GEOTECHNICAL ENGINEERING

dry-08633

MATERIALS STUDIES RELATED TO LUNAR SURFACE EXPLORATION

by

J. K. MITCHELL
I. S. E. CARMICHAEL
R. E. GOODMAN
J. FRISCH
P. A. WITHERSPOON
F. E. HEUZÉ

SUMMARY TECHNICAL REPORT

PREPARED FOR MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA UNDER NASA CONTRACT
NSR 05-003-189

APRIL, 1969

SPACE SCIENCES LABORATORY

UNIVERSITY OF CALIFORNIA · BERKELEY

GEOTECHNICAL ENGINEERING

MATERIAL STUDIES RELATED TO LUNAR SURFACE EXPLORATION

By

James K. Mitchell
Ian C. Carmichael
Joseph Frisch
Richard E. Goodman
Paul A. Witherspoon
Francois E. Heuzé

SUMMARY TECHNICAL REPORT

Prepared for Marshall Space Flight Center
Huntsville, Alabama, under NASA Contract
NSR 05-003-189

April 1969

Space Sciences Laboratory

University of California, Berkeley 94720

TABLE OF CONTENTS

SUMMARIES OF STUDIES AND CONCLUSIONS

LIST OF ILLUSTRATIONS

LIST OF TABLES

PREFACE

This report summarizes the results of studies conducted during the period March 6, 1967 - June 30, 1968, under NASA research contract NSR 05-003-189, "Materials Studies Related to Lunar Surface Exploration." This study was sponsored by the Advanced Lunar Missions Directorate, NASA Headquarters, and was under the technical cognizance of Dr. N. C. Costes, Space Sciences Laboratory, George C. Marshall Space Flight Center. Complete results of the work are presented in a four volume Detailed Technical Report.

The results summarized herein represent the combined effort of five faculty investigators and a full time project manager/engineer assisted by six graduate research assistants, representing several engineering and scientific disciplines pertinent to 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 lunar soil mechanics and the engineering properties of lunar soils. Co-investigators were Ian C. Carmichael, Professor of Geology, in charge of geological studies; Joseph Frisch, Professor of Mechanical Engineering, who was responsible for analysis of friction and adhesion problems and the testing of materials under high-vacuum conditions; 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. Francois E. Heuzé, Assistant Specialist, served as project manager and contributed to studies in the areas of rock mechanics and engineering geology.

INTRODUCTION

It is axiomatic that, among the myriad of technical and scientific factors that must be considered in the lunar exploration program, the nature of lunar soil and rock surface materials is of prime importance in the design of spacecraft landing and surface mobility systems, the design of experiments to be conducted on the lunar surface, mission planning, and, ultimately, to mission success. Without specific knowledge of the mechanical properties of lunar soils, designers and mission planners have no choice but to adopt ultraconservative designs and procedures in an effort to insure astronaut safety. Thus it is of paramount importance that as much specific information as possible about lunar surface material properties be obtained prior to the first manned lunar mission, and that planning and design options for further missions remain open thereafter in order to accommodate changes as more and more specific data become available.

The studies summarized in this report were initiated in an effort to better define both the surface material related engineering problems and the relevant properties of the materials themselves. Information developed as a result of this effort was then utilized in specific studies of problems considered to be of critical importance and for the development of analysis and testing methods that appear particularly promising for the study of lunar surface properties by both remote and tactile means.

The scope of work accomplished during the contract period is indicated by the following list of contents of the Detailed Technical Report. The names of the investigators associated with each phase of the work are indicated.

VOLUME I

LUNAR SOIL MECHANICS AND SOIL PROPERTIES

1. Lunar Soil and Rock Problems and Considerations in Their Solution
   (James K. Mitchell)
2. Engineering Properties of Lunar Soils
   (James K. Mitchell and Scott S. Smith)
3. Material Properties Evaluations from Boulder Tracks on the Lunar Surface
   (James K. Mitchell and Scott S. Smith)
4. Impact Records as a Source of Lunar Surface Material Property Data
   (James K. Mitchell, Donald W. Quigley and Scott S. Smith)

5. Lunar Stratigraphy as Revealed by Crater Morphology
   (Francois E. Heuzé and Richard E. Goodman)
6. Geochemical Studies
   (I. S. E. Carmichael and J. Nicholls)

VOLUME II

APPLICATION OF GEOPHYSICAL AND GEOTECHNICAL METHODS TO LUNAR SITE EXPLORATION

1. The Application of Geophysical Methods to Lunar Site Studies
   (Richard E. Goodman, Jan J. Roggeveen and Francois E. Heuzé)
2. Investigation of Rock Behavior and Strength
   (Francois E. Heuzé and Richard E. Goodman)
3. The Measurement of Stresses in Rock
   (Francois E. Heuzé and Richard E. Goodman)
4. The Measurement of Rock Deformability in Bore Holes
   (Richard E. Goodman and Francois E. Heuzé)

VOLUME III

PRELIMINARY STUDIES ON SOIL/ROCK ENGINEERING PROBLEMS RELATED TO LUNAR EXPLORATION

1. Trafficability
   (James K. Mitchell, Scott S. Smith and Donald W. Quigley)
2. Friction and Adhesion in Ultrahigh Vacuum as Related to Lunar Surface Explorations
   (J. Frisch and U. Chang)
3. Utilization of Lunar Soils for Shielding Against Radiations, Meteoroid Bombardment and Temperature Gradients
   (Francois E. Heuzé and Richard E. Goodman)

VOLUME IV

PRELIMINARY STUDIES FOR THE DESIGN OF ENGINEERING PROBES

1. The NX-Borehole Jack for Rock Deformability Measurements
   (Richard E. Goodman, Tran K. Van and Francois E. Heuzé)
2. Permeability and Thermal Conductivity Studies for Lunar Surface Probes
   (Paul A. Witherspoon and David F. Katz)

The principal conclusions resulting from each of these studies are presented in this Summary Technical Report, followed by a listing of recommendations pertinent to the advancement of lunar exploration technology.

SUMMARIES OF STUDIES AND CONCLUSIONS

LUNAR SOIL AND ROCK PROBLEMS AND CONSIDERATIONS IN THEIR SOLUTION

Geotechnical engineering problems that are related to lunar exploration can be divided into (1) those needing solution for early lunar science missions and (2) those related to extended lunar exploration and the development of lunar bases. Among the most important concerns during early missions are bearing capacity of the lunar surface, surface erosion by rocket exhaust, system contamination, lunar surface trafficability, sampling, and identification of hazard areas. When extended exploration and lunar base development begin, then problems of excavation, underground construction, insulation and shielding, and construction materials will become important.

Tables have been prepared, presented in Vol. I of the Final Report, which indicate

1. The major problem areas and the specific properties of lunar materials that must be known if reasonable solutions are to be obtained.
2. Approaches to determination of the different properties and priorities for property determination.
3. Some specific test methods that might be used to acquire the needed data for evaluation of properties. This table is reproduced here as Table 1.

It is concluded that knowledge of lunar soil density, compressibility, stress-strain, and strength are of greatest importance, but that this knowledge will, for the short range at least, have to be acquired using less than ideal test techniques.

TABLE 1

TEST METHODS FOR LUNAR SOIL AND ROCK ENGINEERING PROPERTY DETERMINATION

Property	Possible Test Methods (In Order of Decreasing Ease of Performance)	Suitability of Existing Methods
1. Visual classification and general description	Direct observation of samples and photographs	Adequate
2. Grain size, shape, and size distribution	Photographs	Limited by camera resolution and to surface material
	Direct observation	Adequate for coarse particles
	Sieving	ERS* only
	Light microscope	Adequate
	Electron microscope	ERS only
3. Penetration resistance	Remote sensing	
	(a) crater ejecta as penetrators	Under investigation
	(b) dropped penetrators	Potentially useful
	Direct	
	(a) cone penetrometers	Probably very useful
	(b) dynamic (hammers)	Standard penetration test used for terrestrial soils not practical on moon
4. Density	Remote sensing	
	(a) penetration records	(a)(b)(c) require assumption of other soil parameters
	(b) thermal properties	
	(c) slope analyses	
	(d) Surveyor scoop type experiments	Not known
	(e) nuclear density meters	Give variable results

---

*Earth-returned samples

TABLE 1 (Continued)

Property	Possible Tests Methods (In Order of Decreasing Ease of Performance)	Suitability of Existing Methods
4. Density (continued)	Sampling — various field density methods	Should be adequate
	Bore hole probes with nuclear units	Under development
5. Strength, including friction and cohesion	Remote sensing — lower bound values from stability of existing slopes	Requires assumption of other soil properties
	Landing dynamics records	Requires assumptions of other soil parameters
	Penetration tests	See 3
	Vane shear tests	Probably useful in fine-grained, weak materials
	Direct shear tests	Good for ERS, may be difficult on moon
	Triaxial shear tests	Good for ERS, may be difficult on moon
	Transient and cyclic loading	Good for ERS, difficult on moon
6. Stress-strain characteristics	Landing dynamics	Requires assumptions
	Instrumented penetrometers	Unknown
	Seismic response characteristics	
	Strength tests	Adequate
	Plate load tests	Adequate
7. Adhesion properties	Observation of material sticking to instruments, etc.	
	Shear along contact surface between unlike materials	Not known

TABLE 1 (Continued)

Property	Possible Tests Methods (In Order of Decreasing Ease of Performance)	Suitability of Existing Methods
8. Dynamic moduli	Records of landing dynamics	Requires assumption of other soil properties
	Data from strength tests	Adequate, but requires undisturbed sample
	Seismic surveys — wave propagation	Depends on complexity of soil and rock profile
	Plate load tests	May be difficult on moon
	Vibration and cyclic load tests	May be useful, at least on ERS
9. Permeability	Calculation from grain size and porosity	Fair for sand sizes, unsatisfactory for finer material
	In-situ bore hole test-gas	Should be developed
	Direct measurement on samples	Adequate for ERS
10. Thermal properties (conductivity and heat capacity)	Remote sensing (a) Infrared (b) Other	(a)(b) require assumptions
	Direct	
	(a) emplaced temperature sensors	Adequate
	(b) borehole probe	Under development
	(c) thermal conductivity tests	Adequate
11. Porosity	Remote sensing	
	(a) albedo	(a)(b)(c) require assumptions
	(b) thermal properties	
	(c) radar, radio wave, etc.	
	(d) photographs	
	Direct determination in-situ or on samples	Adequate

TABLE 1 (Continued)

Property	Possible Tests Methods (In Order of Decreasing Ease of Performance)	Suitability of Existing Methods
12. Relative density	Penetration tests	Large experience factor needed to develop classification
	Sampling	Unsatisfactory for cohesionless materials
13. Durability	Visual observation Response to changes in environmental conditions	
	Standard degration tests	Adequate for ERS
14. Composition	Remote (a) photographs (b) thermal, electrical, magnetic properties	(a)(b) require assumptions
	Direct (a) visual observation (b) borehole camera (c) microscope (d) x-ray diffraction (e) chemical analysis (f) electron microscope	
15. Absolute stresses	Empirical, based on (a) sonic velocity (b) resistivity	Questionable (unreliable)
	Bottom hole convergence	Still being worked on
	Overcoring	To be adapted (satisfactory on earth)
	Flat jack	Cannot use in bore hole

ENGINEERING PROPERTIES OF LUNAR SOILS

A critical review of available information from 34 sources concerning the properties of lunar soils has been made, with emphasis on information derived from Ranger, Orbiter, Surveyor and Luna Programs. A detailed tabulation of the property values and the methods used for their determination is given in Table 2-1 of the Detailed Final Report. As a result of this review tentative values for use in the analysis of engineering problems have been selected and are presented in Table 2. Also indicated in Table 2 are estimates presented by Bank* which reflect the results of studies by the Jet Propulsion Laboratory in connection with the Surveyor Program. It may be seen that in general the values corroborate each other.

---

*Bank, H. Letter to O. H. Vaughan and N. C. Costes, MSFC, March 21, 1968.

TABLE 2

SUMMARY OF LUNAR SOIL PROPERTY VALUES

PROPERTY OR CHARACTERISTIC	PROBABLE VALUE	
	THIS REVIEW	JPL ESTIMATE*
SOIL AND SURFACE PROFILE	Fragmental layer of variable thickness. Max. slopes of 33 - 35° (crater sides)	Max. slopes of 34 - 35°
COMPOSITION	Similar to terrestrial iron-rich basalt	—
PARTICLE SIZES	Size Range: boulders to 2μ; bulky particles; varying angularity	2μ - 60μ (fine friction) 50% < 10μ Distribution curves available for 1 mm - 10 m, Surveyor sites
DENSITY		
UPPER FEW MILLIMETERS	0.6 - 1.2 gm/cm^3	0.7 - 1.2 gm/cm^3
BELOW TOP FEW MILLIMETERS	1.0 - 2.0 gm/cm^3	1.5 gm/cm^3
COMPRESSIBILITY	Relatively incompressible below top few millimeters (under spacecraft and SMSS loadings)	—
STRENGTH PARAMETERS		
COHESION	0.02 - 0.5 psi	0.07 - 0.26 psi (0.048 - 0.180 N/cm^2)
ANGLE OF INTERNAL FRICTION	33 - 37°	37 - 39°
BEARING CAPACITY	Increases with depth and breadth of loaded area. A few psi near surface. See text.	Variable with depth Static (average) - 5 psi Upper few mm - 0.15 psi 2 cm depth - 2.7 psi 5 cm depth - 8.2 psi
DYNAMIC PROPERTIES		
EFFECTIVE SPRING CONSTANT (MODULUS)	7000 psi	
PERMEABILITY	1 x 10^{-8} - 7 x 10^{-8} cm^2 (Reasonable, but assumptions needed for determination)	1 x 10^{-8} - 7 x 10^{-8} cm^2

---

*Bank, H. (see text).

MATERIAL PROPERTY EVALUATIONS FROM BOULDER TRACKS ON THE LUNAR SURFACE

The analysis of boulder tracks on the lunar surface as seen in Lunar Orbiter photographs should be potentially rewarding in terms of yielding information on soil and rock variability at different locations. Reasonable quantitative determinations should be possible in those cases where relatively accurate values of boulder size, track shape and sinkage, and slope angle can be obtained, as should be the case for some of the Surveyor results, and as will be possible during Apollo missions. Theoretical and experimental studies are desirable in order that a rational analytical framework may be developed. The results will be useful not only for boulder track analysis, but also for study of the lunar roving vehicle trafficability problem.

The Sabine D boulder track was analyzed using several methods in addition to those already presented in the literature. The results of these analyses are summarized in Table 3. It was shown, using bearing capacity factors for footings on sand slopes, that a boulder of specific gravity similar to that for terrestrial rocks; i.e., 2.7-3.0, would be unstable on a 30° slope having Surveyor soil characteristics. On the other hand it would be stable on a 13° slope, the estimated slope on which the Sabine D boulder finally came to rest.

Analysis of the boulder within the framework of empirical correlations developed for constant velocity rolling of spheres down slopes of cohesionless soil led to the very reasonable boulder density estimate of 3.0. From application of an empirical equation developed to describe the rolling resistance of a rigid wheel in sand a boulder density of 3.5 was obtained. An estimate obtained using trafficability relationships based on the soil value system gave a density of 2.7 for an assumed value of n equal to 1. An analysis based on similitude relationships for trafficability gave an unrealistically low value for density. In all cases the estimates involved a number of approximations and assumptions.

Whatever the methods ultimately selected for boulder track analysis, it will be imperative that the same method be applied in the same manner to all tracks if meaningful comparative results are to be obtained. It is recommended that a rational theory for description of the mechanics of boulder track formation be developed for this purpose. It should be noted that only regular, continuous tracks have been considered thus far. Tracks formed by bouncing, skipping, and skidding boulders must be analyzed separately.

TABLE 3

ANALYSIS RESULTS — SABINE D BOULDER TRACK

Investigator	Analysis Method	Measured Input Data	Assumed Input Data	Derived Quantities
Nordmeyer (1967)	Static bearing capacity: $Q_{ult} = \pi R^2 \left(1.3\ cN_c + d\rho g\ N_q + 0.6\ \rho g\ RN_\gamma\right)$	Bearing area, Boulder volume	$c = 0.05$ psi, $\phi = 33°$ soil density = 1.55 gm/cm^3	Boulder density = 2.6 (horizontal surface) Boulder density = 2.7 (30° slope)
Authors	Footing on slope (Meyerhof, 1957) $q_{ult} = cN_{cq} + \rho g \frac{B}{2} N_{\gamma_q}$	Footing width, Bearing area	$c = 0$, $\phi = 37°$, $(\rho g)_{soil} = 1.55$ gm/cm^3	Boulder density = 1.76 on 30° slope Boulder density = 3.70 on 13° slope (Analysis shows that boulder of specific gravity ∿ 3.0 will roll on a 30° slope and come to rest on a 13° slope)
Filice (1967)	Lower bound bearing capacity. Front half of circular area under boulder supports boulder.	Bearing area	Boulder density = 2.70 gm/cm^3	Bearing capacity = 25 lb/in.^{2} (17.2 N/cm^2)
Eggleston (1967)	Static bearing capacity. Boulder supported by circular segment	Bearing area	Boulder density = 2.70 gm/cm^3	Bearing capacity
Nordmeyer (1967)	Work done in rolling = work of soil compression	Track dimensions, Boulder volume	$c = 0.05$ psi, $\phi = 33°$, soil density = 1.55 gm/cm^3	Boulder density = 1.2 gm/cm^3
Authors	Empirical correlations by Gray (1967) between track dimensions, soil properties, sphere characteristics, sand slope angle for constant velocity rolling	Track width, Boulder diameter, Boulder sinkage	$\phi = 37°$	Constant rolling velocity on 27.5° slope Boulder density = 3.0 gm/cm
Authors	Rigid wheel in frictional soil. Freitag (1965) equation: $\frac{P_T}{W} = \frac{8}{G}\left(\frac{W^{1/2}}{b^{1/2}\ D}\right)$	Surveyor soil conditions, Boulder volume	Cone index gradient = 5 lb/in^3	Boulder density vs slope angle for constant rolling velocity
Authors	Bekker (1960) soil value system $N = \frac{bK\sqrt{DZ}}{3} \quad Z^n(3 - n)$	Track width, Boulder sinkage, Boulder diameter	$k_c = 0$, $k_\phi = 5$, $n = 1$	Boulder density = 2.72 for 30° slope
Authors	Similitude (Green, 1967) Sand loading number = $\frac{G(bD)^{3/2}}{W}$	Boulder sinkage, Boulder density	Boulder deflection = 0, Cone index gradient = 5 lb/in^3	Boulder density = 0.72 gm/cm^3

IMPACT RECORDS AS A SOURCE OF LUNAR SURFACE MATERIAL PROPERTY DATA

Lunar Orbiter photographs show many secondary impact craters formed by ejecta blocks thrown out during the formation of primary craters on the moon. In an attempt to study the lunar surface homogeneity from these photographic records, Dr. H. J. Moore of the Astrogeology Branch, U. S. Geological Survey, developed the following equation semi-empirically for penetration of a projectile into the ground,

$$\frac{P}{L} = c \left(\frac{\rho_p}{\rho_t}\right)^{\frac{1}{2}} \frac{1}{g^{1/2}} \frac{V_o}{L^{1/2}}$$

where P = depth of penetration, L = length of projectile, c = constant, ρ_p = mass density of the projectile, ρ_t = mass density of the target material, g = acceleration of gravity, and V_o = vertical component of the impact velocity of the projectile. From an analysis of secondary impact crater data from Orbiter photographs using this equation Moore concluded that the lunar surface is inhomogeneous over the areas investigated.

Because this conclusion is at variance with the findings at the five Surveyor landing sites, further study was made of relationships that might be used for study of secondary impact craters. The Moore equation can be modified to the form

$$P = K\, Q^{1/2}\, V_o$$

where K is a soil constant and Q is the weight of the penetrator divided by the cross sectional area. Available data on low impact velocity (<200 fps) projectile penetration into the ground were examined using several equations. The data examined included penetration records for several soil types. It was found that the modified form of the Moore equation provides the best relationship between soil type and projectile penetration on earth. Because of this and because of its simple form, its use for further analysis of secondary impact craters is recommended in preference to the other equations that were examined.

However, examination of the assumptions required for the analysis of lunar secondary impact craters indicate that there exist great possibilities for error which can completely negate the purpose of the analysis if it is applied in the hope of determining absolute soil property values. It appears that at the present time conclusions can only be drawn concerning lunar soil variability on the basis of lunar secondary impact crater data.

Information on secondary impact craters has proved beyond any doubt that large areas of the moon's surface are covered by soil to a depth of at least one to two meters. Because the boulders bounced out of the secondary craters, it would appear that the lunar soil (or underlying rock) offers a significant resistance to penetration.

It is to be hoped that continued study of secondary cratering phenomena will lead to a reduction of the undertainties in the analyses, and that more specific quantitative estimates of soil properties can be obtained.

LUNAR STRATIGRAPHY AS REVEALED BY CRATER MORPHOLOGY

The extent and thickness of the lunar surficial layer will play a major role in

1. Trafficability analysis of planned traverses
2. Optimization of borings for sampling purpose
3. Analysis of foundations for major structures
4. Construction of excavations and embankments.

A critical review was conducted of the techniques used so far to determine lunar stratigraphy from crater morphology. They are:

1. Comparative studies of Ranger photographs--and laboratory simulation of overlay deposition (Jaffe, 1965,1966)
2. Direct studies of Orbiter and Surveyor photographs--Analysis of block fields, terraces and outcrops
3. Comparative studies of Orbiter photographs--Considerations of impact crater morphology (Quaide and Oberbeck, 1967,1968)
4. Use of a mathematical model for time-dependent lunar crater rim-erosion and floor deposition (Roos, 1968)

The results of all studies are summarized in the Detailed Technical Report (Vol. I, Chapter 5) in terms of technique used, location of area studied on the moon, crater diameter range, probable origin of crater, and estimated depth of surficial lunar layer.

Studies based upon visual observation of lunar craters and comparison with experimental results or analytical models have appreciably narrowed the range of conclusions regarding the lunar surface stratigraphy. Most maria surfaces are believed to be overlain by a layer of fine grained, cohesionless to weakly cohesive fragmented rock whose thickness varies from a few meters to a few tens of meters (see Table 5.1, Ch. 5, Vol. I). Compressibility decreases and average grain size increases from the surface down. Rubble is probably present. This fragmental blanket can probably be excavated and handled without the use of explosives except in the vicinity of large craters where very large blocks may be found.

For final mission planning at specific sites, extensive high resolution photographic coverage is required, and the interpretation should rely upon visual observation (Lunar Orbiter Photo Data Screening Group 1967,1968). Other procedures are still too open to varied interpretations at the present time.

GEOCHEMICAL STUDIES

Study was made of the probable characteristics of lunar lava and the implications of these characteristics in the interpretation of lunar composition and history. It was concluded that because the availability of oxygen in the lunar and terrestrial environments is different the properties of lunar and terrestrial basalt may differ, especially with respect to the magnetic minerals.

It is suggested that interpretation and collection of remnant magnitization in returned lunar samples may be constrained by the possibility that the carriers of magnetization, the Fe-Ti oxides, could have Curie temperatures intermediate between the diurnal temperature limits.

THE APPLICATION OF GEOPHYSICAL METHODS TO LUNAR SITE STUDIES

Geophysical methods can be divided into two categories: those which measure naturally existing fields, and those which measure artificially created fields. Measurements of naturally existing fields, such as gravitational and magnetic, reflect average conditions over large volumes. On the other hand, seismic, electrical resistivity, or conductive electromagnetic methods which make use of artificially created fields can usually be so designed as to resolve the effect of local structural features. All geophysical methods however are dependent for their success upon an appreciable contrast in physical properties between the body to be studied and the material surrounding it.

Lunar engineering problems which can be investigated using geophysical methods include those which concern: location and delineation of soil deposits; foundations; excavations; location and delineation of natural cavities; determination of engineering properties of soils and rocks; and characterization of lunar resources.

The applicability of specific techniques to specific problems is summarized in Table 4.

TABLE 4
APPLICABILITY OF GEOPHYSICAL TECHNIQUES TO THE SOLUTION OF LUNAR SOIL/ROCK ENGINEERING PROBLEMS

Soil or Rock Attribute	Application	Geophysical Method*
Deformability of Soils	Foundations	Seismic (M)
Shear Strength	Slope Stability	None
Density	Excavations; Shielding; Foundations	Gravity (M) Seismic (M)
Porosity	Storage Underground	Resistivity**(M)
Soil Profile and Depth to Rock	Excavations; Foundations	Seismic (I) Gravity (I)
Underground Cavities	Trafficability; Storage Underground	Seismic (I) Gravity (I)
Ease of Removal	Excavations	Seismic (I)
Dynamic Response Spectrum	Foundations of Rotating Towers	Seismic (M)

*M = property closely related to directly measured quantities.

I = property inferred through correlations or from comparison of measured response with idealized terrain models.

**Probably inapplicable to lunar exploration because of the expected total absence of pore fluids.

INVESTIGATION OF ROCK BEHAVIOR AND STRENGTH

Whereas, until a few years ago, design of structures in rock was still approached on the basis of experience and rule-of-thumb, recent developments in Rock Mechanics are providing more and more dependable and realistic tools of investigation, the use of which appears vital for sound engineering practice, be it earthly or lunar.

Four steps are involved in the design of any rock structure (Deere, 1967):

1. Determination of boundary conditions
2. Determination of the engineering properties of materials through in situ and laboratory testing programs
3. Prediction of structure behavior
4. Assessment of actual performance

The second step is considered here. A summary listing and rating of rock testing techniques for behavior and strength, in the laboratory and in situ, are presented in Tables 5 and 6.*

In the present state-of-the-art design is mostly based on in situ behavior and laboratory strength analyses, owing to the bulkiness of field equipment. However instruments can be designed to operate in boreholes on the moon, (Goodman, Van and Heuzé, 1968), and meaningful laboratory tests can be performed on a limited quantity of returned samples, to yield, directly or through correlation techniques, reliable data on lunar rock strength and behavior that are needed for a sound planning of lunar exploratory missions.

---

*For bibliography, the reader is referred to the Vol. II, Chapter 2 of the Detailed Final Technical Report.

TABLE 5

IN - SITU TESTING OF ROCK BEHAVIOR AND STRENGTH

	TESTS	REFERENCES	STRENGTH PARAMETERS		BEHAVIOR PARAMETERS			INTERPRETATION FORMULAE	USEFULNESS IN EARTH ROCK ENGINEERING	ADAPTABILITY TO LUNAR EXPLORATION
			ϕ	Others	Elasticity	Linearity	Fracturing			
DYNAMIC	SEISMIC (surface and subsurface)	8, 10, 12, 13, 19, 28, 40, 41, 45, 50, 51, 53, 56, 57	No	No	Yes	No	Yes	$V_\ell = \left[\frac{Ed\,(1-\nu)}{\rho(1+\nu)\,(1-2\nu)}\right]^{1/2}$ $V_s = \left[\frac{Ed}{\rho \cdot 2\,(1+\nu)}\right]^{1/2}$	B E_d not used for design purpose.	A Scientific use. Part of moon drilling program.
STATIC *	PLATE BEARING	5, 18, 24, 26, 52, 67, 68, 69, 76	No	NO Yes in soils	Yes	Yes	Yes ?	$E_{tot} = \frac{K \cdot P\,(1-\nu^2)}{\delta \alpha}$ and E_t	A However very cumbersome.	C Too bulky.
	PRESSURE CHAMBER	18	No	No	Yes	Yes	Yes ?	$E_{tot} = \frac{p_i\, a^2\,(1+\nu)}{r \cdot \delta_r}$	B Very bulky. Too limited use.	C
	FLAT JACK	1, 25, 28, 44, 55, 58, 64, 65, 66, 71	No	No	Yes	Yes	No ?	see ref. 26 for E, ν	B Surface only is investigated Severe edge effects.	C
	SHEAR	7, 28, 63	Yes	C	Yes	Yes ?	Yes ?	$\tan \phi = \frac{F_S - C}{F_N}$	A ? Very cumbersome. Little experience.	C Too bulky
	COMPRESSION	72	Yes?	No	Yes	Yes	Yes ?	$E_t = \frac{\Delta \sigma_1}{\Delta \epsilon_1}$ $\sigma_3 = 0$	? Very little experience.	C
	ROCK DEFORMETERS	15, 42, 43, 55, 73, 74	No	No	Yes	Yes	No ?	$E_t = \frac{\Delta \sigma}{\Delta \epsilon}$ at depth	A Most valuable for deep investigation.	B ?
	LOG OF BORINGS	17, 18	No	RQD ?	No	No	Yes	—	A Should be done at site of any test.	A As a part of moon drilling program.

* Does not include bore-hole techniques (see ref. 22)

ADAPTABILITY RATING		
	A	Feasible in a lunar program.
	B	Severe problems in use on the moon - could be considered in a later stage.
	C	Reject for lunar application.

TABLE 6

LABORATORY TESTING OF ROCK BEHAVIOR AND STRENGTH

TESTS			REFERENCES	STRENGTH PARAMETERS	BEHAVIOR PARAMETERS	NON DESTRUCTIVE	INTERPRETATION FORMULAE	USEFULNESS EARTH ROCK ENGINEERING	PRIORITY FOR TESTING OF E.R.S.
DYNAMIC		PULSE VELOCITY	11, 18, 27, 28, 37, 38, 55, 62, 66	No	E_d , ν	Yes	see Table I seismic	C	A non destructive
		RESONANCE	28	No	E ν need not be known	Yes	$E_d = K_1 \times n^2$ see ref 4	C	B check on pulse velocity non destructive
STATIC	COMPRESSION	Uniaxial	4, 9, 14, 16, 18, 28, 30, 55, 66	ϕ_r , σ_c	E_t , ν	No	$\sigma_c = \sigma_{1\max}$ $E = \Delta\sigma_1 / \Delta\epsilon_1$	A	A
		Biaxial	21, 55	No ?	E , ν need not be known	No	$E_t = -\dfrac{4ab^2 P_o}{(b^2-a^2)U}$	B	B
		Triaxial	14, 18, 28, 35, 39, 46, 49, 55, 61, 66	ϕ_r , σ	E_t , ν	No	$\sigma_1 = C + \sigma_3 \tan\phi$ $E_t = \dfrac{\Delta(\sigma_1-\sigma_3)}{\Delta\epsilon_1}$	A	A
	SHEAR	Direct shear	7, 8, 20, 59, 63, 72, 75	ϕ_r , ϕ_j Smax , Sr , C	No	No	—	A	B heavy apparatus
		Multi-stage triaxial	14, 28	ϕ_j from fracture envelope	No	No	—	A	A can be done in any triaxial test
	TENSION	Direct tension	28, 29, 31, 55	σ_t	E_t , ν (tensile)	No	$\sigma_t = [\sigma_1]\max$ $E = \Delta\sigma_1 / \Delta\epsilon_1$	A	A
		Brazilian	32, 34	σ_t	No	No	$\sigma = \dfrac{2P}{\pi DH}$	B	B simple - check on σ_t
		Rupture	14, 28	R	E	No	$R = 8PH/\pi D^3$ $E = 4PH^3/3\pi D^4 d$	A	A simple
		Torsion	28	S	No	No	$S = \dfrac{T \times D}{2J}$	C	C
	OTHERS	Creep	47, 54	No	$\epsilon = f(\text{time})$	Yes	—	B	B time consuming
		Permeability	7	No	k related to fissuration	Yes ?	see ref 34	A ? little testing done	A ?

PRIORITY RATING
A Highly recommended.
B Could be done if all A-tests conducted.
C Without immediate interest.
E.R.S. Earth returned samples.

THE MEASUREMENT OF STRESSES IN ROCK

Rock differs from many other engineering materials in that it often exists under significant initial stresses. Excavation at the surface or underground disturbs this stress field and induces a new one. The final stress state is thus directly dependent upon the initial one which must therefore be determined for any rational analyses of a rock structure.

An extensive review of techniques used for the determination of stresses in a rock mass on the earth is summarized in Table 7.

A listing and rating of probes being used for the purpose of stress measurements are given in Table 8.* The rating values are assigned using criteria which are pertinent for lunar applications.

One of the most promising gages for earth use has been designed by the U. S. Bureau of Mines and is shown in Fig. 1.

---

*Definitions of probe numbers and reference numbers are contained in the Detailed Final Technical Report, Vol. II, Chapter 3.

TABLE 7

DEVICES FOR MEASURING STRESSES IN ROCK ON THE EARTH

PROBE	REFERENCES	COUNTRY OF ORIGIN	TYPE OF INCLUSION	LOCATION	PRINCIPLE	CALIBRATION IN TERMS OF	STRESS TENSOR OBTAINED	# OF STRESS COMPONENTS A LOCATION	E NEEDED TO REDUCE DATA	OVERALL RATING FOR EARTH OPERATION
1	18, 28, 31, 33, 34, 44	South Africa	Mechanical Soft	Borehole	Overcoring	Frequency and Strain	Yes	1	Yes	B
2	32, 45, 46	South Africa	Mechanical Soft	Borehole	Overcoring	Strain	Yes	2	Yes	B
3	34, 47	South Africa	Mechanical Soft	Borehole	Overcoring	Strain	Yes	3	Yes	A
4	66	Czechoslovakia	Mechanical Soft	Borehole	Overcoring	Strain	Yes	1	Yes	B
5	49, 50	U.S.A.	Mechanical Soft	Borehole	Overcoring	Strain	Yes	1	Yes	B
6	43	U.S.A.	Mechanical Soft	Borehole	Overcoring	Strain	Yes	3	Yes	A
7	19	U.S.A.	Mechanical Soft	Borehole	Overcoring	Strain	Yes	3	Yes	A
8	53	U.S.A.	Mechanical Soft	Surface	Overcoring	Strain	Yes	2 or 3	Yes	C
9	24, 25, 35, 61	U.S.A. South Africa	Mechanical Soft	Borehole Bottom	Overcoring	Strain	No ?	2 or 3	Yes	C
10	56, 57, 59, 60	Great Britain	Mechanical Rigid	Borehole	Prestress and Overcoring	Stress	Yes?	1	No	B
11	38, 39, 40, 41	Canada	Mechanical Rigid	Borehole	Prestress and Overcoring	Stress	Yes?	1	No	B
12	22, 70	Great Britain	Mechanical Rigid	Borehole	Prestress and Overcoring	Stress	Yes?	1	No	B
13	20, 21	Sweden	Mechanical Rigid	Borehole	Prestress and Overcoring	Stress	Yes?	1	No	B
14	63, 64	South Africa	Mechanical Rigid	Borehole	Prestress and Overcoring	Stress	Yes?	3	No	B
15	48	U.S.A.	Mechanical Rigid	Borehole	Overcoring	Strain	Yes	6	No	C
16	62	Great Britain	Photo Elastic Plug	Borehole	Prestress and Overcoring	Stress	Yes?	2 or 3	No	B
17	13, 16, 17, 69	Canada	Photo Elastic Rosette	Borehole Bottom	Overcoring	Stress	No	2 or 3	No	C
18	1, 23, 54, 68	France	Mechanical Soft	Slot	Restore Initial Stress	Pressure	Yes	1	No	B
19	29	Australia	Mechanical Soft	Ring	Restore Initial Stress	Pressure	Yes	3	No	B?
20	5, 11, 12, 15, 35, 55, 58, 67	Several Countries	Electronic	Boreholes (2)	Change in-Rock-Properties with Pressure Level	Wave Velocity in Rock	No	0	No	C
21	6, 7, 8, 9, 27, 37, 65	Canada	Electrical	Borehole		Rock Resistivity	No	0	No	C
22	4	Poland	Nuclear	Boreholes (2)		Radiation Absorbtion	No	0	No	C

TABLE 8

RATING OF IN-SITU STRESS MEASURING DEVICES FOR LUNAR OPERATION

PROBE	PREVIOUS EXPERIENCE IN-SITU	EASY TO OPERATE AND INTERPRET	INSENSITIVE TO SEVERE ENVIRONMENT	REMOTE OPERATION POSSIBILITY	CAN IT BE RETRIEVED AFTER USE	EASILY INTEGRATED TO MULTIPURPOSE PROBE	CAN IT BE MINIATURIZED	OVERALL RATING
1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	B
2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	B
3	Yes	Yes	Yes?	Yes	Yes	Yes	Yes	A
4	Yes	Yes	Yes?	Yes	Yes	Yes	Yes	B
5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	B
6	Yes	Yes	Yes	Yes	Yes	Yes	Yes	A
7	Yes	Yes	Yes	Yes	Yes	Yes	Yes	A
8	Yes	Not Always	No	Yes?	No	No	Yes	C
9	Yes	No	No	Yes?	No	No	Yes	C
10	Yes	No	Yes	Yes	Not Always	No	Yes	C
11	Yes	No	Yes	Yes	Not Always	No	Yes	C
12	Yes	No	Yes	Yes	Not Always	No	Yes	C
13	Yes	No	Yes	Yes	Not Always	No	Yes	C
14	Yes	No	Yes	Yes	Not Always	No	Yes	B
15	Yes	No	Yes	Yes?	No	No	Yes	C
16	Yes	Not Always	Yes	Yes	Not Always	Yes	Yes	C
17	Yes	Not Always	No	Yes	No	No	Yes	C
18	Yes	Yes	Yes	Difficult	No	No	Difficult	C
19	No	?	Yes	Difficult	No	No	Difficult	C
20	Yes	No	Yes	Yes	Yes	No	Yes?	C
21	Yes	No	Yes	Yes	Yes	Yes	Yes	C
22	Yes	No	Yes	Yes	Yes	Yes	Yes	C

ADAPTABILITY RATING

A	USABLE IN LUNAR EXPLORATION
B	SEVERE SHORTCOMINGS - DIFFICULT TO ADAPT
C	REJECT FOR LUNAR APPLICATION

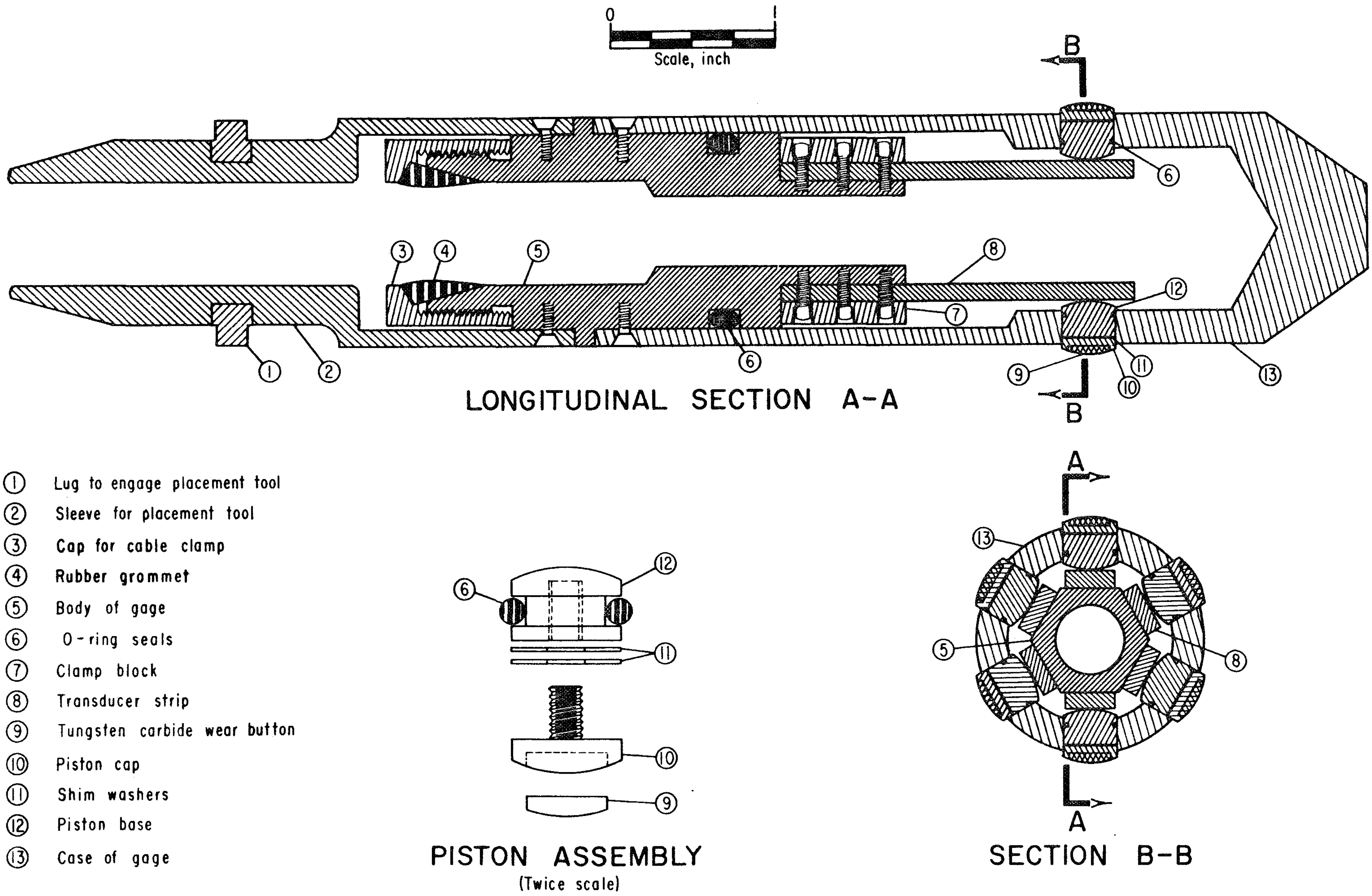

FIG. 1. Drawing of Principal Parts of the 3-Component Stress Gage Designed by the U. S. Bureau of Mines (after Merril, 1967 R. I. 7015)

THE MEASUREMENT OF ROCK DEFORMABILITY IN BOREHOLES

Mapping and description of various rock members within an earth site may require many feet of drill holes. However quantitative characterization of the rock limits on the sole basis of returned samples is apt to be misleading; the softer and weaker components tend to be lost and the fabric of the rock block-fracture system in situ is not sampled. The walls of borings form more complete samples of the rock mass.

Accordingly within the past few years a number of devices (dilatometers, borehole jacks, borehole penetrometers) have been developed which can be inserted into a borehole to apply a load and measure the response directly on its walls. They combine the advantages of reduced size and deeper investigation.

A listing and rating of these probes is summarized in the following tables.* Efforts should be directed towards the lunarization of a borehole jack using LVDT's as monitoring units. It is also recommended that the use of narrow angle jacks be investigated for testing of in situ strength characteristics of soils or rocks.

---

*A list of references is given in Vol. II, Chapter 4 of the Detailed Final Technical Report.

TABLE 9

DEVICES FOR MEASURING ROCK DEFORMABILITY IN BOREHOLES

TYPE	PRESSURE CONDITION	INTERPRETATION FORMULA	NAME OF DEVICE	METHOD OF PRESSURE APPLICATION	METHOD OF MEASURING DEFORMATION	NUMBER OF DIAMETERS MEASURED	DIAMETER OF BOREHOLE (MM)	DIAMETER OF BOREHOLE (INCHES)	LENGTH OF LOADED AREA (MM)	LENGTH OF LOADED AREA (INCHES)	MAX.CONTACT PRESSURE (PSI)	CAN IT BE RECOVERED AFTER USE?	COUNTRY OF ORIGIN	REFERENCES	REMARKS
DILATOMETERS	UNIFORM RADIAL PRESSURE ALL AROUND THE CIRCUMFERENCE OF THE BOREHOLE	$E = \frac{\Delta p}{\Delta (U_d/d)}(1+\nu)$	MENARD PRESSUREMETER	GAS PRESSURE AGAINST WATER FILLING CELL	VOLUME CHANGE ON EXPANSION	INTEGRATED EFFECT OF ALL DIAMETERS	76 60 48 32	3.0 2 3/8 2.0 1 1/2	515 502 686 910	19 1/2 19 26 34 1/2	1500	YES	FRANCE	16, 17	CONSIDERABLE EXPERIENCE RECORD
			GEOPROBE INSTRUMENT	DITTO	DITTO	DITTO	76	3.0		?	1500	YES	?	4	
			L.N.E.C. DEVICE	PUMP OIL TO EXPAND CELL	4 LVDTs	4	76	3.0	540	21.2	2200	YES	PORTUGAL	20	
			JANOD-MERMIN DEVICE	DITTO	3 LVDTs	3	168	6.6	770	30.4	2200	YES	FRANCE	10	
			COMES' CELL	DITTO	3 LVDTs	3	160	6.3	1600	63.0	2200	YES	FRANCE	2	
			TUBE DEFORMETER	DITTO	24 LVDTs	4	297	11.7	1300	51.2	660	YES	JAPAN	22	
			SOUNDING DILATOMETER	DITTO	2 "MCH" INSTRUMENTS	2	200 300	7.9 11.8	1000 1200	39.3 47.2	600 1000	YES	YUGOSLAVIA	11, 12	
BOREHOLE JACKS	UNIDIRECTIONAL FORCE OF 2 STIFF PLATES EACH CONTACTING ROCK OVER AN ANGLE 2β	$E = \frac{\Delta p}{\Delta (U_d/d)} K_1(\nu,\beta)$	N X PLATE BEARING TEST	PUMP OIL TO DRIVE PISTONS	2 LVDTs	1	76	3.0	204	8.0	9300	YES	USA	6, AND THIS ARTICLE	2β = 90°
			CENTEX CELL (CEBTP DEVICE)	PUMP OIL TO DRIVE A CONICAL MANDREL INTO A SPLITCYLINDER	DISTANCE MANDREL IS DRIVEN MEASURED INDUCTIVELY	1	76	3.0	306	12.0	?	NOT ALWAYS IN DEEP HOLES	FRANCE	7, 18	2β ≈ 140°
			GEOEXTENSOMETER (NEW CEBTP DEVICE)	PUMP OIL TO DRIVE PISTONS	2 LVDTs	1	76	3.0	306	12	5000?	YES	FRANCE	1	2β = 143°
			TALOBRE'S JACK	PUMP OIL TO DRIVE PISTONS	?	1?	56	2.2	≈120	4.7	?	YES	FRANCE	23	2β BELIEVED TO BE ABOUT 90°, INTENDED AS STRESS METER; LIMITED TO SHALLOW DEPTH
			GERMAN STRESS STRAIN METER	SPREAD WEDGES BY DRIVING A SCREW	"NO CONTACT" INDUCTION PICK UP	1	50	2.0	63	2.5	HIGH	NOT ALWAYS	GERMANY	15	SLIGHTLY <180°
			PANEK'S BOREHOLE FLAT JACK	PUMP OIL INTO A FLAT JACK CEMENTED IN THE BOREHOLE	NOT DONE AT PRESENT; COULD BE MEASURED BY GAGING ACROSS INSIDE OF FLAT JACK	1	CAN BE TAILOR-MADE FOR ANY LENGTH AND DIAMETER				3-4000	NO	USA	19	2β SLIGHTLY <180°. INTENDED AS STRESS METER; COULD BE ADAPTED BUT SEVERE EDGE EFFECTS
	RADIAL PRESSURE OVER OPPOSED 2β SECTORS	$E = \frac{\Delta p}{\Delta (U_d/d)} K_2(\nu,\beta)$	QUADRANTAL JACKS	PUMP OIL INTO CURVED JACKS IN OPPOSED QUADRANTS	RESPONSE OF PASSIVE JACKS IN OTHER TWO QUADRANTS	INTEGRATED EFFECT OF ALL DIAMETERS	DITTO				3-4000	YES	AUSTRALIA AND SOUTH AFRICA	9	2β = 90°; TEST NEVER ACTUALLY PERFORMED IN SITU· COULD BE ADAPTED FOR SHALLOW APPLICATIONS
BOREHOLE PENETROMETERS	UNIDIRECTIONAL PRESSURE OVER A SMALL AREA	EMPIRICAL RELATIONSHIP	BUREAU OF MINES PENETROMETER	PUMP OIL TO DRIVE PISTON FORCING INDENTING PIN	DIAL GAGE EXTENSOMETER WITH CABLE DRIVE	1	32	1.25	9.5	3/8	VERY HIGH	YES	USA	21	3/8" DIAM INDENTING PIN FORCED INTO WALL; DESIGNED TO MEASURE ROOF BOLT ANCHORAGE CAPABILITY; LIMITED DEPTH
			HULT'S DEVICE	PUMP OIL TO DRIVE PISTON DEFORMING PROVING RING	STRAIN GAGES ON PROVING RING	1	32	1.25	≈3	1/8	VERY HIGH	YES	SWEDEN	8	CA 1/8" SQUARE PIECE FORCED INTO WALL BY DEFORMATION OF PROVING RING. DESIGNED AS ACTIVE STIFF GAGE FOR STRESS MEASUREMENTS
			DRYSELIUS' DEVICE (CTH 3)	PUMP OIL TO DRIVE 3 PISTONS AT 60°	STRAIN GAGES ON CANTILEVER ELEMENTS	3	44		≈5	≈0.2	VERY HIGH	YES	SWEDEN	3	3 PINS FORCED INTO WALL BY OIL PISTONS. DESIGNED AS ACTIVE STIFF GAGE

U_d = DIAMETRAL DISPLACEMENT , d = DIAMETER OF BOREHOLE , p = APPLIED PRESSURE

TABLE 10

RATING OF ROCK DEFORMABILITY MEASURING DEVICES FOR LUNAR OPERATION.

TYPE	REFERENCE	PREVIOUS EXPERIENCE FOR DEFORMABILITY TEST	EASY TO OPERATE AND INTERPRET	INSENSITIVE TO SEVERE ENVIRONMENT	REMOTE OPERATION POSSIBILITY	EASY RETRIEVAL	EASILY INTEGRATED TO MULTIPURPOSE PROBE	POSSIBILITY OF USE IN SOILS	POSSIBILITY OF USE IN RUBBLE	CAN IT BE MINIATURIZED	OVERALL RATING
DILATOMETERS	16, 17	YES	NO	NO	YES	YES	YES	YES	NO	YES	B
	4	?	NO	NO	YES	YES	YES	YES	NO	YES	B
	20	YES	YES	NO	YES	YES	YES	YES	NO	YES ?	B
	10	YES	YES	NO ?	YES	YES	YES	YES	NO	YES	B
	2	YES	YES ?	NO ?	YES	YES	YES ?	YES	NO	YES ?	B
	22	YES	NO	NO	NO	YES	NO	YES	NO	NO	C
	11,12	YES	NO	NO	NO	YES	NO	YES	NO	NO	C
BOREHOLE JACKS	6	YES	YES	YES ?	YES	YES	YES	YES	YES	YES ?	A
	7, 18	YES	NO	YES	NO	NOT ALWAYS	NO	NO	YES	NO	C
	1	YES	YES	YES ?	YES	YES	YES	YES	YES	YES ?	A
	23	NO	NO	YES ?	YES ?	YES	YES	NO	NO	YES ?	B
	15	YES	NO	YES	NO	NOT ALWAYS	NO	NO	NO	NO	C
	19	NO	NO	YES	NO	NO	NO	NO	NO	NO	C
	9	NO	NO	YES	NO	YES	NO	NO	NO	NO	C
BOREHOLE PENETRO-METERS	21	NO	YES IF SHALLOW	YES ?	NO	YES	NO	NO	NO	YES ?	C
	8	NO	NO	YES	YES ?	YES	YES	NO	NO	YES ?	C
	3	NO	NO	YES	YES ?	YES	YES	NO	NO	YES ?	C

RATING:
A COULD BE ADAPTED TO LUNAR MEASUREMENTS.
B ADAPTATION WOULD BE DIFFICULT, THUS UNLIKELY TO BE USED ON THE MOON.
C REJECT FOR LUNAR APPLICATION.

TRAFFICABILITY

Because of the severe constraints on weight, power supply, and time that will be associated with any lunar mission, as well as the need to insure safety to as great an extent as possible, a precision of design and estimation of relevant mobility factors will be needed for lunar vehicles that exceeds by far any requirements imposed on the design and performance prediction of terrestrial vehicles. Both the topographic characteristics of the terrain and the physical properties of the surface materials with which the vehicle interacts are important. Emphasis during this project has been on the surface material related factors with the objectives of (1) reviewing methods for solution of vehicle mobility problems, (2) recommending methods for use in integration of soil data into vehicle design and mission planning, and (3) recommending methods for determination of the needed soil data.

The conclusions resulting from these studies are as follows.

(1) While complete monoscopic photographic coverage of the moon has been provided by Orbiter, the small scale and limited quality and quantity of stereo coverage makes topographic analysis on the scale needed for trafficability studies difficult.

(2) Both the soil value (U. S. Army Ordnance Tank-Automotive Command Land Locomotion Research Laboratory Method) and the cone index (Army Mobility Branch, Corps of Engineers, Waterways Experiment Station) systems of trafficability analysis have been reviewed. These two systems are used most extensively for off-the-road locomotion studies at the present time. The major advantage of the soil value system is that it yields quantitative values of performance parameters, e.g. total thrust, drawbar pull, power requirements, fuel consumption, which can be used for vehicle design and mission planning. Its major disadvantages are that parts of the theoretical basis of the method are questionable, the testing required for determination of the needed soil data is complex and not readily adaptable to lunar surface operations, and it is directly applicable only to level ground conditions.

The cone index method, on the other hand, involves very simple penetration testing which could be easily adapted for lunar operations. The disadvantage of this method, however, is that the information obtained is only suitable for determination of whether a given vehicle will or will not satisfactorily negotiate a given terrain. This may possibly be overcome in the future through further development of similitude analysis techniques.

(3) A review of recent trafficability and mobility literature has indicated the following:

   a. The soil value system appears to be widely used as a basis for lunar roving vehicle analyses.
   b. It would be desirable to continue studies for development of methods of converting c, ϕ, and ρ to k_c, k_ϕ, and n.
   c. A means for conversion of cone index data to soil value system parameters would be very useful.
   d. Further analysis of bearing capacity approaches to vehicle mobility would appear desirable.
   e. An analog computer technique similar to that reported by VanDuesen (Chrysler Corp., Contract NASW-1287, May 1966) for modeling the dynamics of soil-vehicle interaction appears promising and is deserving of further study.
   f. A number of reports were reviewed which are concerned mainly with the design and testing of proposed lunar roving vehicles of various types. Many of these studies were done on simulated lunar-surface materials that were prepared without the detailed knowledge of soil conditions that has been provided by Surveyor. Some reanalysis and further testing using "Surveyor Soil" would appear in order.

(4) The Engineering Lunar Model Surface (ELMS) has been reviewed and found inappropriate for quantitative representation of lunar surface properties for trafficability analyses. Terrain characterization techniques now being developed by the U.S.G.S. are promising.

(5) A similitude approach to the solution of lunar trafficability problems is very appealing, since quantitative measures of vehicle performance could conceivably be obtained using model tests and the

results of simple soil tests; e.g. cone index. Unfortunately the similitude correlations developed by the Waterways Experiment Station for pneumatic tires do not appear suitable for description of the behavior of proposed lunar vehicle wheels; e.g. metal-elastic wheel, wire wheel. It is desirable that accelerated test programs be initiated with the objectives of (1) possible extension of the method for use with proposed lunar vehicle wheel types and (2) evaluation of key trafficability factors such as the influence of slopes, light wheel loads and contact pressures.

(6) A limited study of available data on the performance characteristics of the metal-elastic and wire wheels suggests that these designs may be overly conservative for application to the lunar surface. Some reconsideration of these designs appears in order.

FRICTION AND ADHESION IN ULTRA HIGH VACUUM AS RELATED TO LUNAR SURFACE EXPLORATIONS

Since a high vacuum environment may produce clean surfaces, friction and adhesion between contacting solids may be significantly increased relative to their magnitudes in the normal terrestrial atmosphere. The consequences of these effects may be important in the design and operation of roving vehicles or other equipment on the lunar surface.

As a part of this project a review of studies on friction and adhesion was made, followed by a design for rolling friction tests utilizing a modified form of equipment already available in our laboratories. Included in this design are provisions for ion bombardment of rock specimens to simulate solar wind conditions. The results of four preliminary tests of adhesion in vacuum between copper and obsidian and between aluminum and obsidian are presented. The purposes of these tests were to determine the capability of an existing force dynamometer, to determine the magnitude of rock outgassing and adhesion, and to determine the time needed for pump down to pressure in the range of 10^{-10} to 10^{-11} torr.

An experimental configuration has been designed for the determination of coefficients of rolling friction between a wheel and a rock surface relative to the applied load, temperature, wheel size and wheel velocity. A schematic diagram of the experimental arrangement is shown in Fig. 2. Detail drawings and descriptions of the design and operation of this apparatus are presented in Chapter 2, Vol. III of the Detailed Technical Report.

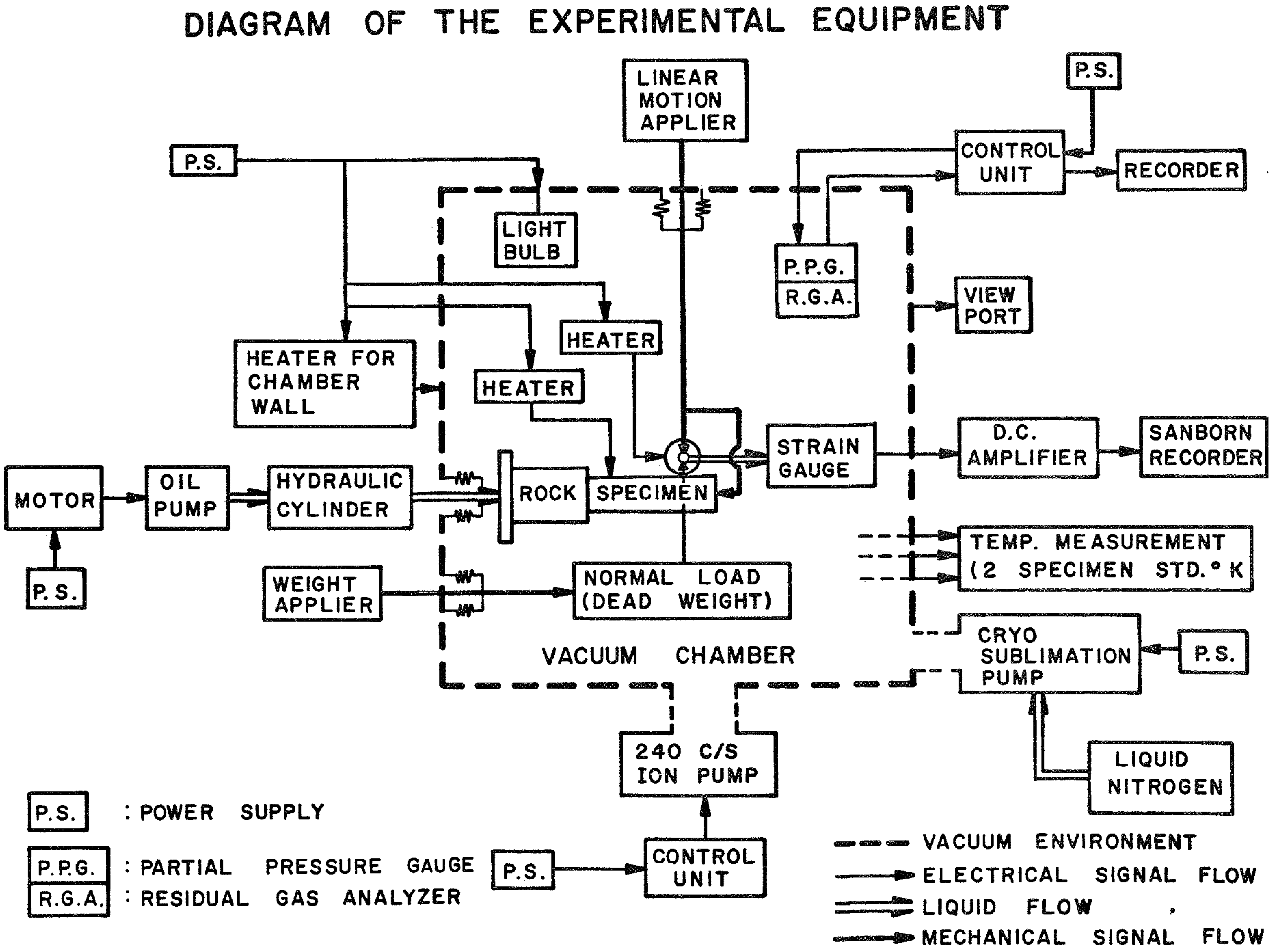

FIG. 2 . Schematic Diagram of Experimental Equipment

UTILIZATION OF LUNAR SOILS FOR SHIELDING AGAINST RADIATIONS, METEOROID BOMBARDMENT AND TEMPERATURE GRADIENTS

Protection has to be provided for astronauts on the moon against three environmental factors: radiations, meteoroid bombardment, and excessive temperature gradients. Extended stay times and payload constraints will require that some of the shielding materials be indigeneous to the lunar surface. Lunar soils may be suitable for this purpose.

Present knowledge regarding each of the mentioned hazards has been reviewed and a model selected. Lunar surface material properties used can be those selected in this report (Ch. 2, Vol. I). First estimates of shielding thicknesses are then established corresponding to a given set of assumptions whose validity is discussed. Further research needed is also outlined where it is felt that major uncertainties still exist for the establishment of final shielding specifications against a given hazard.

Shielding against radiations

Lunar radiation shielding will have to be designed against energetic solar radiation for missions longer than one week. The hazard is probabilistic.

A procedure is presented (Ch. 5, Vol. III) for determining conservative design specifications based upon mission duration, allowable total radiation dose, desired probability of no overexposure, equivalent aluminum shield thicknesses, and average lunar soil density.

Shielding against meteoroids

The meteoroid hazard is probabilistic in nature. A model is selected for the mass flux relationship of meteoroid infall.

A procedure is presented which completely determines the shield specifications against erosion and perforation given the mission length, the shield area, the desired probability of no shield failure and the maximum meteoroid mass against which the shield will be designed. Additional parameters entering the computations are the impact characteristics (ejecta and crater diameter), and the lunar soil density. As in the case of radiation shielding the procedure is expanded into typical computations for different specifications and parameter values.

Shielding against temperature gradients

The objective is to determine under which thickness of lunar soils, diurnal temperature variations will be limited to a prespecified amount (chosen here as 1°K). The problem is independent of mission length ($T > 14$ days) and of shield area.

A review of possible thermal models of the lunar surface layer leads to selection of a likely bracket for diffusion times, and corresponding computations of soil shield thicknesses.

Detailed conclusions have been drawn for each of the hazards considered in this work (Ch. 3, Vol. III). Recurring parameters vital to soil shield design have been assigned specific values or value brackets taking into account the most up-to-date knowledge of lunar surface properties, processes and environment. Overall results are summarized in Table 11.

TABLE 11

SUMMARY OF LUNAR SOIL SHIELDING STUDY

Hazard	Characteristics of the Hazard	Method of Approach	Minimum Adequate Shield Thickness (t)
Radiation	Dependent on mission length	Probabilistic	30 cm
	Independent of shield area		[1 year stay time 99.99% safety level]
Meteoroids	Dependent on mission length	Probabilistic	90 cm
	Dependent on shield area		[1 year stay time 99.99% safety level 100 m^2 shield area 10 g mass of meteoroid]
Temperature Gradients	Independent of mission length ($T > 28$ days)	Deterministic	50 cm
	Independent of shield area		[1° K Maximum temperature fluctuation]

THE NX-BOREHOLE JACK FOR ROCK DEFORMABILITY MEASUREMENTS

As described in the Detailed Technical Report (Ch. 4, Vol. II) a number of instruments have been built to measure rock and soil deformability in boreholes, whose purpose is to guide a rational design of foundations or underground openings.

Particular attention is given to the borehole jack developed by Goodman et. al., 1968, as it seems well suited for the purposes and constraints of the lunar program. This instrument is presented in Figures 3, 4 and 5.

The result of deformability testing in a borehole of diameter, d, is a curve of applied pressure, Q, versus diametral deformation. Data interpretation has been investigated in depth with respect to the following parameters: plate width, rock's Poisson's ratio, non linear rock properties, plate rigidity, crack formation, wall roughness and roundness.

The size of the test is large enough so as to be significant with respect to geologic discontinuities, and its results compare very favorably with other in situ tests for deformability which are much more expensive and cumbersome. (See Table 12).

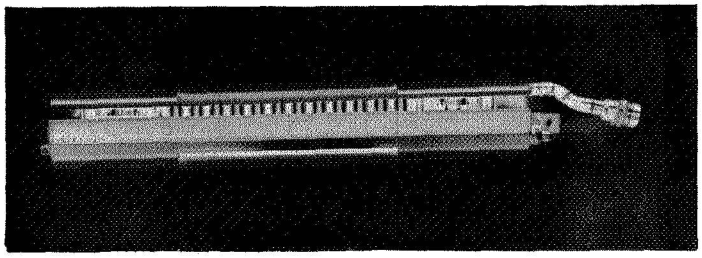

FIGURE 3. NX Borehole Plate Bearing Test Device

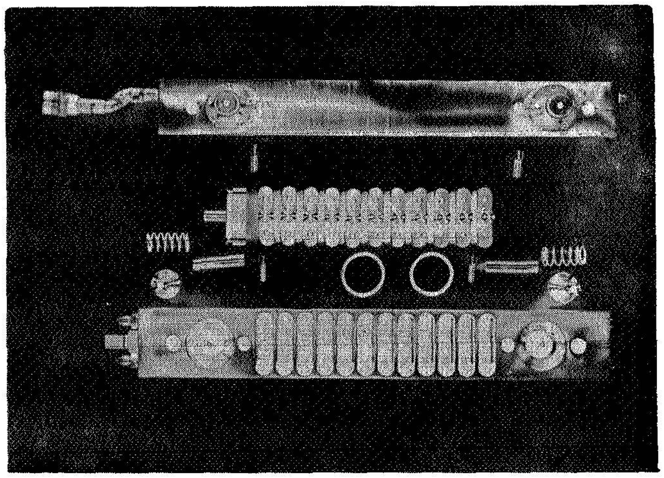

FIGURE 4. Device Disassembled

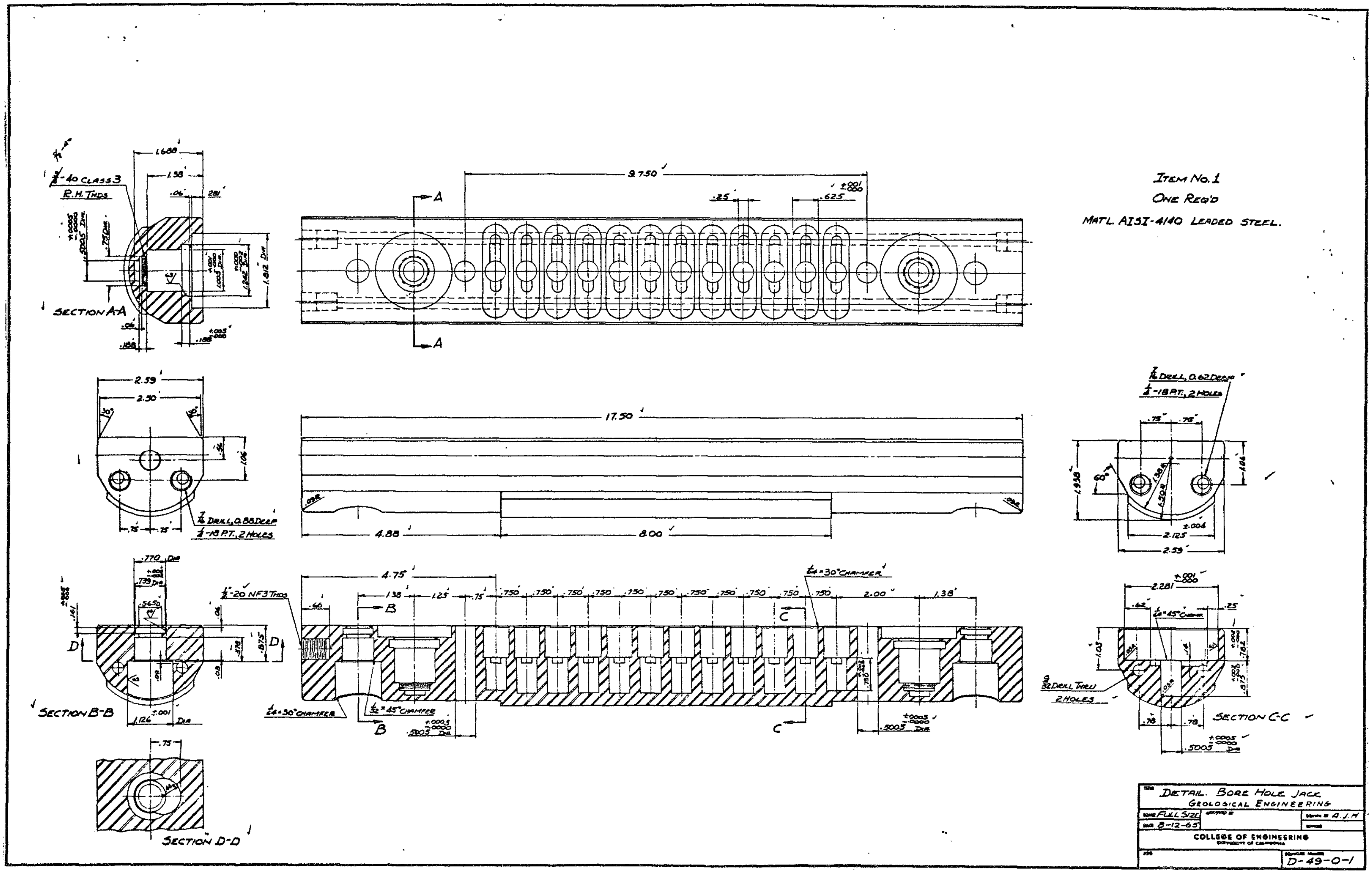

FIGURE 5
BOREHOLE JACK DETAIL

TABLE 12

SUMMARY OF TEST RESULTS

COMPARISON OF IN SITU, CORE, AND BOREHOLE JACK TESTS

Site	Rock Type	Poisson's Ratio	Young's Modulus, 10^6 psi			
			Unconfined Compression (laboratory average)	Plate Bearing (in situ)	Flat Jack* (in situ)	Bore Hole Jack* (in situ)
Tehachapi Tunnel	Diorite gneiss fractured and seamy	0.35	11.3	0.53 to 0.83		0.61 to 1.03
Dworshak Dam	Granite gneiss; massive to moderately jointed	0.20	7.5	0.5 to 5.0		1.54 to 2.70
Crestmore Mine	Marble; massive	0.25	6.9	1.74 to 2.72	1.79 to 2.98	1.35 to 1.95

*in the same pressure range 0 — 3,000 psi

PERMEABILITY AND THERMAL CONDUCTIVITY STUDIES FOR LUNAR SURFACE PROBES

Among the objectives of man's study of the moon is an understanding of the flow of heat and fluids through lunar materials. This knowledge is not only of scientific value, but it is essential to the solution of engineering problems in exploring the moon. In approaching these problems, two parameters of great importance are the transport coefficients: thermal conductivity and fluid permeability.

As a first approach to the measurement of these parameters, it is proposed that consideration be given to a surface probe, i.e. a device that will rest directly on the surface of the material to be measured. In determining thermal conductivity, heat is transferred into the material, and appropriate temperature and heat flow measurements are made. In determining permeability, a gas is injected into the material and appropriate pressure and flow rate measurements are made.

Since both these transport processes are nonlinear from a strict mathematical standpoint, consideration is first given to the corresponding linear problems. For the flow of heat, this amounts to assuming a temperature independent thermal conductivity. For the flow of gases, the problem is more complicated in that the fundamental nature of the flow process changes as pressure varies over several orders of magnitude. Such a pressure range is anticipated, due to the low absolute pressure on the moon and the relatively high pressure in flows of interest. In understanding this complex transport process, the high pressure (or continuum) range cannot be neglected. The low pressure (or rarefied) regimes may not play a significant role in the overall flow process. Consequently, the continuum range is investigated first, and for steady state flow, the process is linear.

Solutions for one possible probe configuration are obtained for both of these linear problems. The applicability of these solutions is investigated. This consists, in part, of a preliminary examination of the effects on gas flow of rarefaction.

This study is clearly only a first step and further investigations, including experimental work, are recommended. For the experiments to be meaningful, they must include investigations on porous media in vacuo.

RECOMMENDATIONS

RECOMMENDATIONS

The following recommendations are made relative to further studies of lunar surface materials and their relationships to lunar surface exploration. They are listed in the same sequence as the summary of studies in the preceding section.

1. Intensive efforts are needed to determine the extent to which data such as those provided by LM landing records, photographic coverage of landing pad sinkage and astronaut footprints, and simple tests (e.g., penetration, trenching, sliding) using the Apollo hand tools can be used to determine quantitative values of the properties of the lunar soil in situ. Useful information will be provided by examination of returned lunar samples from early Apollo missions. Because these samples will be disturbed, however, it is not likely that quantitative measurement of mechanical properties will yield results applicable to the lunar soil in situ. These investigations should be supplemented by further study of Lunar Orbiter photographs and Surveyor data.

2. A rational theory should be developed for description of the mechanics of boulder track formation, and boulder tracks on the lunar surface should be analyzed in a consistent manner. Not only will the development of such a theory be useful for deduction of surface material properties, but it will also be useful in consideration of trafficability problems.

3. Additional study of the problem of dynamic penetration of bodies into the surface of the earth and moon, to enable better interpretation of secondary impact craters and also the possible development of sensing techniques for soil evaluation using penetrators is recommended.

4. High resolution photographic coverage (resolution to at least 0.5 m) is desirable for mission planning at specific sites on the moon. This photography is needed for inference of lunar stratigraphy, definition of surface topography on a scale appropriate for studies of astronaut and vehicle mobility, and definition of possible hazards.

5. Reliable data on lunar rock strength and behavior can be used for scientific interpretation of lunar history and will be needed for proper design and construction of facilities on and under the lunar surface. Instruments should be designed to provide this information.

6. Studies are needed to define more precisely the relationships between soil data obtained using penetrometers and prediction of trafficability parameters.

7. Since the solution of the total trafficability problem requires consideration of both topographic and material characteristics, terrestrial simulations of proposed lunar vehicles or vehicle components should be carried out on carefully selected sites.

8. Abandonment of the Engineering Lunar Model Surface (ELMS) is recommended in favor of power spectral density techniques being developed by the U.S.G.S. for terrain characterization.

9. Although it appears that our knowledge of the mechanical properties of lunar surface soils exceeds our present ability to use that knowledge in a quantitative manner for the design of lunar roving vehicles and prediction of their performance, it is imperative that the tentative conclusion from Surveyor results that surface soils are reasonably similar in properties at different points on the moon be confirmed. Of particular importance also is the need for pressure-sinkage data.

   Earth-based simulations may provide one possible source for this needed information. Simulated lunar soils having the proper gradation, density, cohesion, and angle of internal friction can be prepared and tested under confining pressures representative of those on the moon. The results of such tests would provide insight into the deformation behavior of actual lunar soils. Simple tests; e.g., penetrometers, analysis of spacecraft-soil and astronaut-soil interactions during early Apollo missions, will provide invaluable data concerning lunar soil variability and, to some extent, the stress-strain behavior.

10. It is recommended that research be intensified on the problem of wheel-soil interaction with studies proceeding on two fronts.
    a. For the short range it may be possible to extend the WES similitude method to performance predictions for lunar roving vehicle wheels. Tests should be conducted using appropriate wheel types and loadings and simulated lunar soils. Investigations should be made of the influence of wheel load, wheel size, wheel slip, soil conditions, and terrain inclination as related to wheel performance parameters (sinkage, motion resistance, drawbar pull, torque). Empirical correlations thus established would probably provide as reasonable a basis as any at present for prediction of performance. If possible, soil properties should be introduced into these correlations by means of cone penetrometer test results. The test is simple, the apparatus is simple, and cone penetrometer measurements could easily be made in early Apollo missions.
    b. For the long range, intensified efforts should begin now to develop an improved understanding of the mechanics of wheel-soil interaction with the ultimate objective of the formulation of a rational theory for performance prediction. Such a theory should relate wheel characteristics, loading conditions, soil properties and performance in a consistent manner. The task is formidable and the result may be in a form so complex that it cannot be applied in a practical manner. Nonetheless the results would still serve to focus attention on (1) the relative importance of various vehicle system factors and (2) the soil properties pertinent to solution of the problem. Such a study should begin with an analysis of the interdependent character of the stresses and deformations in the wheel and soil. Modern computation methods often make such analyses possible using numerical techniques.

11. Somewhat conservative design procedures indicate that 3 feet of lunar surface materials will be a sufficient protection against radiations, meteoroid bombardment, and temperature gradients for extended missions on the lunar surface. A reduction in the above thickness might result

from the use of much more sophisticated computational techniques still to be developed. Further experimental research would then be desirable mainly in the field of radiation shielding with soils, and hypervelocity impacts in soil to verify that such reduced thicknesses are indeed adequate. It is not felt however that such investigations are within the capabilities of this working group.

12. Post Apollo development of the moon will require consideration of surface and subsurface structures in rock (shallow and deep boreholes, scientific stations, underground chambers for storage and waste disposal, etc.). Sound engineering will achieve the optimum results only if based on intimate knowledge of the modes of mechanical behavior of the materials involved. This must be true on the moon as it is on earth. Hence, there is a need for determination of moon rock load-deformation characteristics. A borehole test apparatus should be developed for operation on the moon. It should be operable to yield both deformability and strength data if possible. Experimental and theoretical work is needed to provide the basis for interpretation of soil and rock failure characteristics from borehole tests, since this capability has not yet been developed on earth. The most suitable configurations of a test apparatus for lunar boreholes can be decided only upon the basis of the results of such work.

13. Continued investigation of the theory for fluid flow through porous media in vacuo is recommended, as well as experimental work leading to the design of a surface probe for in situ determination of the permeability of lunar soils.