Proceedings of the Third Lunar Science Conference
(Supplement 3, *Geochimica et Cosmochimica Acta*)
Vol. 3, pp. 3235–3253
The M.I.T. Press, 1972

Mechanical properties of lunar soil: Density, porosity, cohesion, and angle of internal friction

J. K. MITCHELL and W. N. HOUSTON
University of California,
Berkeley, California

R. F. SCOTT
California Institute of Technology,
Pasadena, California

N. C. COSTES
Marshall Space Flight Center,
Huntsville, Alabama

W. D. CARRIER, III
Manned Spacecraft Center,
Houston, Texas

and

L. G. BROMWELL
Massachusetts Institute of Technology,
Cambridge, Massachusetts

Abstract—The mechanical properties of lunar soils are remarkably similar to those of terrestrial soils of comparable gradation (silty fine sand), even though the two soil types are compositionally dissimilar. Particle size distribution, density, and particle shape control physical behavior.

A variety of data sources indicate that density and strength characteristics vary locally and with depth. Density may be low (1.0 g/cm^3) at the surface in some areas but may be as high as 2.0 g/cm^3 at depths of a few centimeters in others. Densities greater than 1.5 g/cm^3 are probable at depths of 10 to 20 cm.

For a given lunar soil, porosity appears to be the most important single variable controlling cohesion and friction angle. Most probable values of cohesion appear to be in the range of 0.1 to 1.0 kN/m^2. The most probable range of lunar soil friction angle is about 30° to 50° with the higher values associated with lower porosities. Data from the Soviet Lunokhod I show specific indication of an increase in strength parameters, and therefore also density, with depth. Other data indicate that soil on slopes is less dense and weaker than the soil covering level areas.

INTRODUCTION

THE PHYSICAL AND MECHANICAL PROPERTIES of lunar soil *in situ* have been under study since well before the first lunar landings because of their importance to the interpretation of lunar history and processes, their relevance to the analysis of data from several lunar surface, orbital, and terrestrially based experiments and observations, and because of the need for data to solve engineering and operational problems. Density, porosity, strength, compressibility, and stress-strain characteristics, and their variations both regionally and locally are of particular importance.

The current state of knowledge (through the Apollo 15 mission) of density (ρ), porosity (n), interparticle cohesion (c), and frictional resistance between grains (as reflected by angle of internal friction, ϕ) is reviewed in this paper. Emphasis is on the unconsolidated fine-grained lunar regolith, i.e., soils whose particles are predominantly smaller than 1 mm. Ranges in grain-size distribution for several soil samples returned from the four Apollo landing sites are shown in Fig. 1. With the exception of the curves for the coarse layer in the Apollo 12 double core tube and the coarse layer in the Apollo 14 trench, all samples define a band that is typical of well-graded terrestrial silty fine sands.

METHODS

Pre-Apollo studies

A number of early (pre-Surveyor) estimates of the physical properties of lunar soils are summarized by Mitchell and Smith (1969), and will not be reviewed here, except to note that density estimates centered on values less than 1 g/cm^3. Choate (1966) determined lunar slope angles from Ranger photographs. This information made possible estimation of some lower bound values for soil strength parameters. Jaffe (1964, 1965) estimated a lower bound bearing capacity based on stability analyses of crater walls photographed by Ranger.

A number of boulder tracks and their associated boulders were observed on slopes visible in lunar Orbiter high-resolution photographs. By using assumptions

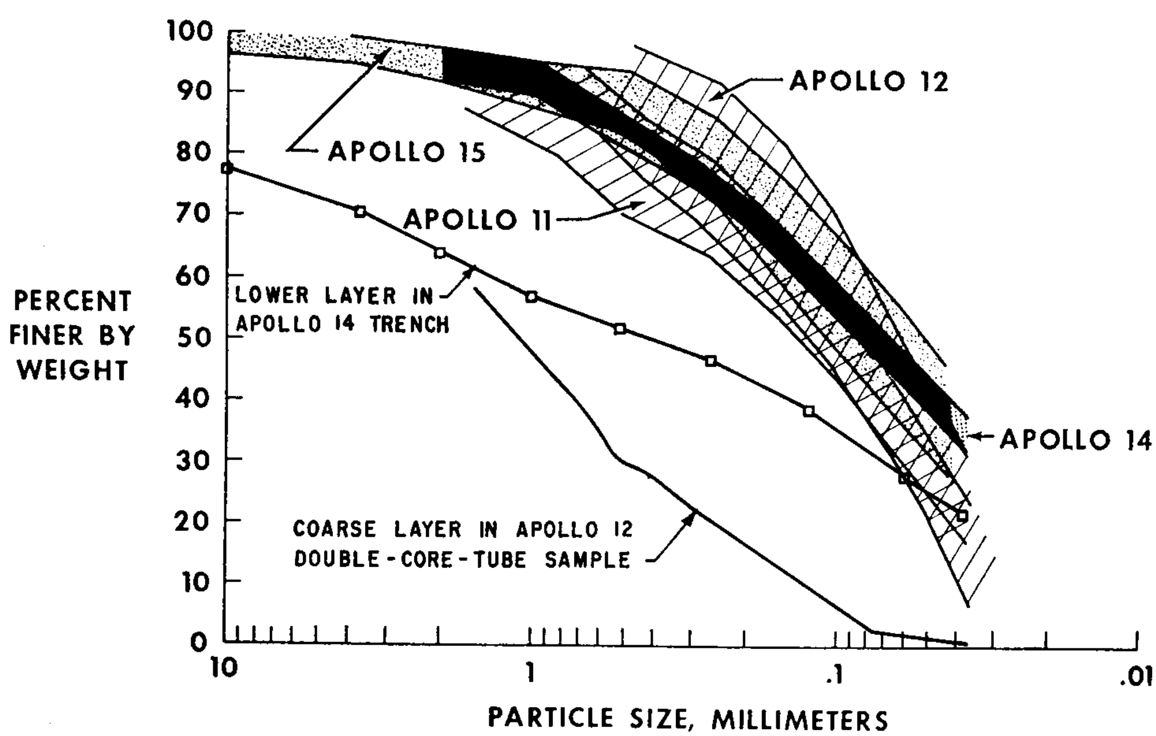

Fig. 1. Grain size distribution ranges, samples from different Apollo sites.

relative to boulder and soil density in conjunction with bearing capacity theory, estimates have been made (Moore, 1970; Hovland and Mitchell, 1971) of the strength characteristics of the soils over which the boulders rolled.

The results of the Surveyor program provided the first conclusive evidence that the lunar surface materials are predominantly fine grained and slightly cohesive and behave in a manner comparable to terrestrial soils of similar gradation. Semiquantitative and quantitative estimates of density, cohesion, and friction angle were made in several ways (Christensen *et al.*, 1967, 1968a, 1968b, 1968c; Scott and Roberson, 1967, 1968a, 1968b, 1969; Scott, 1968)

Simulants for study of lunar soil properties

The definitive information on the texture, particle size, and general behavior of lunar soil provided by the Surveyor results made possible the preparation of lunar soil simulants. Ground basalt has been most widely used, and it has been possible to duplicate closely the range of soil properties believed to exist on the moon (Costes *et al.*, 1969a, 1971; Green and Melzer, 1970; Mitchell *et al.*, 1969, 1971a).

Figure 2 shows the relationship between friction angle and porosity for a lunar soil simulant studied by Mitchell *et al.* (1971a), and Fig. 3 illustrates the variation of cohesion with porosity for the same soil.

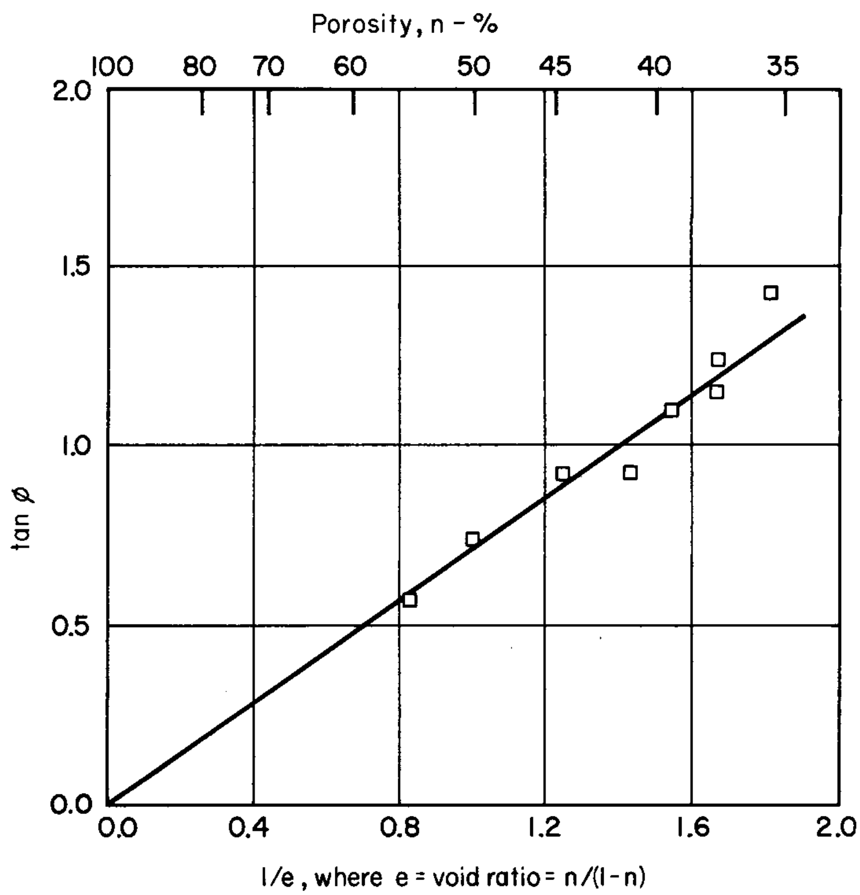

Fig. 2. Friction angle as a function of porosity for a lunar soil simulant (ground basalt).

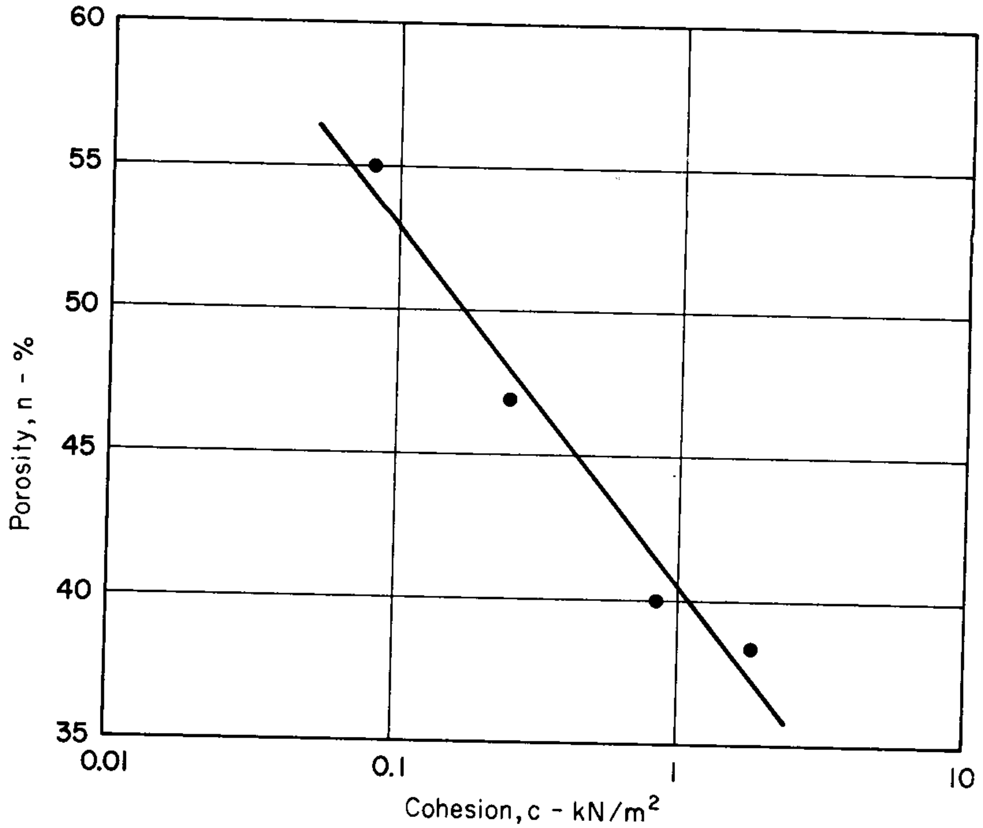

Fig. 3. Cohesion as a function of porosity for a lunar soil simulant (ground basalt).

The application of mechanics analyses

It has been possible to estimate the friction angle and cohesion for soil on the moon using mechanics analyses (usually developed from plasticity theory) of observed interactions; e.g., penetrometers, footprints, boulder and vehicle tracks. With the friction angle and cohesion known, it is then possible to estimate porosity. Conversion of porosity to the *in situ* density on the moon requires a knowledge of the average specific gravity of the soil particles. Only two determinations of specific gravity have been made to the authors' knowledge—on single samples of Apollo 11 and 15 soil. In each case a value of 3.1 was obtained. Other evidence suggests that this value may not be generally applicable and that lower values may hold in many cases.

Core tube samples

Core tube samples returned by each of the Apollo missions and by Luna 16 provide data on soil density. Because of disturbance during sampling, earth return, and handling, the core sample density may differ significantly from the actual *in situ* density (Carrier *et al.*, 1971; Houston and Mitchell, 1971). The larger diameter and reduced wall thickness used for the Apollo 15 core tubes resulted in the acquisition of much less disturbed samples than in previous missions, and the densities of these samples can be considered much more representative of *in situ* values than directly measured densities from core tube samples obtained previously. One drill core sample was returned by the Soviet Luna 16 (Vinogradov, 1971).

Soil mechanics trench

A shallow trench experiment was carried out as part of the Apollo 14 and 15 lunar surface activities for the purposes of observing soil profiles and determining the soil cohesion. Analysis of the failure conditions yields information on the strength parameters, c and ϕ. Two important features of the trench experiment are that the computed cohesion is not a sensitive function of the friction angle, and the calculation is virtually independent of the value used for soil density.

Penetrometer measurements

A self-recording penetrometer was used for the first time during Apollo 15. This device can penetrate to a maximum depth of 76 cm, and could measure penetration force to a maximum of 111 N. The record of each penetration was scribed on a recording drum which was returned to earth for analysis. Two penetration records obtained in the vicinity of the Apollo 15 ALSEP site (Station 8) are shown in Fig. 4. These

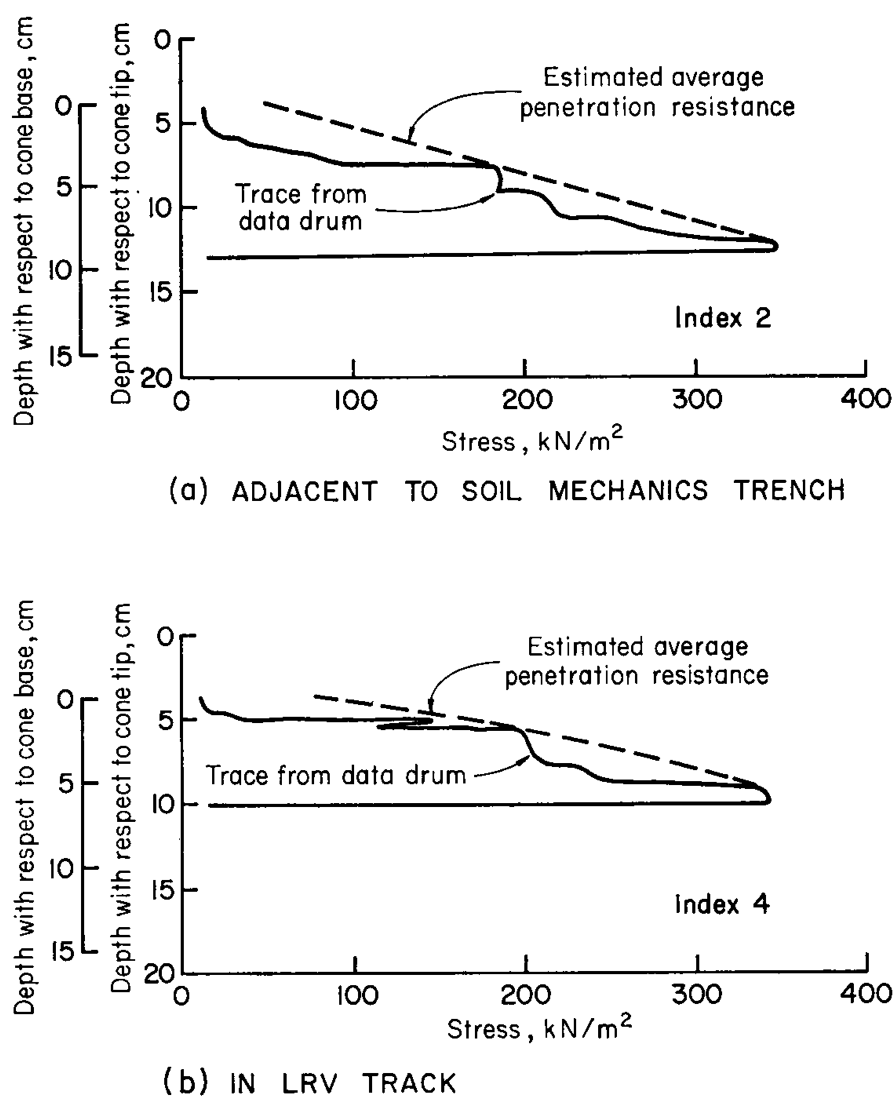

Fig. 4. Stress versus penetration records, Apollo 15.

data were used in conjunction with the trench data to determine porosity, cohesion and friction angle from direct comparison of behavior with that of terrestrial simulants and from theoretical analyses.

Soviet measurements by Lunokhod I

The most systematic and extensive set of quantitative measurement of surface soil mechanical properties to date has been obtained by the Soviet rover, Lunokhod I, delivered to the western part of Mare Imbrium by Luna 17. A cone penetrometer device, configured with vanes, as shown in the upper right of Fig. 5, was used for a total of 327 measurements along a 5224 m traverse (Leonovich *et al.*, 1971). This device could penetrate to a maximum depth of 10 cm and could be twisted in the ground causing the soil to fail in the manner of a conventional vane shear test. Four penetration curves representing different surface conditions are shown in Fig. 5.

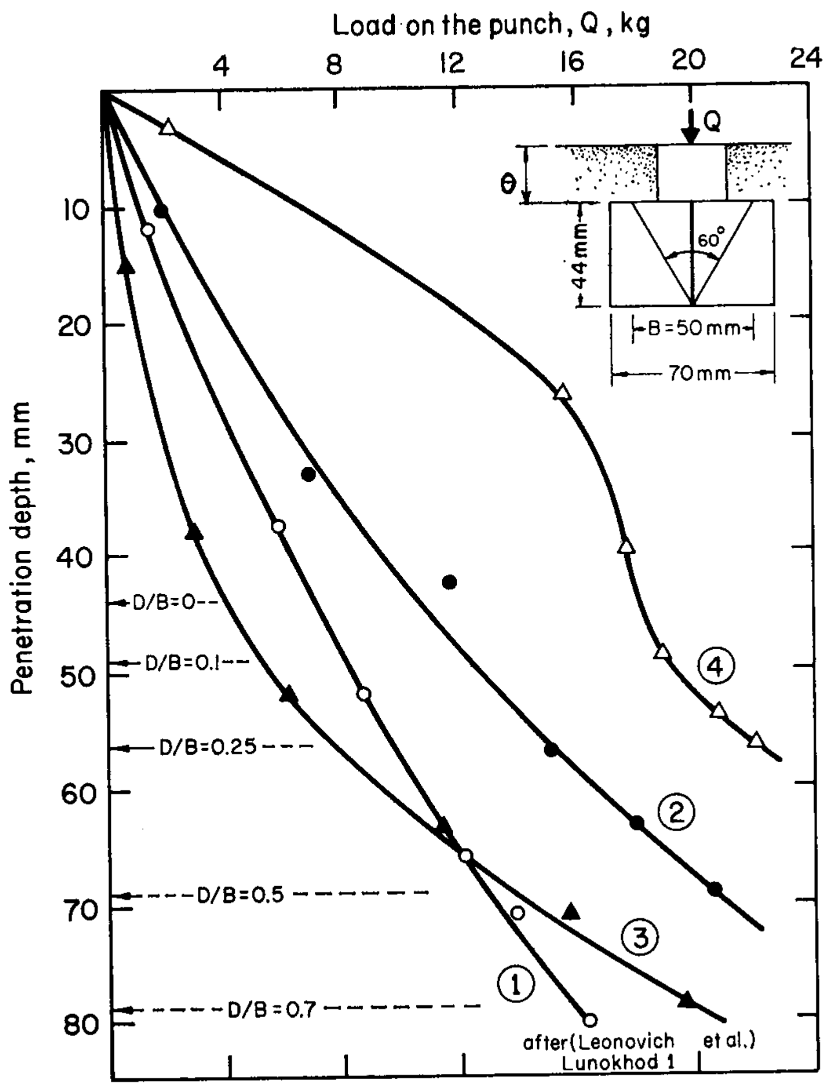

Fig. 5. Penetration data obtained by Lunokhod 1 for four conditions in the western part of Mare Imbrium (data from Leonovich *et al.*, 1971). 1—Level intercrater region; 2—Crater slope; 3—Crater wall; 4—Sector covered by small rocks.

Tests on returned samples

Limited testing of the mechanical properties of the less than 1 mm fraction of the Apollo 11 bulk soil sample was done (Costes *et al.*, 1970), and three direct shear tests on a 200 g sample from Apollo 12 that had not been exposed to a pressure above 2×10^{-6} Torr were conducted by Carrier *et al.* (1972).

DENSITY AND POROSITY

Background

Table 1 summarizes some of the density estimates that have been made since early in the lunar exploration program.

A density of 0.3 g/cm^3 (corresponding to a porosity of 90%) was assumed by Jaffe (1964, 1965) in an effort to calculate lower bound bearing capacities. Halajian (1964) also assumed a very low density, 0.4 g/cm^3, but believed that the strength of the lunar surface was similar to that of pumice. The grain size distribution and the lunar soil-footpad interaction observed on Surveyor I suggested a value of 1.5 g/cm^3 (Christensen *et al.*, 1967). The Russian probe, Luna 13, provided the first in-place (December 1966) measurement of soil density on the moon by means of a gamma-ray device. The calibration curve for this device was double-valued, and it was necessary to choose between a value of 0.8 and 2.1 g/cm^3. Cherkasov *et al.* (1968) chose the lesser value. Based on the results from the soil mechanics surface sampler experiments on Surveyors III and VII, Scott and Roberson (1967, 1968) confirmed the Surveyor I value of 1.5 g/cm^3 and argued (Scott, 1968) that the Russian investigators had chosen the wrong portion of their calibration curve.

The drive tube data from Apollo 11 were also ambiguous because of the shape of the bit. The bulk densities of the soil in the two core tubes were 1.59 and 1.71 g/cm^3 (Costes *et al.*, 1969b), or 1.54 g/cm^3 and 1.75 g/cm^3 as later reported by Costes and

Table 1. Estimates of lunar soil density.

Bulk density ρ (g/cm^3)	Investigator	Mission
0.3	Jaffe (1964, 1965)	
0.4	Halajian (1964)	
1.5	Christensen *et al.* (1967)	Surveyor I
0.8	Cherkasov *et al.* (1968)	Luna 13
1.5	Scott and Roberson (1967, 1968) and Scott (1968)	Surveyor III & VII
1.54 to 1.75	Costes and Mitchell (1970)	Apollo 11
0.74 to > 1.75	Scott *et al.* (1971)	Apollo 11
1.81 to 1.92*	Costes *et al.* (1971)	Apollo 11
1.6 to 2.0	Scott *et al.* (1971)	Apollo 11
1.80 to 1.84*	Costes *et al.* (1971)	Apollo 12
1.55 to 1.90	Houston and Mitchell (1971)	Apollo 12
1.7 to 1.9	Carrier *et al.* (1971)	Apollo 12
1.2	Vinogradov (1971)	Luna 16
1.5 to 1.7	Leonovich *et al.* (1971)	Lunokhod I
1.45 to 1.6	Carrier *et al.* (1972)	Apollo 14
1.35 to 2.15	Mitchell *et al.* (1972)	Apollo 15

*Upper bound estimates.

Mitchell (1970) taking into account possible differences in core tube diameter. These densities could have indicated an *in situ* density anywhere from 0.75 g/cm^3 to more than 1.75 g/cm^3 (Scott *et al.*, 1971).

The shape of the Apollo 12 drive tube bits reduced the uncertainty, and the density at this site was estimated to be 1.6 to 2 g/cm^3 (Scott *et al.*, 1971). Core tube simulations performed later by Houston and Mitchell (1971) and Carrier *et al.* (1971), yielded additional estimates of 1.55 to 1.9 g/cm^3 and 1.7 to 1.9 g/cm^3, respectively. Based on penetration resistance data from the Apollo 11 and 12 landing sites, Costes *et al.* (1971) gave upper bound estimates of the density at the two sites of 1.81 to 1.94 g/cm^3 and 1.81 to 1.84 g/cm^3, respectively. Carrier *et al.* (1972) have determined *in situ* densities of 1.45 to 1.6 g/cm^3 for the Apollo 14 core tube samples. Vinogradov (1971) estimated a value of 1.2 g/cm^3 from a rotary drill sample returned by Luna 16. By comparison of Lunokhod data with the results of studies of the Luna 16 sample, Leonovich *et al.* (1971) estimated densities in the range of 1.5 to 1.7 g/cm^3 for the areas traversed by Lunokhod.

Density of the lunar soil at the Apollo 15 site

A preliminary estimate has been made of density versus depth at the three Apollo 15 core tube locations, as shown in Fig. 6. The top 25 to 35 cm of soil along the

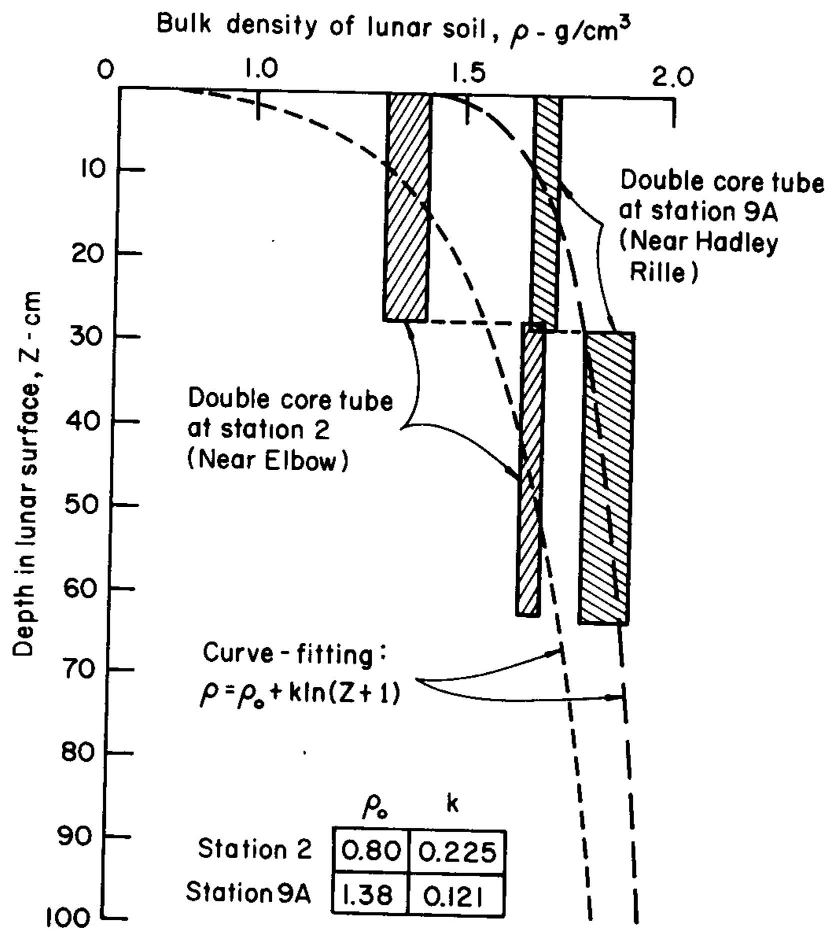

Fig. 6. Density of lunar soil at Apollo 15 core tube sites.

Apennine Front (Stations 2 and 6) have very similar, low average values, 1.35 g/cm^3, so only the data for Station 2 are shown. The soil density evidently increases fairly rapidly with depth. The soil density at the Front is approximately 10% less than observed at any previous Surveyor or Apollo site and approaches that of the Luna 16 site (1.2 g/cm^3). The average soil density at the edge of Hadley Rille (Station 9A) is significantly higher in the top 30 cm (1.69 g/cm^3) and increases less rapidly with depth than at Station 2.

If the density of the lunar soil is assumed to increase with depth primarily because of self-weight, a monotonic curve may be fitted to the data for the two double-core tubes, as shown in Fig. 6. The surface density at the Front would then be 0.80 g/cm^3; the surface density at the Rille is 1.38 g/cm^3, or more than 70% greater. At a depth of 2.8 m, the density at both locations would be 2.07 g/cm^3.

The fact that the density of the soil on the slopes of the Apennine Front is much less than that in the mare area suggests that the soil on the slopes is considerably weaker, although quantitative comparisons are not available. If it can be shown that the soil covering slopes is generally much weaker, then development of reasonable hypotheses for downslope movement of material will be greatly facilitated.

The *in situ* density at the soil mechanics trench (Station 8, near the ALSEP site) has been estimated to be in the range of 1.92 to 2.01 g/cm^3 based on penetration test results. A density range of 1.62 to 1.93 g/cm^3 has been estimated (Carrier *et al.*, 1972) for the samples in the deep drill stem obtained from the same area. Average density of these samples is of the order of 1.8 g/cm^2.

Cohesion and Friction

Introduction

Most estimates of lunar soil cohesion and friction angles have been based on the results of analyses of soil failure conditions, e.g., under rolling boulders, by penetration, and by failure of a trench wall. Both soil cohesion (c) and internal friction (ϕ) are important in resisting the applied loads, since soil shear strength (s) is given by

$$s = c + \sigma \tan \phi, \tag{1}$$

where σ is the stress normal to the failure plane. Thus, in many cases it is impractical to discuss the magnitude and variation of one parameter independently of the other. A number of estimates of lunar soil cohesion and friction angle developed from data available prior to the Apollo and Lunokhod missions is summarized in Table 2.

Regional variability as indicated by boulder track records

A large range of friction angle and cohesion values is indicated by the data in Table 2. Because of the assumptions and uncertainties associated with most of the analyses, it is difficult to establish whether or not such variations really exist on the lunar surface.

Some light is shed on this question by the results of boulder track analyses reported by Hovland and Mitchell (1971). In this study 69 boulder tracks from 19 different

Table 2. 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 (1968)
(5) Surveyor III, landing data	0 for 10 for	45–60 0	Christensen *et al.* (1968c)
(6) Surveyor VI, vernier engine firing	> 0.07 for	35	Christensen *et al.* (1968a)
(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.

locations were selected from Lunar Orbiter high resolution photography. These tracks were formed on slopes estimated to range from 0° to 30°. Analyses for friction angle values were made using bearing capacity theory for footings on slopes (Meyerhof, 1951) modified for application to the boulder track formation mechanisms (Hovland and Mitchell, 1971). The range in values of friction angle computed in this study is shown in Table 2, together with the value of cohesion assumed for the analyses. These friction angles were converted to porosity by Houston *et al.* (1972) and analyzed statistically. A mean porosity of about 44% was obtained with a standard deviation of 6.6%. Additional evidence of variability in lunar soil properties was obtained from analyses of astronaut footprint depth (Houston *et al.*, 1972).

Cohesion and friction angle values from Apollo 11, 12, and 14 data

During the first three Apollo landings, no force or deformation measuring devices were utilized to determine directly the in place mechanical properties of the lunar soil. Consequently, inferences on these properties were made from (a) observed soil deformations resulting from the interaction of the soil with objects of known geometry and weight; (b) assumptions on the ranges of loads applied by the astronauts in pushing the Apollo simple penetrometer (Apollo 14 mission), core tubes or other shafts and poles into the soil; (c) slope stability analyses applied to natural crater slopes, incipient slope failures of soft-rimmed craters due to loads imposed by walking astronauts, and to the collapse of the soil mechanics trench during the Apollo 14 mission; (d) LM landing dynamics and soil erosion caused by the LM engine exhaust; (e) penetration tests on loose and densely compacted Apollo 11 soil bulk sample; and (f) studies on simulated lunar soils. Values of c and ϕ obtained on the basis of these analyses are listed in Table 3.

Table 3. Estimates of lunar soil cohesion and friction angle based on Apollo 11, Apollo 12, and Apollo 14 data.

Mission	Basis	Cohesion c (kN/m^2)	Friction angle ϕ (deg)	Reference
Apollo 11	Astronaut footprints, LM landing data, crater slope stability	Consistent with lunar soil model from Surveyor data		Costes *et al.* (1969)
Apollo 11	Penetrometer tests in LRL on bulk soil sample	0.3–1.4	35–45	Costes *et al.* (1970)
Apollo 11	Penetration of core tubes, flagpole, SWC shaft	0.8–2.1	37–45	Costes *et al.* (1971)
Apollo 12	Astronaut footprints, LM landing data, crater slope stability	Consistent with lunar soil model from Surveyor data		Scott *et al.* (1970)
Apollo 12	Penetration of core tubes, flagpole, SWC shaft	0.6–0.8	38–44	Costes *et al.* (1971)
Apollo 14	Soil mechanics trench	<0.03–0.3	35–45	Mitchell *et al.* (1971b)
Apollo 14	Apollo simple penetrometer	Soil shear strength equal to or greater than that of soil model from Surveyor data		Mitchell *et al.* (1971b)
Apollo 14	MET tracks		37–47	Mitchell *et al.* (1971b)

Variability of lunar soil properties within the Fra Mauro landing site from MET track analysis

Analysis of tracks left by the Modular Equipment Transporter (MET) at various points of the geological traverses during the Apollo 14 mission yielded information on the variability of lunar soil properties near the surface on a landing site scale (maximum distance from the LM was about 1450 m).

Tracks left by the MET were analyzed using a dimensional analysis relating to the interaction of pneumatic tires with granular, primarily cohesionless soils, results of studies on lunar soil simulants under terrestrial and lunar gravity levels (Green and Melzer, 1970; Costes *et al.*, 1971), and bearing capacity theory as applied to cone penetrometers. Details of this analysis are given by Mitchell *et al.* (1971b).

The results showed that soil located in intercrater areas on firm level ground was weaker than soil located in soft pockets and on fresh crater rims and slopes. No appreciable differences in lunar soil properties between regions of different geologic age were discernible, however, on the basis of the computed values.

Cohesion and friction angle values at the Hadley-Apennine landing site

The Apollo 15 mission provided the first U.S. opportunity for definitive evaluation of cohesion and friction at a given location. The results of simulation studies, drill stem examination, the soil mechanics trench analysis, and measurements using the self-recording penetrometer have been used *collectively* to determine properties at Station 8 (ALSEP site).

Using the penetration test data in Fig. 4 in conjunction with the results of simulation studies (Houston and Namiq, 1971; Costes *et al.*, 1971; Green and Melzer, 1970), the ranges in, and best estimates of, porosity, density, and friction angle for the near surface soil in a level intercrater region near the Apollo 15 ALSEP site have been estimated as indicated in Table 4. It may be noted that these values of density and friction angle are near the high end of the ranges associated with previous estimates. The firmness of the soil at this location as indicated by its resistance to drilling during installation of the heat flow experiment is consistent with this result.

Soil mechanics analysis of the trench wall failure and the measured values of penetration resistance (Mitchell *et al.*, 1972; Durgunoglu, 1972) give values of cohesion and friction angle which are consistent with the values obtained by comparison of observed behavior with simulants. The dashed line in Fig. 7 shows the values of cohesion and friction angle which satisfy equilibrium equations at incipient failure of the

Table 4. Soil characteristics at Station 8 (near the ALSEP site), Apollo 15 mission.

	Porosity n (%)	Void ratio e	Density* ρ (g/cm^3)	Friction angle ϕ
Range	35–38	0.54–0.61	1.92–2.01	47.5–51.5
Best estimate	36.5	0.58	1.97	49.5

* Assumes average specific gravity of soil grains to be 3.1.

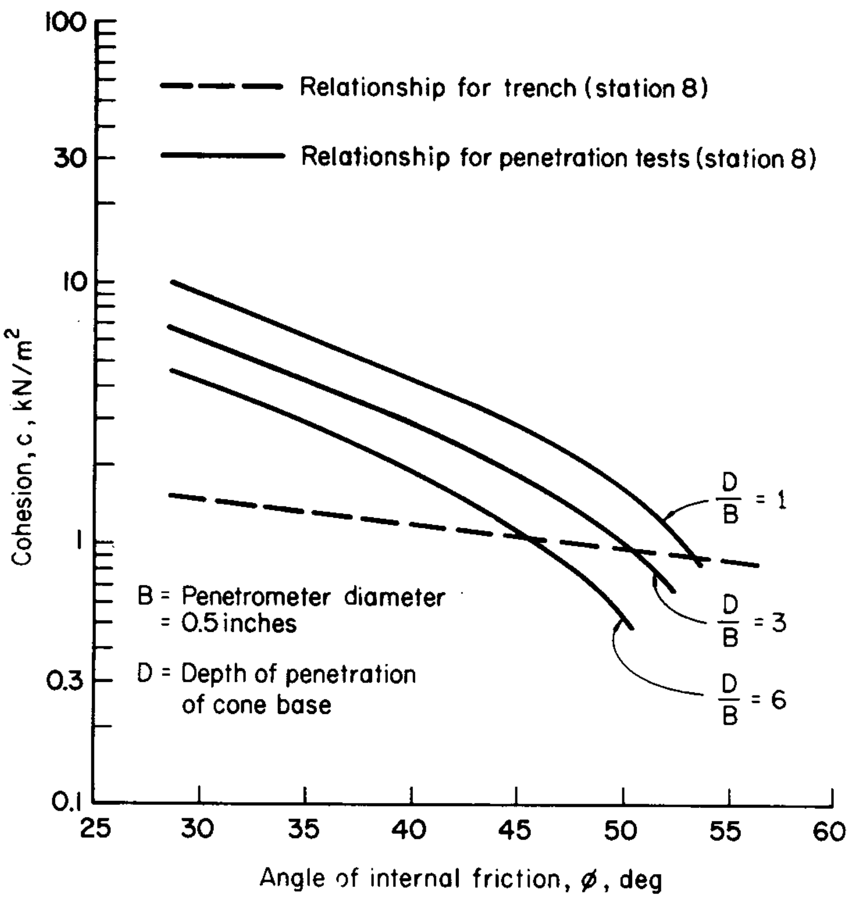

Fig. 7. Values of cohesion and friction angle at incipient failure of the soil mechanic trench wall and for a 25-pound force applied to the self-recording penetrometer at different penetration depths, Apollo 15 ALSEP site.

trench wall. Also shown in Fig. 7 (solid curves) are values of cohesion and friction angle which correspond to loading of the 0.5 sq in. cone penetrometer to its maximum recordable capacity (25 pounds) and three penetration depths.

The depth-to-cone base diameter (D/B) ratio for tests at Station 8 fell in the range of about 2.5 to 4.1. Thus the curve in Fig. 7 for $D/B = 3$ is appropriate. The interaction of this curve with that for the trench wall failure gives conditions that satisfy both the trench and penetration test simultaneously. All the data taken collectively are quite consistent and indicate values of properties that can be summarized as follows for the soil at the soil mechanics trench in the Hadley-Apennine landing area:

Porosity	36.5%
Void ratio	0.58
Density	2 g/cm^3 or slightly less (for a specific gravity = 3.1)
Cohesion	1 kN/m^2
Angle of internal friction	50°

This value of angle of internal friction may be compared with that to be expected for a terrestrial soil of similar characteristics. Koerner (1970) has proposed relationships for angle of internal friction in terms of particle shape, particle size, gradation, relative density, and mineral type. When applied to the lunar soil *in situ* at Station 8, these relationships give an estimated friction angle of 50° to 52°. This compares well with the value of 50° deduced from simulation studies and theoretical analyses.

Analysis of Lunokhod I data

It was indicated earlier in this paper that the Soviet rover, Lunokhod I, was equipped with a cone penetrometer and vane shear test device and that a large number (327) of measurements to depths up to 10 cm had been made along a traverse exceeding 5 km in length in the western part of Mare Imbrium. An analysis of some of the data reported by Leonovich *et al.* (1971) has been made which provides quantitative indication of soil property variations between different areas and with depth.

In the analysis of vane shear test results the usual assumptions are that the soil fails as a cylinder defined by the vane dimensions (see upper right of Fig. 5) when it rotates and that the resistance to the torque applied to the vane is provided by soil cohesion; i.e., a $\phi = 0$ soil is assumed. This approach appears to have been used by Leonovich *et al.* (1971), who report values of "torque resistance" in the range of 2–9 kN/m^2, with a greatest frequency of 4.5 kN/m^2. These values are of a magnitude several times greater than have been estimated previously for lunar soil cohesion. The Lunokhod data have been reanalyzed using an expression derived by Farrent (1960) for vane shear tests in soils exhibiting both cohesive and frictional resistance.

Values of c and ϕ corresponding to the maximum and minimum measured torque are shown by the upper and lower curves in Fig. 8, and the middle curve corresponds to the highest frequency torque resistance.* It may be seen that for friction angles in the probable range of 35° to 50° the corresponding values of cohesion are well within

* Since both c and ϕ are unknown, they cannot be determined uniquely by Farrent's (1960) equation.

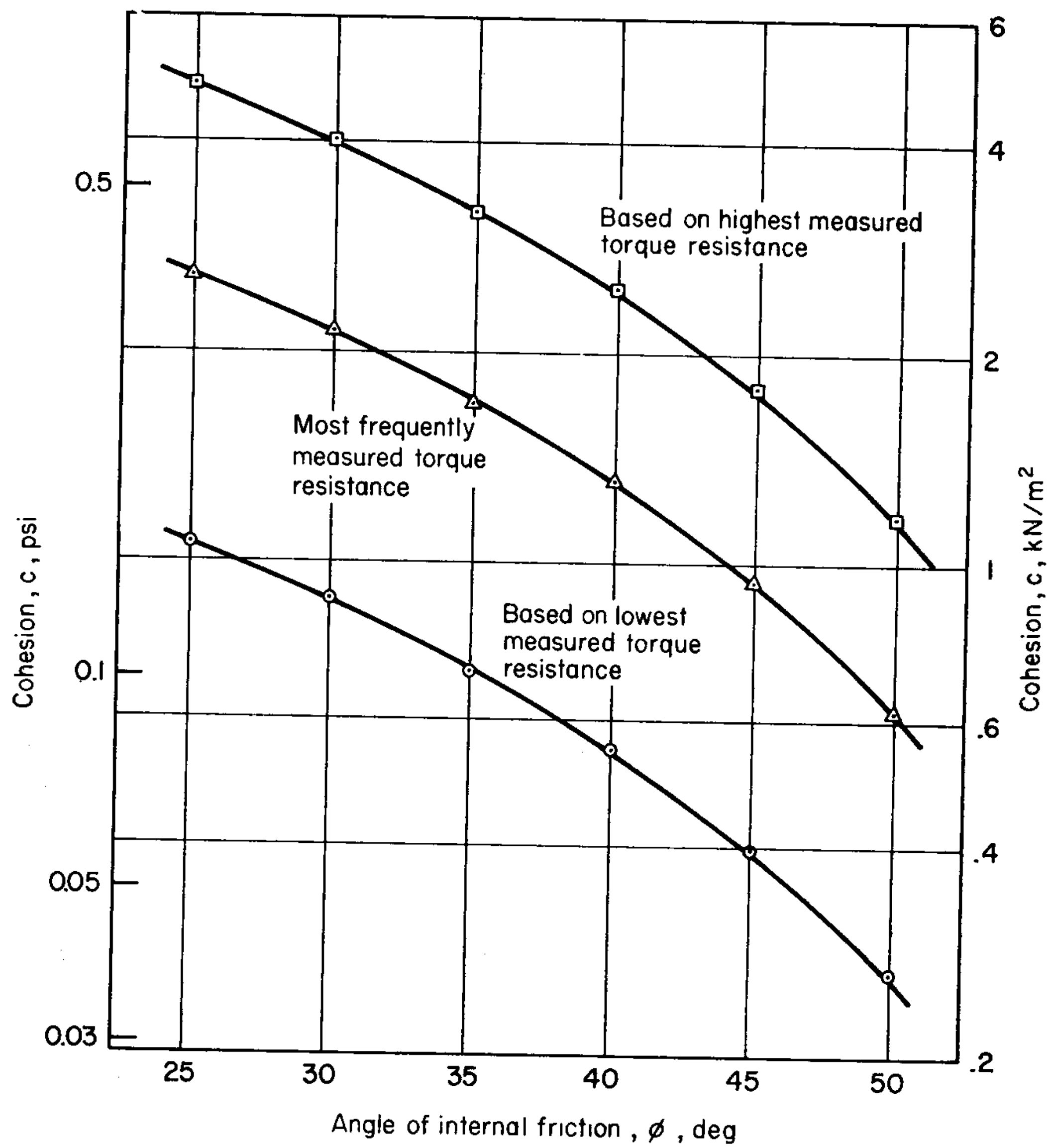

Fig. 8. Range of cohesion and friction angle values obtained from Lunokhod vane shear test data (data from Leonovich *et al.*, 1971).

the range established by previous studies. For an assumed ϕ of 50° one would anticipate a high density and high torque resistance which, according to Fig. 8 would indicate a cohesion of about 1 kN/m^2, as was the case also at the Apollo 15 ALSEP site.

An analysis of the penetration data shown in Fig. 5 has been made using the method developed by Durgunoglu (1972). According to classical plasticity theory, unit penetration resistance q is given by

$$q = cN_c\xi_c + B\rho g N_{\gamma q}\xi_{\gamma q}, \tag{2}$$

where c = cohesion; ρ = soil density; g = acceleration due to gravity; B = cone base diameter = 50 mm; N_c, $N_{\gamma q}$ = bearing capacity factors = $f(\phi, \alpha, \delta/\phi, D/B)$; ξ_c, $\xi_{\gamma q}$ = shape factors; ϕ = soil friction angle; δ = soil to cone friction angle; $\alpha = \frac{1}{2}$ cone apex angle; D = penetration depth (cone base). For the present analysis

$\alpha = 30°$ and δ/ϕ was assumed as 0.5. The computed results are insensitive to soil density, and it was assumed to be 1.7 g/cm^3.

From a histogram of "carrying capacity" (i.e., q for $D/B = 0$) values, upper and lower bounds, as well as the most frequently measured values, were taken, and corresponding values of c and ϕ were computed. The penetrometer and vane shear device gave comparable results.

It is important to note in connection with plots of the type shown in Figs. 7 and 8 that increases in friction angle do not, in general, imply decreases in soil cohesion. The curves simply indicate corresponding values of c and ϕ that could account for the measured values of strength or penetration resistance. For a given soil—and in the absence of significant cementation between particles, for which there is no evidence thus far—variations in c and ϕ are closely related to variations in density. As density increases both c and ϕ tend to increase.

Combinations of c and ϕ corresponding to the penetration resistance at several depths according to Curve 1 of Fig. 5 (level intercrater region) were computed. The results showed clearly that strength, and probably also density, increase significantly with depth. Similar results were obtained from analysis of Fig. 5, Curve 2 for penetration into a crater slope and Curve 3 for penetration into a crater wall. The results for the crater wall show a particularly marked increase in strength with depth.

Curves corresponding to $D/B = 0$ for the level ground, crater slope, and crater wall are compared in Fig. 9. Unfortunately, Leonovich *et al.* (1971) do not describe the nature or size of the crater in which the curves shown in Fig. 5 were obtained. Because of trafficability considerations, however, it is not likely that the crater was sharp, blocky, or deep. The curves in Fig. 9 would appear compatible with a subdued shallow crater where soil on the inside had a long history of downslope movement and could be expected to be in a relatively loose and weak condition.

Conclusions

The fine-grained soil that blankets the lunar surface has a grain size distribution that corresponds to terrestrial silty fine sands, although coarser material may be found locally. Available evidence from a variety of sources—photographs, simulation studies, core tube samples, trenching experiments, and penetrometer measurements—indicate that the mechanical properties of the soil are remarkably similar to those of terrestrial soils of comparable gradation, even though the two types of soil are compositionally dissimilar. This is a direct reflection of the fact that for soils in this particle size range, density and particle size and shape distribution exert a larger influence on mechanical properties than does composition.

Lunar soils do differ from terrestrial soils, however, in that the lunar materials are somewhat more cohesive. Whether this is due to compositional or environmental differences is not yet known.

The density may be less than 1 g/cm^3 at the surface in some areas and as high as 2 g/cm^3 at very shallow (a few centimeters) depth in others. There is strong evidence that density and strength increase with depth, rapidly in the case of low surface densities, and gradually in the case of high surface densities. Densities greater than 1.5 g/cm^3 are probable below depths of 10 to 20 cm.

the ranges in, and best estimates of, porosity, density, and friction angle for the near surface soil in a level intercrater region near the Apollo 15 ALSEP site have been estimated as indicated in Table 4. It may be noted that these values of density and friction angle are near the high end of the ranges associated with previous estimates. The firmness of the soil at this location as indicated by its resistance to drilling during installation of the heat flow experiment is consistent with this result.

Soil mechanics analysis of the trench wall failure and the measured values of penetration resistance (Mitchell *et al.*, 1972; Durgunoglu, 1972) give values of cohesion and friction angle which are consistent with the values obtained by comparison of observed behavior with simulants. The dashed line in Fig. 7 shows the values of cohesion and friction angle which satisfy equilibrium equations at incipient failure of the

Table 4. Soil characteristics at Station 8 (near the ALSEP site), Apollo 15 mission.

	Porosity n (%)	Void ratio e	Density* ρ (g/cm^3)	Friction angle ϕ
Range	35–38	0.54–0.61	1.92–2.01	47.5–51.5
Best estimate	36.5	0.58	1.97	49.5

* Assumes average specific gravity of soil grains to be 3.1.

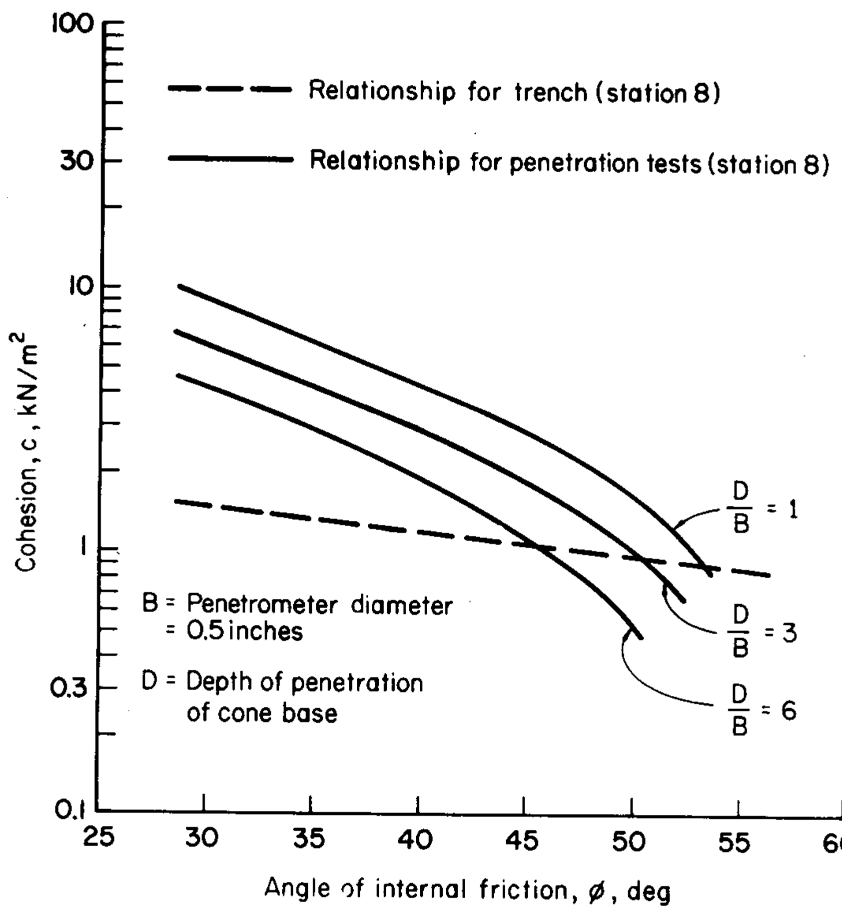

Fig. 7. Values of cohesion and friction angle at incipient failure of the soil mechanic trench wall and for a 25-pound force applied to the self-recording penetrometer at different penetration depths, Apollo 15 ALSEP site.

trench wall. Also shown in Fig. 7 (solid curves) are values of cohesion and friction angle which correspond to loading of the 0.5 sq in. cone penetrometer to its maximum recordable capacity (25 pounds) and three penetration depths.

The depth-to-cone base diameter (D/B) ratio for tests at Station 8 fell in the range of about 2.5 to 4.1. Thus the curve in Fig. 7 for $D/B = 3$ is appropriate. The interaction of this curve with that for the trench wall failure gives conditions that satisfy both the trench and penetration test simultaneously. All the data taken collectively are quite consistent and indicate values of properties that can be summarized as follows for the soil at the soil mechanics trench in the Hadley-Apennine landing area:

Porosity	36.5%
Void ratio	0.58
Density	2 g/cm^3 or slightly less (for a specific gravity = 3.1)
Cohesion	1 kN/m^2
Angle of internal friction	50°

This value of angle of internal friction may be compared with that to be expected for a terrestrial soil of similar characteristics. Koerner (1970) has proposed relationships for angle of internal friction in terms of particle shape, particle size, gradation, relative density, and mineral type. When applied to the lunar soil *in situ* at Station 8, these relationships give an estimated friction angle of 50° to 52°. This compares well with the value of 50° deduced from simulation studies and theoretical analyses.

Analysis of Lunokhod I data

It was indicated earlier in this paper that the Soviet rover, Lunokhod I, was equipped with a cone penetrometer and vane shear test device and that a large number (327) of measurements to depths up to 10 cm had been made along a traverse exceeding 5 km in length in the western part of Mare Imbrium. An analysis of some of the data reported by Leonovich *et al.* (1971) has been made which provides quantitative indication of soil property variations between different areas and with depth.

In the analysis of vane shear test results the usual assumptions are that the soil fails as a cylinder defined by the vane dimensions (see upper right of Fig. 5) when it rotates and that the resistance to the torque applied to the vane is provided by soil cohesion; i.e., a $\phi = 0$ soil is assumed. This approach appears to have been used by Leonovich *et al.* (1971), who report values of "torque resistance" in the range of 2–9 kN/m^2, with a greatest frequency of 4.5 kN/m^2. These values are of a magnitude several times greater than have been estimated previously for lunar soil cohesion. The Lunokhod data have been reanalyzed using an expression derived by Farrent (1960) for vane shear tests in soils exhibiting both cohesive and frictional resistance.

Values of c and ϕ corresponding to the maximum and minimum measured torque are shown by the upper and lower curves in Fig. 8, and the middle curve corresponds to the highest frequency torque resistance.* It may be seen that for friction angles in the probable range of 35° to 50° the corresponding values of cohesion are well within

* Since both c and ϕ are unknown, they cannot be determined uniquely by Farrent's (1960) equation.

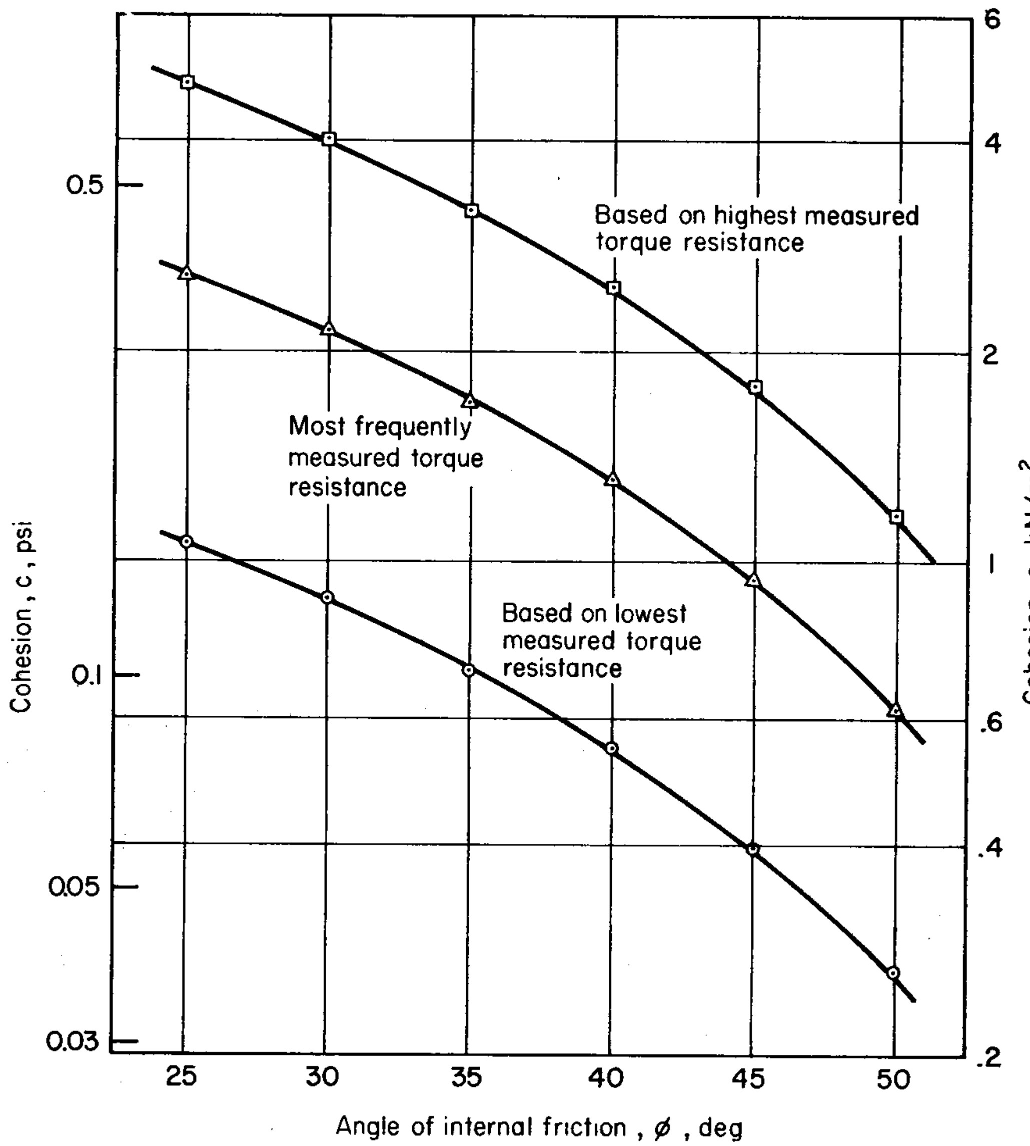

Fig. 8. Range of cohesion and friction angle values obtained from Lunokhod vane shear test data (data from Leonovich *et al.*, 1971).

the range established by previous studies. For an assumed ϕ of 50° one would anticipate a high density and high torque resistance which, according to Fig. 8 would indicate a cohesion of about 1 kN/m^2, as was the case also at the Apollo 15 ALSEP site.

An analysis of the penetration data shown in Fig. 5 has been made using the method developed by Durgunoglu (1972). According to classical plasticity theory, unit penetration resistance q is given by

$$q = cN_c\xi_c + B\rho g N_{\gamma q}\xi_{\gamma q}, \tag{2}$$

where c = cohesion; ρ = soil density; g = acceleration due to gravity; B = cone base diameter = 50 mm; N_c, $N_{\gamma q}$ = bearing capacity factors = $f(\phi, \alpha, \delta/\phi, D/B)$; ξ_c, $\xi_{\gamma q}$ = shape factors; ϕ = soil friction angle; δ = soil to cone friction angle; $\alpha = \frac{1}{2}$ cone apex angle; D = penetration depth (cone base). For the present analysis

$\alpha = 30°$ and δ/ϕ was assumed as 0.5. The computed results are insensitive to soil density, and it was assumed to be 1.7 g/cm^3.

From a histogram of "carrying capacity" (i.e., q for $D/B = 0$) values, upper and lower bounds, as well as the most frequently measured values, were taken, and corresponding values of c and ϕ were computed. The penetrometer and vane shear device gave comparable results.

It is important to note in connection with plots of the type shown in Figs. 7 and 8 that increases in friction angle do not, in general, imply decreases in soil cohesion. The curves simply indicate corresponding values of c and ϕ that could account for the measured values of strength or penetration resistance. For a given soil—and in the absence of significant cementation between particles, for which there is no evidence thus far—variations in c and ϕ are closely related to variations in density. As density increases both c and ϕ tend to increase.

Combinations of c and ϕ corresponding to the penetration resistance at several depths according to Curve 1 of Fig. 5 (level intercrater region) were computed. The results showed clearly that strength, and probably also density, increase significantly with depth. Similar results were obtained from analysis of Fig. 5, Curve 2 for penetration into a crater slope and Curve 3 for penetration into a crater wall. The results for the crater wall show a particularly marked increase in strength with depth.

Curves corresponding to $D/B = 0$ for the level ground, crater slope, and crater wall are compared in Fig. 9. Unfortunately, Leonovich *et al.* (1971) do not describe the nature or size of the crater in which the curves shown in Fig. 5 were obtained. Because of trafficability considerations, however, it is not likely that the crater was sharp, blocky, or deep. The curves in Fig. 9 would appear compatible with a subdued shallow crater where soil on the inside had a long history of downslope movement and could be expected to be in a relatively loose and weak condition.

Conclusions

The fine-grained soil that blankets the lunar surface has a grain size distribution that corresponds to terrestrial silty fine sands, although coarser material may be found locally. Available evidence from a variety of sources—photographs, simulation studies, core tube samples, trenching experiments, and penetrometer measurements—indicate that the mechanical properties of the soil are remarkably similar to those of terrestrial soils of comparable gradation, even though the two types of soil are compositionally dissimilar. This is a direct reflection of the fact that for soils in this particle size range, density and particle size and shape distribution exert a larger influence on mechanical properties than does composition.

Lunar soils do differ from terrestrial soils, however, in that the lunar materials are somewhat more cohesive. Whether this is due to compositional or environmental differences is not yet known.

The density may be less than 1 g/cm^3 at the surface in some areas and as high as 2 g/cm^3 at very shallow (a few centimeters) depth in others. There is strong evidence that density and strength increase with depth, rapidly in the case of low surface densities, and gradually in the case of high surface densities. Densities greater than 1.5 g/cm^3 are probable below depths of 10 to 20 cm.

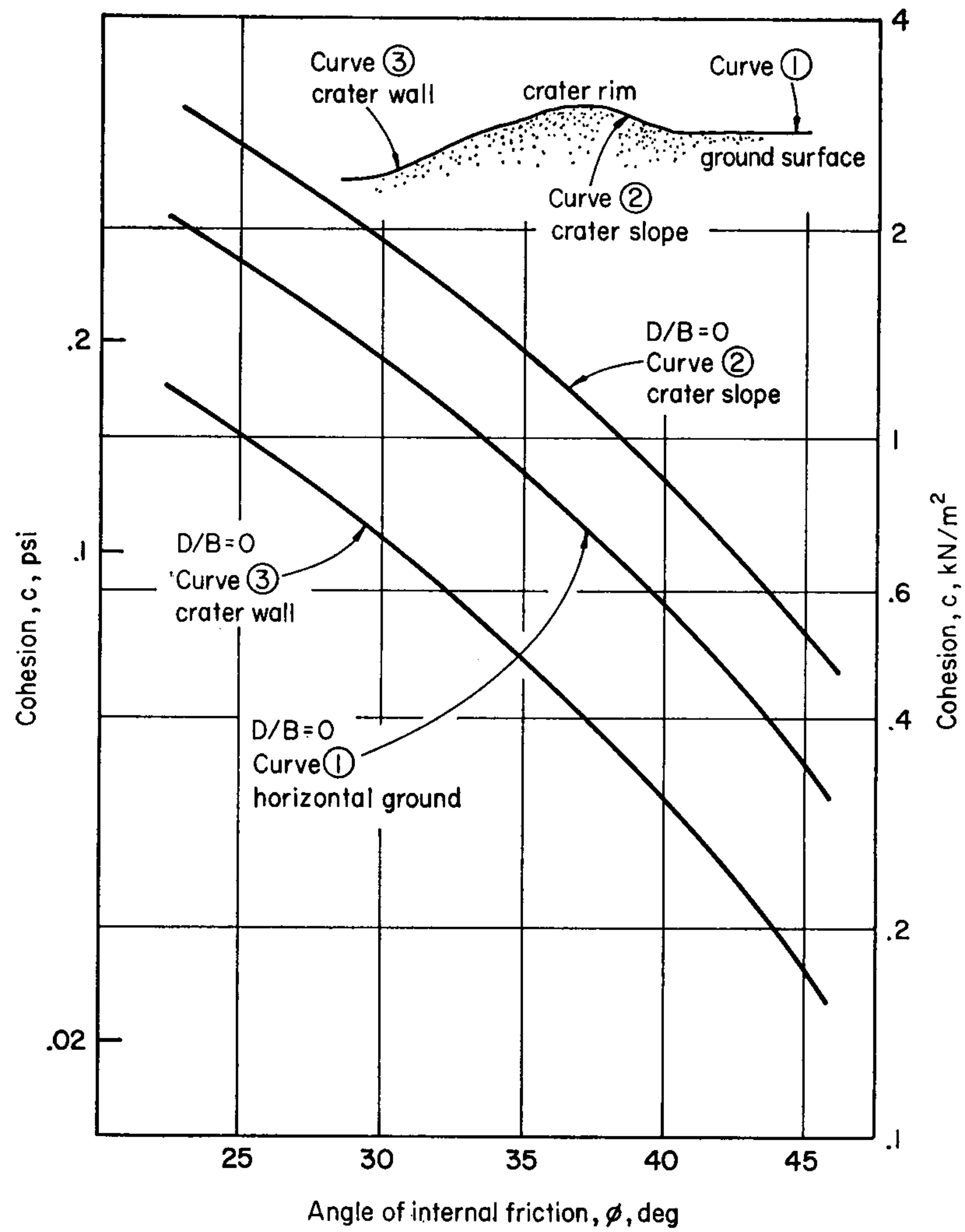

Fig. 9. Comparison of strength characteristics for level ground, crater wall, and crater slope (data from Leonovich *et al.*, 1971).

The soil on slopes may be significantly less dense and weaker than the soil on level areas. This finding may be important in understanding mechanisms of downslope movement of soil, since the relationship between strength and slope angle will influence the extent to which different driving forces can cause movement.

For a given grain size distribution, porosity appears to be the most important single variable controlling cohesion and friction angle, and relationships similar to those in Figs. 2 and 3 are probable, although present data are insufficient to define them uniquely. Most probable values of cohesion appear to be in the range of 0.1 to 1 kN/m^2.

Evidence is accumulating that the angle of internal friction of lunar soils varies in a manner similar to that of terrestrial soils and that its most probable range is from about 30° to 50°.

The most comprehensive set of data thus far available are for the soil at shallow depth near the soil mechanics trench (Station 8) at the Hadley-Apennine site. From these data the determined soil properties are:

Porosity	36.5%
Void ratio	0.58
Density	2 g/cm^3
Cohesion	1 kN/m^2
Angle of internal friction	50°

These results indicate that the soil at this location is near the lower end of the range of porosities likely to be encountered (Houston *et al.*, 1972).

Analysis of penetration and vane shear data obtained by the Soviet Lunokhod 1 has yielded cohesion and friction angle estimates that are consistent with other information gathered to date. Lunokhod data provide specific indication of an increase in strength parameters, and therefore also density, with depth below the surface. The results show further that the soil properties differ between level intercrater areas, crater walls, and crater slopes.

Acknowledgments—This paper was prepared under NASA Contract NAS 9-11266, Principal Investigator Support for the Soil Mechanics Experiment. H. Turan Durgunoglu, Department of Civil Engineering, University of California, Berkeley, assisted in the analysis of Lunokhod data.

References

Carrier W. D. III, Bromwell L. G., and Martin R. T. (1972) Strength and compressibility of returned lunar soil (abstract). In *Lunar Science—III* (editor C. Watkins), pp. 119–121, Lunar Science Institute Contr. No. 88.

Carrier W. D. III, Johnson S. W., Carrasco L. H., and Schmidt R. (1972) Core sample depth relationships: Apollo 14 and 15 (abstract). In *Lunar Science—III* (editor C. Watkins), pp. 122–124, Lunar Science Institute Contr. No. 88.

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.

Cherkasov I. I., Vakhnin V. M., Kemurjian A. L., Mikhailov L. N., Mikheyev V. V., Musatov A. A., Smorodinov M. I., and Shvarey V. V. (1968) Determination of the physical and mechanical properties of the lunar surface layer by means of Luna 13 automatic station. *Moon and Planets II* (editor A. Dollfus), pp. 70–76, North-Holland.

Choate R. (1966) Lunar slope anales and surface roughness from Ranger photographs. Jet Propulsion Lab. Tech. Report 32-994, pp. 411–432.

Christensen E. M., Batterson S. A., Benson H. E., Chandler C. E., Jones R. H., Scott F. R., Shipley E. N., Sperling F. B., 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. (1968a) Lunar surface mechanical properties, in Surveyor VI, a preliminary report. NASA SP-166, pp. 41–95.