases in Lunar Samples 10058 and 12013," Proc., Second Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 2, Vol. 1, pp. 645-664, MIT Press.

Christensen E. M., Batterson S. A., Benson H. E., Chandler C. E., Jones R. H., Scott F. R., Shipley E. M., Sperling F. P., and Sutton G. H. (1967) "Lunar Surface Mechanical Properties - Surveyor I," J. Geophys. Res. 72, 801-813.

Christensen E. M., Batterson S. A., Benson H. E., Choate R., Hutton R. E., Jaffe L. D., Jones R. H., Ko H. Y., Schmidt F. N., Scott R. F., Spencer R. L., Sperling F. B., and Sutton G. H. (1968b) "Lunar Surface Mechanical Properties, in Surveyor VI, a preliminary report," NASA SP-166, pp. 41-95.

Christensen E. M., Batterson S. A., Benson H. E., Choate R., Jaffe L. D., Jones R. H., Ko H. Y., Spencer R. L., Sperling F. B., and Sutton G. H. (1968a) "Lunar Surface Mechanical Properties at the Landing Site of Surveyor III," J. Geophys. Res. 73, pp. 4081-4094.

Clanton, U. S., McKay, D. S., Taylor, R. M. and Heiken, G. H. (1972) "Relationship of Exposure Age to Size Distribution and Particle Types in the Apollo 15 Drill Core," The Apollo 15 Lunar Samples, ed. by J. W. Chamberlain and C. Watkins, Lunar Science Institute, Houston, Texas, pp. 54-56.

Costes N. C., Carrier, W. D., Mitchell J. K., and Scott R. F. (1969) "Apollo 11 Soil Mechanics Investigation," Apollo Preliminary Science Report, NASA SP-214, pp. 85-122.

Costes N. C., Carrier W. D. III, Mitchell J. K., and Scott R. F. (1970) "Apollo II: Soil Mechanics Results," J. Soil Mechanics and Foundations Div., ASCE 96, 2045-2080.

Costes N. C., Cohron G. T., and Moss D. C. (1971) "Cone Penetration Resistance Test - An Approach to evaluating the In-Place Strength and Packing Characteristics of Lunar Soils," Proc. Second Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl. 2, Vol. 3, pp. 1973-1987, MIT Press.

Costes, N. C., Farmer, J. C., and George, E. B. (1972) "Mobility Performance of the Lunar Roving Vehicle," Terrestrial Studies - Apollo 15 Results, Proc. of the 4th Int. Conf. of the International Society for Terrain-Vehicle Systems, Stockholm-Kiruna, Sweden.

Costes, N. C. (1973) "Regional Variations in Physical and Chemical Properties of Lunar Surface Regolith. Proc. of the Fourth Lunar Science Conference.

Cremers, C. J., Birkebak, R. C. (1971) "Thermal Conductivity of Fines from Apollo 11," Proc., Apollo 11 Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 2, Vol. 3, pp. 2311-2315, MIT Press.

Cremers, C. J. (1972) "Thermal Conductivity of Apollo 14 Fines," Proc. Third Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 3, Vol. 3, pp. 2611-2617, MIT Press.

Cremers, C. J. and Hsia, H. S. (1973) "Thermal Conductivity of Apollo 15 Fines at Low Density," Lunar Science IV, (editors J. W. Chamberlain and C. Watkins), pp. 164-165, Lunar Science Institute, Houston.

Crozaz, G., Drozd, R., Hohenberg, C. M., Hoyt, H. P., Jr., Ragan, D., Walker, R. M. and Yuhas, D. (1972) "Solar Flare and Glactic Cosmic Ray Studies of Apollo 14 and 15 Samples," Proc. Third Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 3, Vol. 3, pp. 2917-2931, MIT Press.

Crozaz, G., Walker, R., and Woolum, D. (1971) "Nuclear Track Studies of Dynamic Surface Processes on the Moon and the Constancy of Solar Activity,: Proc., Second Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 2, Vol. 3, pp. 2543-2558, MIT Press.

Duke, M. B., Woo, C. C., Bird, M. L., Sellers, G. A. and Finkelman R. B. (1973a) "Lunar Soil: Size Distribution and Mineralogical Constituents," Science, Vol. 167, pp. 648-650.

Duke, M. B., Woo, C. C., Sellers, G. A., Bird, M. L. and Finkelman, R. B. (1973b) "Genesis of Lunar Soil at Tranquility Base," Proc. Apollo 11 Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 1, Vol. 1, pp. 347-361, Pergamon.

Gault, D. E., Quaide, W. L. and Oberbeck, V. R. (1968) "Impact Cratering Mechanics and Structures," Shock Metamorphism of Natural Materials, ed. by B. M. French and N. M. Short, pp. 87-99, Mono Books, Baltimore.

Gibson, E. K., Jr. and Moore, G. W. (1973) "Volatile-rich Lunar Soil: Evidence of Possible Cometary Impact," Science, Vol. 179, January 5.

Görz, H., White, E. W., Roy, R. and Johnson, G. G., Jr. (1971) "Particle Size and Shape Distributions of Lunar Fines by CESEMI," Proc. Second Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 2, Vol. 3, pp. 2021-2025, MIT Press.

Gorz, H. White, E. W., Johnson, G. G., Jr. and Pearson, M. W. (1972) "CESEMI Studies of Apollo 14 and 15 Fines," Proc. Third Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 3, Vol. 3, pp. 3195-3200, MIT Press.

Green, A. J., and Melzer, K. J. (1971) "Performance of the Boeing LRV Wheels in a Lunar Soil Simulant: Effect of Wheel Design and Soil," Tech. Report. M-71-10, Rept. 1, USAE, WES, Vicksburg, Miss.

Gromov, V. V., Leonovich, A. K., Lozhkin, V. A., Rybakov, A. V., Pavlov, P. S., Dmitriev, A. D. and Shvarev, V. V. (1971) "Results of Investigations of the Physical and Mechanical Properties of the Lunar Sample from Luna-16," Paper K13 at the 14th COSPAR Session, Seattle, Wash., USA.

Hartmann, W. K. (1972) "Paleocratering of the Moon: Review of Post-Apollo Data," Astrophysics and Space Science, Vol. 17, pp. 48-64.

Heywood, H. (1971) "Particle Size and Shape Distribution for Lunar Fines Sample 12057, 72," Proc. Second Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 2, Vol. 3, pp. 1989-2001, MIT Press.

Houston, W. N., and Namiq, L. I. (1971) "Penetration Resistance of Lunar Soils," Journal of Terramechanics, Vol. 8, No. 1, pp. 59-69.

Houston, W. N., Hovland, H. J., and Mitchell, J. K. (1972) "Lunar Soil Porosity and its Variation as Estimated from Footprints and Boulder Tracks," Proc. of the Third Lunar Sci. Conf., Vol. 3, pp. 3255-3263.

Houston, W. N., Moriwaki, Y., and Chang, C-S. (1973) "Downslope Movement of Lunar Soil and Rock Caused by Meteor Impact, Proc. of the Fourth Lunar Sci. Conf.

Hovland, H. J. (1970) "Mechanics of Rolling Sphere-soil Slope Interaction," Ph.D. Dissertation, Department of Civil Engineering, University of California, Berkeley, California.

Hovland, H. J. and Mitchell, J. K. (1971) "Mechanics of Rolling Sphere-Soil Slope Interaction," Final Report, Vol. II of IV, NASA Contract 8-21432, Space Sciences Laboratory, University of California, Berkeley.

Hovland, H. J. and Mitchell, J. K. (1972) "Variability of Lunar Surface Materials as Indicated by Boulder Tracks," Science.

Jaffe, L. D. (1967) "Surface Structure and Mechanical Properties of the Lunar Maria," J. Geophy. Res. 72, 1727-1731.

Jaffe, L. D. (1972) "Bearing Strength of Lunar Soil," The Moon, Vol. 3, pp. 337-345.

Krumbein, W. C. (1941) "Measurement and Geological Significance of Shape and Roundness of Sedimentary Particles," Journal of Sedimentary Petrology, Vol. 11, pp. 64-72.

Lindsay, J. F. (1971) "Sedimentology of Apollo 11 and 12 Lunar Soils," Journal of Sedimentary Petrology, Vol. 41, No. 3, pp. 780-797.

Lucks, A. S. (1970) "The Influence of Particle Shape on the Strength of Granular Material," Thesis submitted in partical fulfillment of the requirements for the degree of Doctor of Philosophy at the Massachusetts Institute of Technology.

McKay, D. S., Morrison, D. A., Clanton, U. S., Ladle, G. H. and Lindsay, J. F. (1971) "Apollo 12 Soil and Breccia," Proc. Second Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 2, Vol. 1, pp. 755-773, MIT Press.

McKay, D. S., Heiken, G. H., Taylor, R. M., Clanton, U. S. and Morrison, D. A. (1972) "Apollo 14 Soils: Size Distribution and Particle Types," Proc. Third Lunar Sci. Conf., Geochim. Cosmochim, Acta, Suppl. 3, Vol. 1, pp. 983-994, MIT Press.

Melzer, K. J. (1971) "Performance of the Boeing LRV Wheels in a Lunar Soil Simulant: Effect of Speed, Wheel Load, and Soil," Tech. Rept. M-71-10, Rept. 2, USAE, WES, Vicksburg, Miss.

Mitchell, J. K., Bromwell, L. G., Carrier, W. D., Coates, N. C., and Scott, R. F. (1971a) "Soil Mechanics Experiment,"Apollo 14 Preliminary Science Report, NASA SP-272, pp. 87-108.

Mitchell, J. K., Houston, W. N., Vinson, T. S., Durgunoglu, T., Namiq, L. I., Thompson, J. B., and Treadwell, D. D. (1971b) "Lunar Surface Engineering Properties Experiment Definition," Final Report: Vol. I of IV, Mechanics, Properties, and Stabilization of Lunar Soils, Contract No. NA S8-21932, Space Sciences Laboratory Series II, Issue 48, July.

Mitchell, J. K., Bromwell, L. G., Carrier, W. D., III, Costes, N. C., and Scott, R. F. (1972) "Soil Mechanics Properties at the Apollo 14 Site," Journal of Geophy. Res., Vol. 77, No. 29, pp. 5641-5666.

Mitchell, J. K., Bromwell, L. G., Carrier, W. D., III, Costes, N. C., Houston, W. N., and Scott, R. F. (1972a) "Soil Mechanics Experiment," Section 7 of Apollo 15 Preliminary Science Report, NASA Special Publication SP-289, pp. 7-1--7-28.

Mitchell, J. K., Scott, R. F., Houston, W. N., Costes, N. C., Carrier, W. D. III, and Bromwell, L. G. (1972c) "Mechanical Properties of Lunar Soils: Density, Porosity, Cohesion, and Angle of Internal Friction," Proc. Third Lunar Sci. Conf., Geochim. Cosmochim, Acta, Suppl. 3, Vol. 3, MIT Press.

Mitchell, J. K., Carrier, W. D., III, Houston, W. N., Scott, R. F., et al. (1972b) "Soil Mechanics,"Section 8 of Apollo 16 Preliminary Science Report, NASA SP 315.

Mitchell, J. K., and Houston, W. N. (1973) "Lunar Soil Properties and Soil Mechanics," Semiannual Status Report, NASA Grant NGR 05-003-906, Space Science Laboratory Series M, Issue 6, January.

Mitchell, J. K., Carrier, W. D., III, Costes, N. C., Houston, W. N., and Scott, R. F. (1973b) "Surface Soil Variability and Stratigraphy at the Apollo 16 Site," Proc. Fourth Lunar Sci. Conf.

Mitchell, J. K., Carrier, W. D., III, Costes, N. C., Houston, W. N., Scott, R. F., and Hovland, H. J. (1973a) "Soil Mechanics," Apollo 17 Preliminary Science Report, NASA SP-330.

Moore, H. J. (1970) "Estimates of the Mechanical Properties of Lunar Surface Using Tracks and Secondary Impact Craters Produced by Blocks and Boulders," Interagency Report: Astrogeology 22, United States, Dept. of the Interior, Geological Survey.

Namiq, L. I. (1970) "Stress-deformation Study of a Simulated Lunar Soil," Ph.D. dissertation, Department of Civil Engineering, University of California, Berkeley, California.

Nordmeyer, E. F. (1967)"Lunar Surface Mechanical Properties Derived From Track Left by Nine Meter Boulder," MSC Internal Note No. 67-TH-1, NASA.

Oberbeck, V. R., and Quaide, W. L. (1968) "Genetic Implications of Lunar Regolith Thickness Variations," Icarus, Vol. 9, pp. 446-465.

Quaide, W. L., Oberveck, V. R., and Bunch, T. (1971) "Investigation of the Natural History of the Regolith at the Apollo 12 Site," Proc. Second Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 2, Vol. 1, pp. 701-718, MIT Press.

Scott, R. F. (1963) "Principles of Soil Mechanics," Addison-Wesley, Reading, Mass.

Scott, R. F., and Roberson, F. I. (1967) "Soil Mechanics Surface Sampler: Lunar Surface Tests and Analysis," Chap. IV of Surveyor III Mission Report, Part II: Science Results, TR32-1177, Jet Propulsion Laboratory, California Institute of Technology, pp. 69-110, June.

Scott, R. F. (1968) "The Density of Lunar Surface Soil," J. Geophys. Res., 73, pp. 5469-5471.

Scott, R. F., and Roberson, F. I. (1968a) "Surveyor III - Soil Mechanics Surface Sampler: Luna Surface Tests, Results, and Analysis," J. Geophys. Res., 73, pp. 4045-4080.

Scott, R. F., and Roberson, F. I. (1968b) "Soil Mechanics Surface Sampler," Chap. V of Surveyor VII Mission Report, Part II: Science Results, TR32-1264. Jet Propulsion Laboratory, California Institute of Technology, pp. 135-185.

Scott, R. F., and Roberson, F. I. (1968c) "Soil Mechanics Surface Sampler," Surveyor Project Final Report, Part II: Science Results, Tech. Report 32-1265, pp. 195-206.

Scott, R. F., and Roberson F. I. (1969) "Soil Mechanics Surface Sampler," In Surveyor Program Results, NASA SP-184, pp. 171-179.

Scott, R. F., and Carrier, W. D., Costes, N. C., and Mitchell, J. K. (1970) "Mechanical Properties of the Lunar Regolith," Apollo 12 Preliminary Science Report, NASA SP-235, pp. 161-182.

Shoemaker, E. M., Bailey, N. G., Batson, R. M., Dahlem, D. H., Foss, T. H., Grolier, M. J., Goddard, E. N., Hait, M. H., Holt, H. E., Larson, K. B., Rennilson, J. J., Schaber, G. G., Schleicher, D. L., Schmitt, H. H., Sutton, R. L., Swann, G. A., Watters, A. C., and West, M. N. (1969) "Geologic Setting of the Lunar Samples Returned on the Apollo 11 Mission," Apollo 11 Preliminary Science Report, NASA SP-214, pp. 41-83.

Shoemaker, E. M., Batson, R, M., Bean, A. L., Conrad, C., Jr., Dahlem, D. H., Goddard, E. N., Hait, M. H., Larson, K. B., Schaber, G. G., Schleicher, D. L., Sutton, R. L., Swann, G. A., and Waters, A. C. (1970) "Geology of the Apollo 12 Landing Site," Part A of "Preliminary Geologic Investigation of the Apollo 12 Landing Site," Apollo 12 Preliminary Science Report, NASA SP-235, pp. 113-156.

Shoemaker, E. M. (1971) "Origin of Fragmental Debris on the Lunar Surface and the History of the Bombardment of the Moon," Instituto de Investigaciones Geologicas de la Disputacion Provincial, Universidad de Barcelona, Spain, Vol. XXV, pp. 27-56.

Swann, G. A., Bailey, N. G., Batson, R. M., Eggleton, R. E., Hait, M. H., Holt, H. E., Larson, K. B., McEwen, M. C., Mitchell, E. D., Schaber, G. G., Schafer, J. B., Shepard, A. B., Sutton, R. L., Trask, N. J., Ulrich, G. E., Wilshire, H. G., and Wolfe, W. W. (1971) "Preliminary Geologic Investigations of the Apollo 14 Landing Site," Apollo 14 Preliminary Science REport, NASA SP-272, pp. 39-85.

Swann, G. A., Bailey, N. G., Batson, R. M., Freeman, V. L., Hait, M. H., Head, J. W., Hold, H. E., Howard, K. A., Irwin, J. B., Larson, K. B., Muehlberger, W. R., Reed, V. S., Rennilson, J. J., Schaber, G. G., Scott, D. R., Silver, L. T., Sutton, R. L., Ulrich, G. E., Wilshire, H. G., and Wolfe, E. W. (1972) "Preliminary Geologic Investigation of the Apollo 15 Landing Site," Apollo 15 Preliminary cience Report, NDSA SP-289, pp. 5-1--5-112.

Treadwell (1974) Ph.D. dissertation, Department of Civil Engineering University of California, Berkely, California, in press.

Vinogradov, A. P. (1973) "Peredvizhnaya Laboratoriya na Lunokhod-1. Nanka Publishers, Moscow (Translation by Jont Publ. Res. Service, JPRS 54525).

Wadell, H. (1935) "Volume Shape and Roundness of Quartz Particles," Journal of Geology, Vol. 43, pp. 250-280.

Williams, R. J. (1972) "Lithification and Metamorphism of Lunar Breccias," Earth and Planetary Science Letters, Vol. 16, pp. 250-256.

APPENDIX I - PUBLICATIONS RESULTING FROM LUNAR RESEARCH BY SOIL MECHANICS TEAM MEMBERS

1964

"Current Lunar Soil Research," (by James K. Mitchell), Journal of the Soil Mechanics and Foundations Divisions, ASCE, Vol. 90, No. SM3, pp. 53-83, May 1964.

1967

"Lunar Soil Engineering and Engineering Geology," (by James K. Mitchell and T. W. Lambe) Position paper for NASA 1967 Summer Conference on Lunar Exploration and Science at Santa Cruz, July 31 - August 13, 1967.

"Soil Mechanics Surface Sampler: Lunar Surface Tests and Analyses," (by R. F. Scott and F. I. Roberson), Chap. IV of Surveyor III Mission Report, Part II: Science Results, TR32-1177, Jet Propulsion Laboratory, California Institute of Technology, pp. 69-110, June 1, 1967.

1968

"Surveyor III - Soil Mechanics Surface Sampler: Luna Surface Tests, Results, and Analysis," (by R. F. Scott and F. I. Roberson), Journal of Geophysical Research 73, 4045-4080, 1968.

"Soil Mechanics Surface Sampler," (by R. F. Scott, and F. I. Roberson), Chap. V of Surveyor VII Mission Report, Part II: Science Results, TR32-1264, Jet Propulsion Laboratory, California Institute of Technoloty pp. 135-185, March 15, 1968.

"Soil Mechanics Surface Sampler," (by R. R. Scott and F. I. Roberson), Surveyor Project Final Report, Part II: Science Results. Technical Report 32-1265, JPL, Pasadena, California, pp. 195-206, 1968.

1969

"Apollo 11 Soil Mechanics Investigation," (by N. C. Costes, W. D. Carrier, III, James K. Mitchell and R. F. Scott), Preliminary Science Report, NASA SP-214, pp. 85-122, Ocotber 1969.

"Apollo 11 Soil Mechanics Investigation," (by N. C. Costes and J. K. Mitchell), Proceedings of the Apollo 11 Lunar Science Conference, Vol. 3, pp. 2025-2044.

"Determination of Lunar Soil Properties Using Penetrometers," (by James K. Mitchell), Paper presented at the Lunar Soil Mechanics Session, ASCE Convention, Chicago, Illinois, October 17, 1969.

"Materials Studies Related to Lunar Surface Exploration," (by J. K. Mitchell, R. E. Goodman, J. Frisch, P. A. Witherspoon and F. E. Heuze), Report to Marshall Space Flight Center, NASA, 5 vols. plus Summary Report, March 1969.

"Preliminary Examination of Lunar Samples from Apollo 11," (by Lunar Sample Preliminary Examination Team), Science, Vol. 165, No. 3899, pp. 1211-1227, September 19, 1969.

"Soil Mechanics Surface Sampler," (by R. F. Scott and F. I. Roberson), Surveyor Program Results, NASA SP-184, pp. 171-179, 1969.

1970

"Apollo 11 Drive-Tube Core Samples: An Initial Physical Analysis of Lunar Surface Sediment," (by R. Fryxell, D. Anderson, D. Carrier, W. Greenwood and G. Heiken), Science, Vol. 167, No. 3918, pp. 734-737, Jan. 30, 1970.

"Apollo 11 Drive-Tube Core Samples: An Initial Physical Analysis of Lunar Surface Sediment," (by Roald Fryxell, Daniel Anderson, David Carrier, William Greenwood and Grant Heiken), Proceedings of the Apollo 11 Lunar Science Conference, Vol. 3, pp. 2121-2126, Pergamon Press, New York, 1970.

"Apollo 11 Soil Mechanics Investigation," (by N. C. Costes, W. D. Carrier, J. K. Mitchell and R. F. Scott), Science, Vol. 167, pp. 739-741, Jan. 30, 1970.

"Apollo 11: Soil Mechanics Results," (by N. C. Costes, W. D. Carrier, III, J. K. Mitchell and R. F. Scott), Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 96, No. SM6, Paper 7704, pp. 2045-2080, Nov. 1970.

"Lunar Soil Mechanics on the Apollo Missions," abstract, (by W. David Carrier, III), Texas Civil Engineer, Vol. 40, No. 4, p. 7, April 1970.

"Lunar Surface Engineering Properties Experiment Definition," (by J. K. Mitchell, K. Drozd, R. E. Goodman, F. E. Heuze, W. N. Houston, D. R. Willis, P. A. Witherspoon), 4 vols. plus Summary Technical Report, prepared for Marshall Space Flight Center, Huntsville, Alabama, under NASA Contract NAS 8-21432, Jan. 1970.

"Mechanical Properties of the Lunar Regolith," (by R. F. Scott, W. D. Carrier, N. C. Costes, and J. K. Mitchell), Part C (pp. 161-182) of "Preliminary Geologic Investigation of Apollo 12 Landing Site," by E. M. Shoemaker, et al.(pp. 113-182), Apollo 12 Preliminary Science Report, NASA SP-235, 1970. Also,"Lunar Science-III, Revised Abstracts of papers presented at the Third Lunar Science Conference (editor Carolyn Watkins), pp.545-546, Lunar Science Institute Contribution no. 88, 1972.

"Penetration Resistance of Lunar Soils," (by W. N. Houston and L. I. Namiq), Proceedings of the Symposium on Off-Road Mobility, Los Angeles, California, Nov. 3-4, 1970. TRW Systems Group and International Society for Terrain Vehicle Systems. (Also published in the Journal of Terra Mechanics, Vol. 8, No. 1, pp. 59-69, 1971.

"Preliminary Examination of Lunar Samples from Apollo 12," (by Lunar Sample Preliminary Examination Team), Science. 167, No. 3923, pp. 1325-1339, March 6, 1970.

"Preliminary Geologic Investigation of the Apollo 12 Landing Site: Part C. Mechanical Properties of the Lunar Regolith," (by J. K. Mitchell, R. F. Scott, W. C. Carrier, and N. C. Costes), Preliminary Science Report, NASA SP-235, pp. 161-181, 1970.

"Pressure Distribution and Soil Failure Beneath a Towed, Rigid Spherical Wheel in Air Dry Sand," (by J. K. Mitchell and H. J. Hovland), Proc., ISTVS-TRW Off-Road Mobility Symposium, Los Angeles, Calif., pp. 107-127, Nov. 3-4, 1970.

1971

"Apollo 12 Soil Mechanics Investigation," (by R. F. Scott, W. D. Carrier, III, N. C. Costes, and J. K. Mitchell), Geotechnique, Vol. 21, No. 1, pp. 1-14, March 1971.

"Cone Penetration Resistance Test - An Apporach to Evaluating In-Place Strength and Packing Characteristics of Lunar Soils," (by N. C. Costes, G. T. Cohron and D. C. Moss), Proceedings of the Second Lunar Science Conference, Vol. 3, The MIT Press, pp. 1973-1987, 1971.

"Disturbance in Samples Recovered with the Apollo Core Tubes," (by W. David Carrier, III, Stewart W. Johnson, Richard A. Werner, and Ralf Schmidt), Proceedings of the Second Lunar Science Conference, Vol. 3, The MIT Press, pp. 1959-1972, 1971.

"Lunar Core Tube Sampling," (by W. N. Houston and J. K. Mitchell), Proc., Apollo 12 Lunar Science Conference, Vol. 3, Houston, Texas, pp. 1953-1958, Jan. 1971.

"Lunar Soil Mechanics," (by Stewart W. Johnson and W. David Carrier, III), The Military Engineer, Vol. 63, No. 415, pp. 324-327, Sept.-Oct., 1971.

"Lunar Surface Closeup Stereoscopic Photography on the Ocean of Storms (Apollo 12 Landing Site)," (by Grant Heiken and W. David Carrier, III, NASA Technical Memorandum TM X-58078, December, 1971.

"Mechanics of Rolling Sphere-Soil Slope Interaction," (by H. J. Hovland and J. K. Mitchell), Final Report, Vol. II of IV, NASA Contract 8-21432, Space Sciences Laboratory, Univeristy of California, Berkeley, 1971.

"Soil Mechanics Experiment," (by James K. Mitchell, L. G. Bromwell, W. D. Carrier, III, N. C. Costes and R. R. Scott), Chapter 4 of Apollo 14 Preliminary Science Report, NASA SP 272, pp. 87-108, 1971.

"The Lunar Soil as Revealed by Apollo Core Tube Samples, Trenching, and the Simple Penetrometer," abstract, (by W. David Carrier, III, and Stewart W. Johnson, Texas Civil Engineer, Vol. 41, No. 3, pp. 13-14, March 1971.

1972

"A Petrographic and Chemical Description of Samples from the Lunar Highlands," (by Lunar Sample Preliminary Examination Team), Apollo 16 Preliminary Science Report, NASA SP-315, pp. 7-1 to 7-24, 1972.

"Apollo 16 Special Samples," (by Friedrich Hörz, W. D. Carrier, III, J. W. Young, C. M. Duke, J. S. Nagle and R. Fryxell), Appollo 16 Preliminary Science Report, NASA SP-315, pp. 7-24 to 7-54, 1972.

"Core Sample Depth Relationships: Apollo 14 and 15," (by W. D. Carrier, III, S. W. Johnson, L. H. Carrasco, and R. Schmidt), Proc. Third Lunar Science Conference, Vol. 3, pp. 3213-3221, MIT Press, 1972.

"Flow of Gases in Granuair Media at Low Pressures," Abstract, (by S. W. Johnson, R. T. Martin, W. D. Carrier, III, and J. L. Winkler), Transactions, American Geophysical Union, Vol. 53, No. 4, p. 440, April, 1972.

"Lunar Soil Porosity and its Variation as Estimated from Footprints and Boulder Tracks," (with W. N. Houston, J. K. Mitchell, and H. V. Hovland), Proc. Third Lunar Science Conference, Supplement 3, Geochemica et Cosmochimica Acta: 3, pp. 3255-3263, MIT Press, 1972.

"Lunar Surface Closeup Stereoscopic Photography at Fra Mauro (Apollo 14 Site)," (by W. D. Carrier, III and G. Heiken), NASA Technical Memcrandum TM x-58072, January, 1972.

"Mechanical Properties of Lunar Soil: Density, Cohesion, and Angle of Internal Friction," (by J. K. Mitchell, R. F. Scott, W. N. Houston, N. C. Costes, W. D. Carrier, III, and L. G. Bromwell), Proc. Third Lunar Science Confer- Vol. 3, pp. 3235-3253, MIT Press, 1972. also: "Lunar Science III," Revised Abstracts of Papers Presented at the Third Lunar Science Conference (editor Carolyn Watkins), Lunar Science Institute Contribution No. 88, pp. 545-546, 1972.

"Mobility Performance of the Lunar Roving Vehicie: Terrestrial Studies - Apollo 15 Results," (by N. C. Costes, J. E. Farmer and E. B. George), Proc. of the 4th International Conference of the International Society for Terrain - Vehicle Systems, Stockholm and Kiruna, Sweden, April 24-28, 1972. Also: NASA TR R-401.

"Model Studies of the Failure Mechanism Associated with a Sphere Rolling Down a Soil Slope," (by H. J. Hovland and J. K. Mitchell), Journal of Terramechanics, Vol. 9, No. 1, pp. 37-50, 1972.

"Polyurethane Foamed Plastics in Soil Grouting," (by T. S. Vinson and J. K. Mitchell), Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 98, No. SM6, Proc. Paper 8947, pp. 479-602, June, 1972.

"Preliminary Analysis of Soil Behavior," (by J. K. Mitchell, L. G. Bromwell, W. D. Carrier, III, N. C. Costes, W. N. Houston and R. F. Scott), Apollo 15 Preliminary Science Report, NASA SP-289, pp. 7-1 to 7-28, 1972.

"Preliminary Description of the Apollo 15 Lunar Samples," (by Lunar Sample Preliminary Examination Team), Apollo 15 Preliminary Science Report, NASA SP-289, pp. 6-1 to 6-25, 1972.

"Soil Mechanics," (by J. K. Mitchell, W. D. Carrier, III, W. N. Houston, R. F. Scott, L. G. Bromwell, H. T. Durgunoglu, H. J. Hovland, D. D. Treadwell, and N. C. Costes), Sec. 8 of Apollo 16 Preliminary Science Report, NASA SP-315, pp. 8-1 to 8-29, 1972.

"Soil Mechanical Properties of the Apollo 14 Site," (by J. K. Mitchell, L. G. Bromwell, W. D. Carrier, III, N. C. Costes, and R. F. Scott), Journal of Geophysical Research, Vol. 77, No. 29, pp. 5641-5664, October, 1972.

"Soil Property Determination by Impact Penetrometer," (by J. K. Mitchell and James B. Thompson), Paper presented at the Conference on Rapid Penetration of Terrestrial Meterials Held at Texas A & M University, February 1-3, 1972.

"Stratigraphy of the Apollo 15 Drill Core," (G. Heiken, M. Duke, R. Fryxell, J. S. Nagle, R. Scott, and G. A. Sellers), NASA TMX-58101, 1972.

"Strength and Compressibility of Returned Lunar Soil," (W. D. Carrier, III, L. G. Bromwell, and R. T. Martin), Proc. Third Lunar Science Conference, Vol. 3, pp. 3223-3234, MIT Press, 1972.
Also: "Lunar Science III, Revised Abstracts of Papers Presented at the Third Lunar Science Conference," (editor Carolyn Watkins), Lunar Science Institution Contribution No. 88, pp. 119-121, 1972.

"The Apollo 15 Lunar Samples: A Preliminary Description," Science, Vo.. 175, No. 4020, pp. 363-375, January, 1972.

"Variability of Lunar Surface Materials as Indicated by Boulder Tracks," (by H. J. Hovland, and J. K. Mitchell), Science, 1972, submitted for publication.

<u>1973</u>

"Apollo Drill Core Depth Relationships," (by W. D. Carrier, III) Submitted to The Moon, April, 1973.

"Behavior of Returned Lunar Soil in Vacuum," (by W. D. Carrier, III, L. G. Bromwell, and R. T. Martin), ASCE, JSFMD, Vol. 99, No. SM11, pp. 979-996, November, 1973.

"Boulder Tracks and Nature of Lunar Soil," (by H. J. Hovland, and J. K. Mitchell), The Moon, Vol. 6, pp. 164-175, 1973.

"Downslope Movement of Lunar Soil and Rock Caused by Meteoroid Impact," (by W. N. Houston, Y. Moriwaki, and C. S. Chang), Proc. Fourth Lunar Science Conference, 1973.

"Fabric-Mechanical Property Relationships in Fine Granular Soils," (by A. Mahmood). Thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at the University of California, Berkeley.

"In-Situ Strength by Static Cone Penetration Test," (by H. T. Durgunoglu and J. K. Mitchell), Proc. Eighth Int. Conf. on Soil Mech. and Found. Eng., Moscow, Aug. 1973.

"Lunar Soil Grain Size Distribution," (by W. David Carrier, III), The Moon, Vol. 6, No. 314 in press.

"Lunar Soil Properties and Soil Mechanics," (by J. K. Mitchell and W. N. Houston), Semiannual Status Report, NASA Grant NGR 05-003-706, Space Science Laboratory Series M, Issue 6, January, 1973.

"Lunar Surface Engineering Properties Experiment Definition," (by J. K. Mitchell, W. N. Houston, T.S. Vinson, T. Durgunglu, L. I. Namig, J. B. Thompson and D.D. Treadwell), Final Report: Volume I of IV - Mechanics, Properties and Stabilization of Lunar Soils, Contract No. NASB-21932, Space Sciences Laboratory, Series 11, Issue 48, July, 1971.

"Mechanics of Wheel-Soil Interaction," (by H. J. Hovland), Geotechnical Engineering Report, Space Sciences Laboratory Series 14, Issue 23, University of California, Berkeley, April, 1973.

"Preliminary stratigraphy of the regolith at the Apollo 15 site," (by G. H. Heiken, U. S. Clanton, D. S. McKay, M. B. Duke, R. Fryxell, G. A. Sellers, R. Scott and J. S. Nagle, Lunar Science IV (ed. J. W. Chamberlain and C. Watkins), Lunar Science Institute, Houston, Texas, 1973.

"Regional Variations in Physical and Mechanical Properties of Lunar Surface Regolith," (by N. C. Costes), Lunar Science IV, J. W. Chamberlain and C. Watkins, ed., pp. 159-161, Lunar Science Institute, January 1973.

"Soil Mechanics," (by W. D. Carrier, W. N. Houston, R. F. Scott, L. G. Bromwell, H. T. Durgunoglu, H. J. Hovland, D. D. Treadwell and N. C. Costes), Apollo 16 Preliminary Science Report, NASA, SP-315, Chapt. 8, pp. 8-1 - 8-29, 1973.

"Static Penetration Resistance of Soils," (by H. T. Durgunoglu and J. K. Mitchell), Report to NASA Headquarters under Grant NGR 05-003-406, Univ. of Calif., Space Sciences Report Series 14, Issue 24, 1973.

"Surface Soil Variability and Stratigraphy at the Apollo 16 Site," (by J. K. Mitchell, W.D. Carrier, III, N. C. Costes, W. N. Houston and R. F. Scott), Proceedings, Fourth Lunar Science Conference, 1973.

"The Apollo 16 Lunar Samples: Petrographic and Chemical Description," (by the Lunar Sample Preliminary Examination Team), Science, Vol. 179, No. 4068, Jan. 5, 1973, pp. 23-24.

"The Nature of Lunar Soil," (by W. David Carrier, III, James K. Mitchell, and Arshud Mahmood), ASCE, JSMFD, October 1973, 99 SM10, pp. 813-832.

"The Relative Density of Lunar Soil," (by W. David Carrier, III, J. K. Mitchell and A. Mahmood), Proceedings, Fourth Lunar Science Conference, 1973.

1974

Ph.D. Dissertation, Department of Civil Engineering, University of California, Treadwell 1974, in press.

"Soil Mechanics," (by J. K. Mitchell, W. D. Carrier, III, N. C. Costes, W. N. Houston, R. F.Scott and H. J. Hovland), Apollo 17 Preliminary Science Report, NASA SP-330, 1974.