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LUNAR SURFACE ENGINEERING PROPERTIES EXPERIMENT DEFINITION

SUMMARY TECHNICAL REPORT

by

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UNIVERSITY OF CALIFORNIA · BERKELEY

University of California

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PREFACE

This report summarizes the results of studies conducted during the period June 20, 1968 - July 19, 1969, under NASA research contract NAS 8-21432, "Lunar Surface Engineering Properties Experiment Definition." This study was sponsored by the Advanced Lunar Missions Directorate, NASA Headquarters, and was under the technical cognizance of Dr. N. C. Costes, Space Science Laboratory, George C. Marshall Space Flight Center.

The report reflects the combined effort of four faculty investigators, a research engineer, a project manager, and six graduate research assistants, representing several engineering and scientific disciplines pertinent to the study of lunar surface material properties. James K. Mitchell, Professor of Civil Engineering, served as Principal Investigator and was responsible for those phases of the work concerned with problems relating to the engineering properites of lunar soils and lunar soil mechanics. Co-investigators were William N. Houston, Assistant Professor of Civil Engineering, who was concerned with problems relating to the engineering properties of lunar soils; Richard E. Goodman, Associate Professor of Geological Engineering, who was concerned with the engineering geology and rock mechanics aspects of the lunar surface; and Paul A. Witherspoon, Professor of Geological Engineering, who conducted studies related to thermal and permeability measurements on the lunar surface. Dr. Karel Drozd, Assistant Research Engineer, performed laboratory tests and analyses pertinent to the development of a borehole probe for determination of the in-situ characteristics of lunar soils and rocks. John Hovland, David Katz, Laith I. Namiq, James B. Thompson, Tran K. Van, and Ted S. Vinson served as Graduate Research Assistants and carried out many of the studies leading to the results presented in this report. Francois Heuzé, Assistant Specialist, served as project manager and contributed to studies concerned with lunar rock mechanics.

Ultimate objectives of this project are:

1) Assessment of lunar soil and rock property data using information obtained from Lunar Orbiter and Surveyor missions.
2) Recommendation of both simple and sophisticated in-situ testing techniques that would allow determination of engineering properties of lunar surface materials.
3) Determination of the influence of variations in lunar surface conditions on the performance parameters of a lunar roving vehicle.
4) Development of simple means for determining the fluid and thermal conductivity properties of lunar surface materials.
5) Development of stabilization techniques for use in loose, unconsolidated lunar surface materials to improve the performance of such materials in lunar engineering application.

The scope of specific studies conducted in satisfaction of these objectives is indicated by the following list of contents from the Detailed Final Report which is presented in four volumes. The names of the investigators associated with each phase of the work are indicated.

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2. Lunar Surface Trafficability Studies
(J. B. Thompson and J. K. Mitchell)

3. Foamed Plastic Chemical Systems for Lunar Soil Stabilization Applications
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1. Studies on Fluid Conductivity of Lunar Surface Materials
(D. F. Katz, P. A. Witherspoon, and D. R. Willis)

SUMMARIES OF STUDIES AND CONCLUSIONS

LUNAR SOIL SIMULATION

1. It has been possible to prepare a lunar soil simulant whose composition, gradation, density, and shear strength parameters are sufficiently close to those values estimated for actual lunar soil to allow meaningful correlations. Figure 1 presents the gradation curve for the basic test soil used in the simulation studies, and Table 1 summarizes the mechanical properties of the lunar soil simulant.*

2. A combination of theoretical and experimental analyses were used to develop probable correlations between average soil density and soil behavior on the lunar surface. Most properties appear to be a sensitive function of soil density. Therefore, if the average soil density can be determined, most all other properties of interest can be estimated.

3. Results of the lunar soil simulation studies indicate that the average density for the top 40 cm of lunar soil may be slightly higher than the value 1.50 g/cm^3 suggested in the Final Surveyor Report. In addition, consideration of probable variations in degree of initial densification due to vibration on the lunar surface has led to the conclusion that the lunar soil density probably varies somewhat from one location to another. On this basis an estimated range of 1.55 to 1.65 g/cm^3 for the average density of the top 40 cm was established.

4. The estimated range in depth of astronaut footprints (with contact stress = 1.1 psi) on the lunar surface is 1.0 in. to 2.1 in. for a corresponding range in soil density of 1.65 g/cm^3 to 1.55 g/cm^3 assuming a compressible soil layer to a depth of 40 cm. This is shown in Figure 2. Astronaut footprints during Apollo 11 were from a fraction of an inch to a maximum of about 6 inches deep.

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*Preliminary analysis of Apollo 11 soil mechanics data suggest good agreement between actual lunar soil properties and properties of the simulant.

TABLE 1

PROPERTIES OF LUNAR SOIL SIMULANT

Bulk Density	1.5 to 2.0 gm/cm^3 depending on method of placement and stress history.
Angle of Internal Friction	30^o at low density to 46^o at high density in triaxiaxial compression. Plain strain values about 10 percent higher.
Cohesion	0.01 to 0.15 psi depending on density and moisture content.
Permeability	7×10^{-4} cm/sec at $\rho = 1.8\ gm/cm^3$ 21×10^{-4} cm/sec at $\rho = 1.5\ gm/cm^3$
Compressibility	$\rho = K_1 + K_2 \log_{10} \sigma$ σ = compressive stress K_1, K_2 = f (placement density)

5. As indicated in Figure 3, the estimated range in Cone Index Gradient G, for the lunar surface is 1.2lb/in^3 to 4.0lb/in^3 for a corresponding range in average soil density of 1.50 gm/cm^3 to 1.75 gm/cm^3. Test data show that penetration resistance is influenced by both the type of penetrometer used and the positioning of the penetrometer with respect to the feet of the man performing the test. The estimated G values given above are applicable to the WES 30-degree cone penetrometer placed 2 in. in front of the toes with 6 in. clear space between the feet. If a flat-ended rod penetrometer of about 1 in. diameter were used, it is expected that the G values would be about 50 percent higher. If the penetrometer were placed entirely outside the influence of the man's feet, it is expected that the G values would be about 40 percent lower.

6. Experience obtained with the lunar soil simulant indicates that in-place density measurements on the lunar surface may be very difficult. Success during attempts to remove a "cake-like" block of the lunar soil simulant by excavating around it was only marginal.

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GRADING ANALYSIS

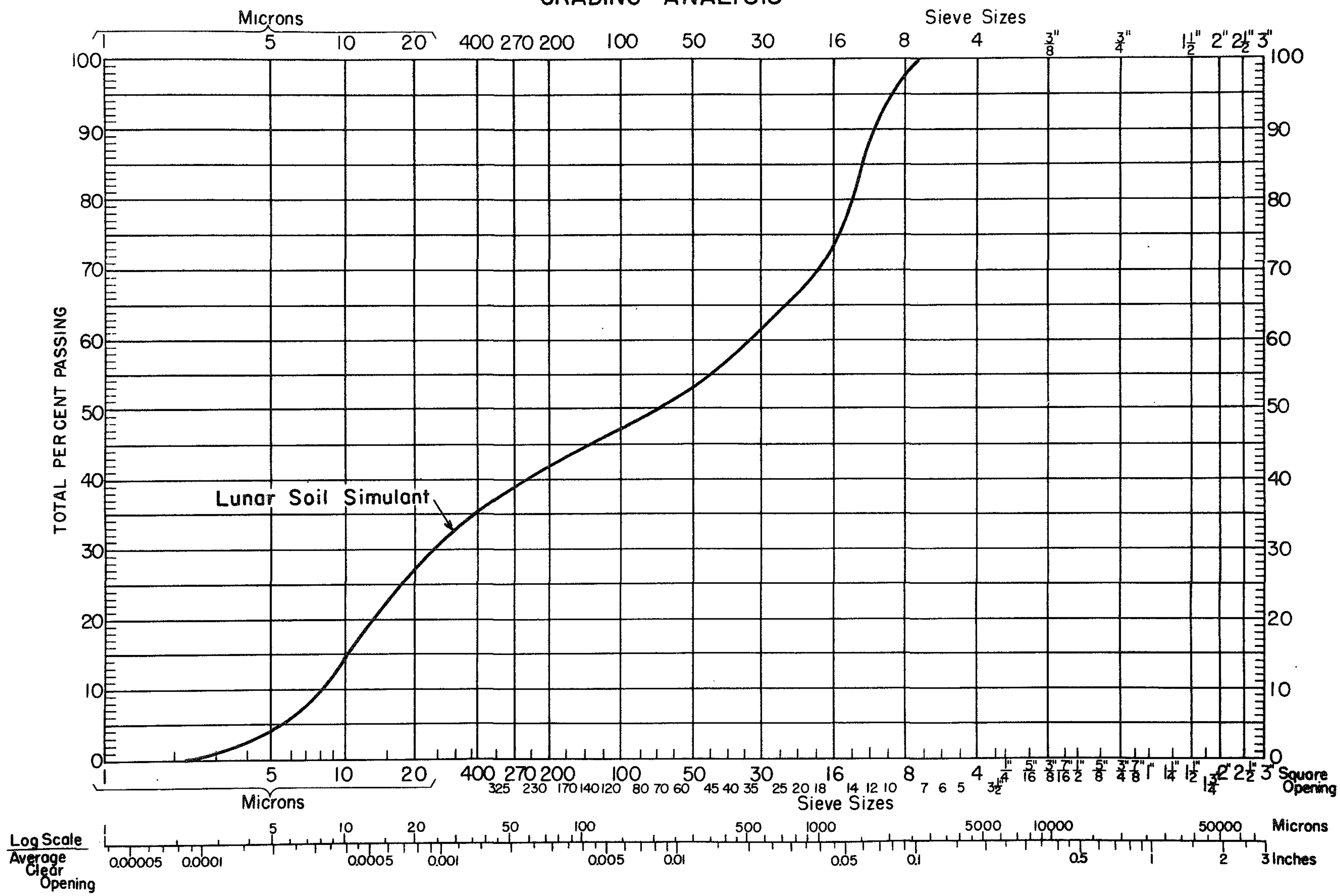

FIGURE I GRADATION CURVE FOR BASIC TEST SOIL.

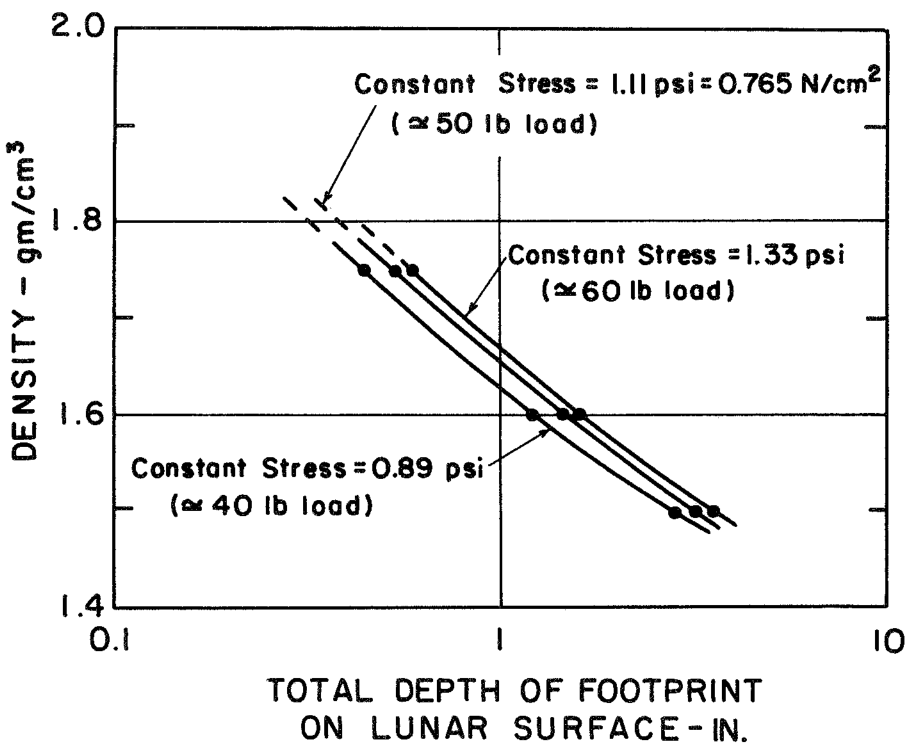

FIGURE 2 RELATIONSHIPS BETWEEN TOTAL DEPTH OF FOOTPRINT AND DENSITY FOR A COMPRESSIBLE LUNAR SURFACE LAYER 40 cm THICK.

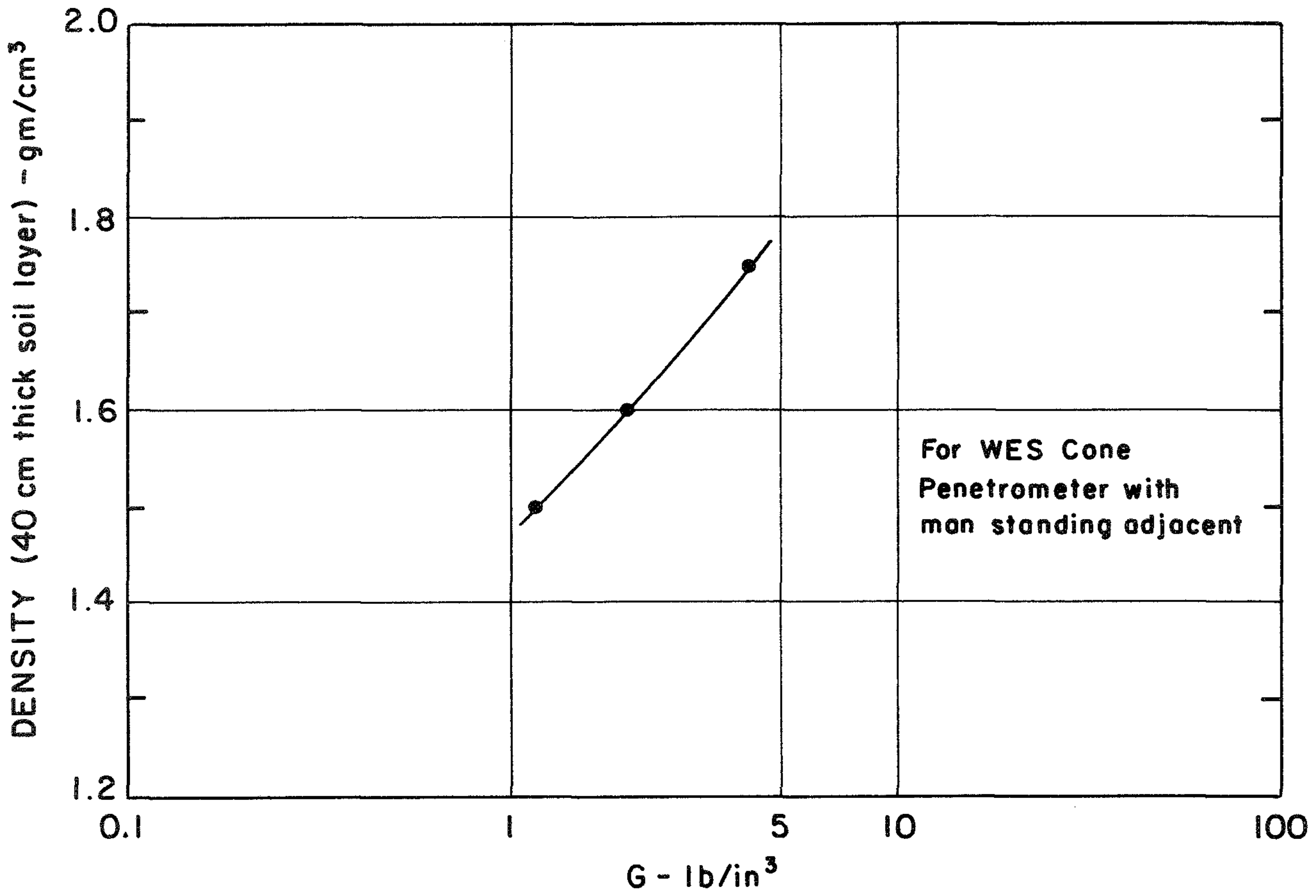

FIGURE 3 PROBABLE VARIATION OF CONE INDEX GRADIENT WITH DENSITY FOR LUNAR SOIL.

LUNAR SURFACE TRAFFICABILITY STUDIES

1. If the Bekker "Soil Value System" equations can be assumed to give a reasonable measure of the performance characteristics of a lunar roving vehicle, then analysis based on reasonable assumptions for wheel dimensions, wheel loads, and soil properties shows that:

   A. Thrust increases with slip up to values of about 30% slip. Further increase in slip does not lead to significant increases in thrust, but may result in wasted propulsion energy.

   B. The value of the soil sinkage constant, n, has relatively little effect on motion resistance.

   C. The value of the soil sinkage constant, $k = \frac{k_1}{b} + k_2$, has little effect on motion resistance. Unfortunately, the form of the pressure-sinkage relationship developed on the basis of this parameter is not realistic.

   D. Variations of soil cohesion and friction over ranges considered to be reasonable for lunar soils; i.e., $0.05 < c < 0.20$ psi and $33° < \phi < 41°$, may lead to variations in predicted thrust of up to $\pm 35\%$ from the values calculated for $c = 0.10$ psi and $\phi = 35°$. Thus accurate knowledge of lunar strength will be important if precise predictions of performance, fuel consumption, etc. are to be made.

   E. According to the "Soil Value System" the maximum slope that a vehicle can climb is given by the Drawbar Pull to Weight ratio. On this basis wheel loads should be minimized if slope climbing ability is to be maximized. Unfortunately the prediction of the slope climbing ability must also take into account slip sinkage and gross soil failure. Furthermore the suitability of the "Soil Value System" equations for thrust and motion resistance when applied to wheels on slopes has yet to be demonstrated. Thus, the questions of vehicle slope climbing ability and stability of vehicles on slopes remain largely unanswered.

F. The "Soil Value System" predicts that performance parameters should improve with increasing wheel width and diameter and increasing wheel-soil contact length. Clearly, however, there are other factors which will limit the size and deformability of the wheels that are used.

2. In spite of the limitations of the "Soil Value System" method of analysis, a comparison between predicted behavior and that exhibited by the wire mesh and metal-elastic wheels tested by AC Electronics (1967) was reasonably good, particularly at low wheel loads. The metal wheels gave a performance intermediate between that to be expected for a rigid wheel and a track.

3. Proper solution of the lunar soil trafficability problem will depend ultimately on the solution of the basic wheel-soil interaction problem. An approach to this problem has been suggested in the Detailed Final Report which is based on consideration of the stresses and deformations in the soil and wheel and their mutual compatability. Such a method will require detailed knowledge of the soil and wheel load-deformation characteristics, and will probably require the use of iterative computational methods.

4. The stability of vehicles on slopes remains largely unknown.

FOAMED PLASTIC CHEMICAL SYSTEMS FOR LUNAR SOIL STABILIZATION APPLICATIONS

Improvement of the engineering properites of lunar soil and fractured rock zones, i.e. stabilization, may be desirable if not necessary in connection with exploration and future construction on the moon. Potential applications of suitable soil and rock stabilization techniques include the following:

1. Sealing of fissures and voids in otherwise intact soil and rock masses to enable utilization of lunar cavities as shelters, storage chambers, waste disposal chambers, etc.
2. Mixing of stabilizing agents with lunar soil or fragmental lunar rock for utilization as a construction material in insulation, shielding or launching facilities.
3. Protection and preservation of the structure of lunar surface material samples for earth-return.

Relative to lunar payload limitations foamed plastics represent perhaps the best type of stabilizing agent because of their very low density. In this research program attention has been directed toward the use of urethane foamed plastic as a lunar stabilizing agent.

Injection of clean Monterey Sand cylinders with four different urethane chemical systems indicated: (1) the plastic could be made to foam in the voids of a soil mass, (2) soil cylinders stabilized with urethane foamed plastic have a relatively high unconfined compressive strength, (3) soil cylinders stabilized with urethane foamed plastic can apparently be made impermeable. These results are given in Table 2.

A urethane foamed plastic chemical system has been developed for use in vacuo and the next phase of the project will be to attempt soil injection in vacuo.

TABLE 2

RESULTS OF STRENGTH AND PERMEABILITY TESTS

ON STABILIZED MONTEREY SAND SOIL CYLINDERS

Test No.	Chemical System	Unconfined Compressive Strength, psi	Permeability cm/sec
371	53.7% TDI 46.3% triethylene glycol 0.5% (of total weight) L-531 0.5% (of total weight) diacetone alcohol 0.5% (of total weight) MIBK		5.10×10^{-4}
37G1	as in 371 + 0.1 (of total weight) catalyst		1.28×10^{-4}
37G2	as in 371 + 0.1 (of total weight) catalyst		1.65×10^{-4}
37M1	as in 371 + 0.2 (of total weight) catalyst		0.85×10^{-5}
37M2	as in 371 + 0.2 (of total weight) catalyst		2.96×10^{-5}
37R1		1960	
37Q1	as 37G1 or 37G2	3460	
37P1	as 37M1 or 37M2	3700	
39F1	60.5% TDI 20.7% triethylene glycol 18.6% TMP	1080	
44G1	53.7% TDI 46.3% triethylene glycol 1.5% (of total weight) polyethylene glycol (MW=400) 3.0% (of total weight) adipic acid 0.5% (of total weight) diacetone alcohol 5% (of total weight) castor oil 1% (of total weight) L-351	5240	
44H1	as 44G1	5265	
44J1	as 44G1	5190	
44J2	as 44G1		2.77×10^{-5}

TABLE 2 (Con't.)

Test No.	Chemical System	Unconfined Compressive Strength, psi	Permeability cm/sec
48A1	57.8% TDI 24.9% triethylene glycol 17.3% 1,5 pentanediol 10.0% (of total weight) castor oil 0.8% (of total weight) adipic acid 3.0% (of total weight) diacetone alcohol 1.0% (of total weight) L-531	5140	
48B1	as 48A1	4780	
48D1	as 48A1	4540	
48D2	as 48A1		Impermeable

SOIL PROPERTY EVALUATIONS FROM BOULDER TRACKS ON THE LUNAR SURFACE

Lunar boulder track from 19 different locations on the moon were utilized to study lunar soil properties. A total of 69 boulder tracks have been analyzed. This is believed to be a sufficient number to form a preliminary basis for certain inferences and conclusions.

1. Boulder track analysis appears to be a promising remote reconnaissance technique for study of soil conditions.
2. Lunar soil and rock properties (cohesion, density, and friction angle) are possibly more variable than anticipated from previous investigations.
3. For the conditions assumed, most of the results centered around a friction angle of 32 degrees, with a range of 18 to 43 degrees with the majority of values between 26 and 39 degrees.

TABLE 3A

Results of Boulder Track Analysis, Orbiter II Photographs

Location	Frame	Framelet (boulder location)	Longitude (degrees)	Latitude (degrees)	Boulder diam. (D) (meters)	Track width (w) (meters)	Slope (α) (degrees)	$\frac{z}{w}$	Bearing capacity (q_m)		ϕ
									(psf)	$\frac{dynes}{cm^2} \times 10^5$	(°)
Mare Tranquillitatis (Approx. 100 Km from Apollo Site 1)	II-27H	921	36.54	3.56	6.0	6.0	15	0.50	740	3.55	21
Sabine D (Approx. 30 km from Surveyor 5 and Apollo Site 2)	II-76H*	364	23.68	1.20	8.7	6.4	13	0.23	1970	9.47	32
Sinus Medii (Approx. 20 Km from Surveyor 6 and Apollo Site 3)	II-122H	464	-1.32	0.32	6.3	6.3	15	0.50	770	3.70	21
Sinus Medii (Approx. 20 Km from Surveyor 6 and Apollo Site 3)	II-123H	594 + 15mm, 28mm	-1.89	0.29	5.9	5.4	10	0.35	850	4.09	24

Note: To express bearing capacities in Newton's per square centimeter, multiply the value in $dynes/cm^2$ by 10^{-5}.

* Slope angle primarily based on slope determined by photogrammetry.

TABLE 3B

Results of Boulder Track Analysis, Orbiter III Photographs

Location	Frame	Framelet (boulder location)	Longitude (degree)	Latitude (degree)	Boulder diam. (D) (meters)	Track width (w) (meters)	Slope (α) (degrees)	$\frac{z}{w}$	Bearing capacity (q_m)		ϕ
									psf	$\frac{\text{dynes}}{\text{cm}^2} \times 10^5$	(°)
Mare Fecunditatis (Approx. 150 Km WNW of Messier A)	III-35H	396 + 4 mm, 258mm	42.81	-1.05	5.0	4.6	25	0.35	725	3.48	27.5
N E Mösting	III-107H	868 + 1mm, 21mm	-5.67	-0.33	3.6	2.8	10	0.23	725	3.48	30
Rima Hipparchus	III-111H	364 + 1mm, 286mm	4.83	-4.92	5.2	5.2	30	0.50	640	3.07	22.5
		373 + 13mm, 392mm			6.0	4.9	10	0.26	1100	5.28	27
Reinhold (Approx. 30Km E. of Reinhold K)	III-125H	204 + 1.5mm, 69mm	-20.04	-0.60	2.3	1.6	15	0.21	580	2.78	33
		204 + 3mm, 75mm			2.5	2.5	15	0.50	310	1.49	20
		204 + 5mm, 76mm			2.5	1.9	15	0.23	530	2.54	31
		205 + 13mm, 53mm			2.7	2.1	15	0.23	550	2.64	31
		206 + 15mm, 64mm			4.1	3.7	20	0.31	610	2.93	28
Oceanus Procellarum (Approx. 40 Km from Surveyor 1)	III-181H	567 + 7mm, 284mm	-43.54	-2.11	3.2	2.2	10	0.21	830	3.98	32
Oceanus Procellarum (Approx. 40 Km from Surveyor 1)	III-189H	615 + 1mm, 77mm	-44.17	-2.41	2.9	2.4	5	0.27	520	2.50	26
		617 + 7mm, 91mm			6.2	5.1	5	0.28	1130	5.41	26

TABLE 3C

Results of Boulder Track Analysis, Orbiter V Photographs

Location	Frame	Framelet (boulder location)	Longitude (degrees)	Latitude (degrees)	Boulder diam. (D) (meters)	Track width (w) (meters)	Slope (α) (degrees)	$\frac{z}{w}$	Bearing capacity (q_m) psf	Bearing capacity (q_m) $\frac{\text{dynes}}{\text{cm}^2} \times 10^5$	φ (°)
Central mountains of Petavius (rille)	V-34H	880 + 12mm, 176mm	60.57	-25.70	23.3	13.7	20	0.16	8400	40.40	38
		891 + 6mm, 146mm			19.0	13.7	20	0.21	4500	21.60	34
Mare Tranquillitatis (Approx. 40 Km west of Censorinus)	V-63H	738 + 14mm, 147mm	32.75	-0.44	7.35	4.8	0	0.18	2110	10.10	32
		738 + 16mm, 147mm			8.2	6.0	0	0.23	1910	9.17	29
Large hill south of Alexander	V-88H**	011 + 8.5mm, 230mm	13.54	38.92	19.5	10.6	20	0.15	8150	39.20	42
S. E. part of Hyginus	V-95H*	942 + 18mm, 365mm	5.94	7.56	13.1	8.8	30	0.19	3600	17.30	41
		957 + 11.5mm, 164mm			8.9	6.2	15	0.20	2270	10.90	34
		959 + 12.5mm, 161mm			9.5	5.6	15	0.17	3360	16.10	38
		962 + 3mm, 167mm			8.6	4.6	15	0.15	3690	17.70	40
		965 + 11mm, 239mm			10.0	5.7	15	0.16	3800	18.30	38
		968 + 13mm, 253mm			11.2	4.2	20	0.11	9760	47.00	47
		970 + 7mm, 246mm			14.4	9.2	20	0.18	4350	20.90	38
		978 + 13mm, 252mm			6.0	4.8	15	0.25	1160	5.58	30
		960 + 9mm, 146mm			4.9	4.9	30	0.50	600	2.88	22

**Photogrammetrically determined slope is about 30°: 20° slope is primarily based on shadow technique.

TABLE 3C (contd)

Location	Frame	Framelet (boulder location)	Longitude (degrees)	Latitude (degrees)	Boulder diam. (D) (meters)	Track width (w) (meters)	Slope (α) (degrees)	$\frac{z}{w}$	Bearing capacity (q_m) psf	Bearing capacity (q_m) $\frac{dynes}{cm^2} \times 10^5$	ϕ (°)
N E part of Hyginus	V-96H*	092 + 1mm, 46mm	5.96	7.85	15.9	10.6	10	0.19	4410	21.20	34
N E part of Hyginus	V-97H	175 + 11mm, 268mm	5.98	8.14	11.0	5.7	15	0.14	5040	24.30	40
		175 + 13mm, 275mm			7.6	4.3	25	0.15	2900	14.00	41
		178 + 10mm, 224mm			7.1	4.3	10	0.17	2370	11.40	36
		178 + 14mm, 222mm			7.1	4.0	10	0.16	2760	13.30	36
		180 + 5mm, 230mm			6.2	4.3	15	0.20	1580	7.60	34
		180 + 4mm, 229mm			7.6	4.8	15	0.17	2340	11.30	36
		180 + 1mm, 235mm			7.1	5.2	15	0.21	1620	7.80	33
Hadley Rille	V-105H*	233 + 8mm, 232mm	2.95	25.00	14.9	9.6	25	0.19	4400	21.20	39
		233 + 11mm, 234mm			13.5	8.9	15	0.19	3820	18.40	35
		234 + 8mm, 235mm			13.2	8.6	5	0.19	3830	18.50	33
Rima Bode	V-122H	475 + 9mm, 121mm	-3.97	12.92	12.2	9.0	15	0.22	2770	13.40	32
Copernicus (center)	V-151H	280 + 17mm, 184mm	-20.34	9.42	9.1	6.6	10	0.21	2130	10.30	32
		315 + 11mm, 282mm			12.2	5.5	5	0.12	7350	35.40	40

TABLE 3C (contd)

Location	Frame	Framelet (boulder location)	Longitude (degrees)	Latitude (degrees)	Boulder diam. (D) (meters)	Track width (w) (meters)	Slope (α) (degrees)	$\frac{z}{w}$	Bearing Capacity (q_m)		ϕ
									psf	$\frac{\text{dynes}}{\text{cm}^2} \times 10^5$	(°)
Copernicus (NW of center)	V-155H	845 + 14mm, 340mm	-20.24	10.58	10.6	4.8	0	0.12	6300	30.40	39
Copernicus (NW of center)	V-156H	962 + 8mm, 135mm	-20.21	10.87	11.9	10.7	10	0.32	1800	8.68	27
Center of Vitello	V-168H	518 + 9mm, 188mm	-37.57	-30.61	19.2	19.2	15	0.50	2360	11.40	21
		519 + 1mm, 185mm			11.4	5.4	10	0.12	6200	29.90	41
		520 + 2mm, 184mm			8.0	4.8	15	0.17	2730	13.20	37
		520 + 9mm, 188mm			11.9	7.9	15	0.19	3310	16.00	35
North rim of Gassendi	V-179H	972 + 7mm, 250mm	-39.97	-16.29	8.6	5.5	15	0.18	2580	12.45	34
		972 + 15mm, 333.4mm			5.6	5.3	15	0.35	765	3.69	25
		972 + 15.2mm, 338mm			5.4	4.7	15	0.31	880	4.25	27
		005 + 15mm, 244mm			16.4	14.1	15	0.29	2720	13.10	29
		973 + 10mm, 345mm			9.4	6.0	10	0.18	2830	13.70	34
		973 + 3mm, 285mm			6.8	6.0	20	0.29	1080	5.20	30
		977 + 10mm, 340mm			16.0	14.0	15	0.30	2570	12.40	29
		977 + 17mm, 325mm			7.0	6.1	20	0.28	1140	5.50	30
		977 + 17mm, 305mm			5.6	5.0	25	0.31	860	4.15	30
		979 + 6mm, 352mm			7.5	4.8	10	0.19	2250	10.90	34

TABLE 3C (contd)

Location	Frame	Framelet (boulder location)	Longitude (degrees)	Latitude (degrees)	Boulder diam. (D) (meters)	Track width (w) (meters)	Slope (α) (degrees)	$\frac{z}{w}$	Bearing Capacity (q_m) psf	Bearing Capacity (q_m) $\frac{\text{dynes}}{\text{cm}^2} \times 10^5$	ϕ (°)
Schröter's Valley	V-203H	111 + 7mm, 246mm	-49.51	25.13	7.4	5.4	10	0.22	1700	8.20	31
		111 + 7mm, 246mm			7.4	5.4	20	0.22	1700	8.20	35
Schröter's Valley	V-203H*	227 + 8mm, 41mm	-49.48	25.52	9.4	6.2	15	0.19	2640	12.70	35
		221 + 18mm, 161mm			12.6	6.5	5	0.14	5800	28.00	38
		210 + 15mm, 242mm			12.6	7.2	15	0.16	4750	22.90	39
		210 + 14mm, 177mm			10.5	5.5	25	0.14	4670	22.50	44
		202 + 7mm, 253mm			19.4	12.3	20	0.18	5930	28.60	38
Oceanus Procellarum (Approx. 130 Km NW of Marius)	V-213H	417 + 7mm, 294mm	-56.03	13.50	7.4	4.3	20	0.16	2710	13.10	40
		431 + 10mm, 290mm			6.4	3.3	15	0.14	2940	14.20	41

DEDUCTION OF LUNAR SURFACE MATERIAL STRENGTH PARAMETERS FROM LUNAR SLOPE FAILURES CAUSED BY IMPACT EVENTS - FEASIBILITY STUDY

Lunar Orbiter photographs provide evidence of slope failures on the moon. In the present study the extent to which dynamic loadings might account for lunar slope failures and the feasibility of estimation of lunar surface material strength parameters from observed slope failures has been undertaken. Specifically, attention was directed at the influence of ground accelerations, generated by impact events, on nearby slopes.

In the method employed in this study to predict the response of a slope an analogy was drawn between craters formed by shallow nuclear explosive events and impact craters. Using empirical observations and recordings of ground response for nuclear cratering events the response of a lunar slope to an impact event was determined. Necessarily, many assumptions were required. Knowing the ground response to an impact event, an upper or lower bound on the material strength could be determined depending on whether or not a nearby slope has failed or is stable. This was possible using an equation expressing the "yield acceleration," i.e. the acceleration at which sliding will begin to develop under a dynamic load, as a function of the angle of internal friction of the material, the initial slope inclination, and a correction factor to account for apparent cohesion. It is felt that with this general approach erroneous conclusions may be reached, and that the assumptions required are so great as to produce results with an extremely low confidence level. In addition, it is felt that few of the Orbiter photographs allow positive identification of lunar slope failures. They can provide, with proper judgement, a reasonable assessment of variations in lunar slopes that indicate probable slope failures. It is concluded, therefore, that analysis of lunar slopes using dynamic considerations and Orbiter photographs is not at the present time a particularly fruitful approach for the quantitative determination of lunar soil strength parameters.

STUDIES ON FLUID CONDUCTIVITY OF LUNAR SURFACE MATERIALS

The overall objective of this investigation is to develop a means of measuring the permeability of lunar soils and rocks in situ. It has been proposed to design and test a surface probe that can measure permeabilities with reasonable accuracy. Because of the lack of any atmosphere on the moon, it will be necessary to utilize gas in operating the probe. In the current year's work, a theory of gas flow in porous media appropriate to the surface probe has been developed. The theory is applicable to probe operation in the lunar environment as well as on earth.

Due to the high vacuum in the lunar environment, there exists a basic problem of determining the dominant flow regime during probe operation. As the average pore size and/or fluid pressure decrease, the fundamental nature of gas flow changes. The initial departure from viscous flow is the relaxation of the no slip boundary condition on the interstitial surfaces. The resulting, agumented flow, while still viscous in nature, exhibits a greater temperature dependence than previously. As the effective degree of rarefaction increases further, the continuum nature of the fluid breaks down, and the flow must be modeled from a molecular point of view. In general, account must be taken of both intermolecular collisions, and collisions between molecules and the interstitial boundaries. However, when a high degree of rarefaction is achieved, the former become negligible due to the relative scarcity of fluid molecules.

It seems likely that in the immediate neighborhood of the fluid source, the flow will be viscous in nature, and, thus, basically predictable by current techniques. However, the nature of the evolution of Knudsen flow, as the distance from the source increases, is extremely difficult to foresee at this time. Detailed theories for transition flow, namely solutions of the Boltzmann equation, for even the simplest geometries are quite scarce. As a result, this report introduces the concept of local similarity in treating the gas flow. This approach makes maximum use of physical intuition about the flow field, and requires experimental calibration of the probe on a sample of known material. It does not, however, require actual solution of the fluid equations of motion, and it is not contradicted by what is considered the best of the rather scarce work done previously on transitional flows in porous media.

The concept of local similarity contains the following basic assumptions:

(1) flow is steady

(2) flow is independent of the initial pressure in the porous medium

(3) a single length characterizes the fluid conductivity of the porous medium

(4) flow is isothermal

(5) the porous medium is isotropic.

In applying this concept, data from all probe measurements, suitably plotted, fall on the same "universal" curve. Probe calibration consists of determining this curve. Once this is done, both the permeability and area fraction of an unknown material can be determined from a single measurement operation. A simple graphical procedure for calculating these quantities is presented.

In addition, the design of experiments aimed at developing a probe prototype is discussed. All such work is to be carried out under vacuum conditions (10^{-6} - 10^{-8} torr) in order to simulate the lunar environment.

STUDIES RELATED TO BOREHOLE JACK PROBE AND TESTING

Borehole testing on the earth can define in situ strengths and deformabilities and it is proposed that similar testing procedures be developed for the moon. Upon thorough review of borehole devices used for in situ determination of mechanical properties of soils and rocks, the available mathematical solutions relevant to borehole testing were studied. In order to measure rock and soil strength in situ, it was proposed to induce failure in the borehole wall by a borehole jack. Unfortunately, there is little information available on the mechanisms of failure associated with the loading condition of the jack plate, as only deformability properties, and not strength properties, had heretofore been measured.

Two general boundary value problems were proposed for plate jack loading against the wall of a borehole in rock masses. One problem is based on uniform unidirectional rigid plate displacement; this consideration leads to the condition of unidirectional contact pressure variable across the width of the bearing plate. The second problem is based on the assumption that the contact shear stress at a point is proportional to the differential circumferential displacement between the bearing plate and the wall; this consideration is compatible with the assumption of unidirectional displacement between the bearing plate and the wall and is compatible with the assumption of unidirectional principal contact stress, variable across the width of the bearing plates.

The analytical solutions to the two problems proposed were obtained. The stress distributions under different conditions of jack loading and of different in situ stress fields were found. Then the ultimate loads and locations of tensional failures were calculated. These solutions are particularly relevant to tests in rock. In addition, theoretical considerations on the modes of failure of a borehole in a soil mass subjected to the borehole jack loadings were presented for very dense, very loose and medium dense soils.

Experimental work was attempted to clarify the actual behavior of soils and rocks when subjected to a uniaxial load in a borehole. Previous work had been devoted to the possibility of the determination of deformation characteristics. The present work extends the studies for the determination of shearing characteristics. Model studies were made also to verify mathematical solutions in which failure by tensile cracks and shearing failure was supposed.

Tests were conducted by loading the walls of boreholes, in slices of varying material, constrained in plane strain conditions. Four different widths of bearing plates were used in this program. The borehole tests showed that in brittle material, the predominant failure was caused by cracking in a tension zone, whose location agreed with the mathematical solutions. In plastic material and in soils, we observed only indentation (punching), which for our range of displacement and load did not culminate in shearing failure.

A large number of factors were varied in an attempt to create shearing failure. However, neither peak load behavior nor a classical thrust of material from below the bearing plates were observed. Model bearing capacity tests carried out on the same test materials and with the same bearing plates as used for borehole jack tests did, in fact, display shearing failure. However, high displacements -- in some cases higher than the maximum stroke of the piston in the borehole jack tests -- preceeded the shearing failure.

Taking the point of view that the shearing characteristics of the tested material are involved in the punching process, it is possible to estimate the shearing resistance from the load corresponsing to a certain deformation. Such an evaluation of load-displacement curves was made from the borehole jack test results.

A prototype borehole jack device, which will enable greater displacements was proposed. It will be calibrated in a tank with materials of different properties. In these tests, the stress parallel to the borehole axis will be controlled simulating testing at depth in a borehole.

The theoretical results explain some of the phenomena associated with the failures observed in the experimental work. Certain assumptions based on the known behavior of non-ideally elastic materials help to explain fairly well the remaining phenomena observed with the rock-like materials.

In soils that can stand without casing in a borehole, the experimental work demonstrated the feasibility of determining strength parameters from borehole tests but left the final interpretation key to await a calibration program with the prototype hardware.

RECOMMENDATIONS

RECOMMENDATIONS

The following recommendations are made relative to the solution of critical problems related to the behavior of lunar surface materials and their effects on the scientific exploration and development of the moon. They are listed in the same sequence as the summary of studies in the preceding section.

1. Good measurements of in-place density of lunar surface soil and the thickness of the soil layer should be made during early Apollo missions if possible. The results of lunar soil simulations indicate that most soil properties of interest may be estimated through correlation with density. It appears that the most promising method for density determination may be the excavation of an undisturbed block of lunar soil, as described in the Geotechnical Investigations Section of the Definitive Experiment Plan for the Apollo Lunar Field Geology Experiment.
2. If attempts to measure the in-place density of the lunar surface materials are successful, the density, and the soil layer thickness should be correlated with astronaut footprint depth and penetration test results. This correlation should be used to check and modify, if necessary, the relationship between density and depth of footprint presented in Figure 2. If attempts to measure in-place density are unsuccessful, a relationship of this type presented in Figure 2 may be used as an indicator of lunar soil density.
3. Penetration resistance tests should be performed during early Apollo missions. Measurement of the penetration resistance, in terms of the slope of the stress-penetration curve, G, serves at least three purposes. First, the measured G values may be used to estimate soil density and other important properties through correlations. Second, the penetrometer serves as a probe in determining the homogeneity of the soil profile. Third, the G values obtained may be used in design of lunar roving vehicles.

4. If possible, the G values should be measured using a WES cone penetrometer, since vehicle design studies using this penetrometer are currently being made. Of course G values may be obtained with other penetrometers and the G value which would have been obtained with the WES cone can be estimated through correlations; however, some accuracy is lost in using an intermediate correlation.
5. A standard procedure (especially with respect to the relative position of the man's feet and the penetrometer) for performance of penetration resistance tests should be adopted and publicized. Our studies indicate that placement of the penetrometer about 4 in. in front of the toes (centered) with about 10 in. between the feet may be the best arrangement. With this arrangement the G value for the first 5 or 6 in. of penetration will probably not be significantly affected by the presence of the man's feet. Secondly, for tests performed in the terrestrial environment, the rate of penetration must be sufficiently low to allow dissipation of pore air pressures.
6. Additional laboratory and model tests on the lunar soil simulant should be conducted to expand and verify the correlations developed thus far. Special attention should be given to the determination of stress-strain parameters appropriate for very low densities and very low confining pressures. Also at least one additional lunar soil simulant with somewhat different gradation should be studied to further explore the influence of gradation on other properties. A gradation matching exactly that found from samples taken during Apollo 11 would be of the most interest. Penetration tests under conditions of reduced gravity should be simulated by using soil layers submerged in various heavy liquids.
7. Theoretical analyses using the finite-element approach should be performed in an effort to assess the influence of reduced gravity on deformations. These analyses, including both plane-strain and axisymmetric loading conditions, should be correlated with corresponding model test results.

8. Trafficability analyses based on the "Soil Value System" of analysis give some indication of the possible behavior of vehicles on the lunar surface. However, they were intended mainly to develop a feel for the relative importance of soil conditions on wheel performance. More detailed information is needed concerning the actual influences of wheel load, wheel size, wheel slip, soil conditions, and slope inclination on performance. The experimental investigations now underway by the Mobility Branch of the U.S. Army Engineering Waterways Experiment Station should provide tentative answers to many of these questions. Determination of the soil constants to be employed in the "Soil Value System" method of analysis can not readily be made during Apollo missions. On the other hand, simple tests such as the cone penetration test can be easily conducted. Thus every effort must be made to determine whether the similitude method can be extended to lunar conditions and the treatment of special wheel types likely to be associated with lunar roving vehicles.
9. Solution of the wheel-soil interaction problem following a procedure such as that suggested in our Detailed Final Report, Section 2-IV, will be difficult and will involve full scale tests of wheels under a variety of conditions but should be undertaken nonetheless. Such a program is beyond the capabilities of our group, but should be encouraged elsewhere. Our studies of lunar rolling boulders are relevant to this effort and the theoretical analyses to be made, as well as the test results to be obtained during the summer of 1969 should provide valuable information.
10. As much information as possible must be obtained during early Apollo missions concerning the stress-deformation and strength characteristics of lunar surface soils. It is recognized that most data will not be in a form suitable for direct insertion into trafficability equations; however, these data in conjunction with test results obtained on simulated lunar soil should make the derivation of reasonable values for use in such analyses possible.

11. The following studies related to lunar vehicle trafficability are desirable.
    A. Evaluation of the strength and stress-deformation characteristics of actual and simulated lunar soils and their significance in evaluating lunar roving vehicle trafficability.
    B. Studies of gravity effects on lunar soil behavior and on the slope climbing ability of lunar vehicles.
    C. Lunar slope stability analyses.
    D. Development and testing of a cone penetrometer for gathering lunar soil data applicable to a trafficability analysis.
    E. Evaluation of other devices proposed for acquisition of lunar soil data.
    F. Theoretical and experimental study of the interaction between rolling spheres and soil and extension of the findings to the assessment of probable wheel-soil interaction mechanisms.
12. The encouraging results of the engineering performance tests on stabilized soil cylinders and the successful formation of urethane foamed plastic in vacuo suggest that the potential lunar engineering applications of urethane foamed plastics might become realities. However, the techniques developed to this point fall short of those that will be necessary for full-scale lunar application. Among many proposals to be considered for further work in the research program, the following emerge as the most critical:
    A. The continued development of foamed plastic chemical systems for use in vacuo.
    B. Study of the effect of extreme temperature conditions on the foaming process and the subsequent development of chemical systems to operate effectively under these conditions.
    C. Study of the relationship of the properties of stabilized soil cylinders to those of stabilized soil deposits as simulated by larger scale tests.

D. Combining the results of the research on (A), (B), and (C) for stabilization of a simulated lunar soil deposit under simulated lunar environmental conditions.

13. Concurrent with the above research it would be desirable, although secondary in importance, to investigate the following:

A. Characteristics of stabilized soil that might be achieved by mixing a chemical foamed plastic system directly with soil.

B. The use of foamed plastic for protection and preservation of lunar surface material samples for earth-return operations.

14. If the actual lunar soil proves to be as impervious as the simulated soil, injection grouting will not be a suitable means for stabilization, although direct mixing with foamed plastics might be. Injection of jointed rock masses and rubble may still be desirable objectives. Furthermore direct application of foams to the walls of cavities or structures may be useful for sealing and insulating purposes. Because of the versatility and adaptability of these materials for such purposes, continued serious study is recommended in conjunction with planning for extended lunar exploration and future development of the moon.

15. It is recommended that the boulder track analysis be further studied to refine the method and to accumulate more data on lunar surface materials. Development of a better theory based on a more realistic failure mechanism for the rolling sphere-slope interaction problem is needed. It is planned to investigate the actual failure mechanism involved in the formation of a track by

a rolling boulder. A rational solution to this problem will be valuable not only because of its relevance to the analysis of lunar boulder tracks, but also because of the insight it may provide into soil-wheel interaction, a problem of great importance in connection with lunar roving vehicles.

16. It is recommended that dynamic analyses of lunar slope failures be discontinued for the present. Static analyses based on data acquired during Apollo missions will, however, be of extreme value if the stability of different areas is to be assessed, and hazards related to the operation of roving vehicles and astronauts on slopes are to be estimated. Dynamic studies may be practical at a later time after suitable data are returned from Apollo seismometers.

17. It is recommended that studies on the theory of the flow of gases through porous media under lunar environmental conditions be extended and that a permeability probe that can operate under lunar conditions be designed, constructed, and tested.

18. It is recommended that a working model of a borehole probe, capable of measuring the deformability and critical stress deformation values of lunar soils and rocks under quasi-static loading, be designed, constructed, and tested in the laboratory and the field. Parallel with the development of this instrument, theoretical and experimental studies presently underway should be continued toward developing analytical techniques for the quick handling, processing and evaluation of return data obtained from the probe.