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LUNAR SOIL ENGINEERING AND ENGINEERING GEOLOGY

Prepared under NASA Contracts NSG-496 and NSR-05-003-189 by
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MASSACHUSETTS INSTITUTE OF TECHNOLOGY and
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Massachusetts Institute of Technology
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and

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For

Space Sciences Laboratory

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NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER

PREFACE

This paper presents the results of one phase of studies conducted during the period July 1-31, 1967, under NASA research contracts NSG-496, "Lunar Surface Engineering Properties Experiment Definition," with the Massachusetts Institute of Technology, Cambridge, Massachusetts, and NSR-05-003-189, "Materials Studies Related to Lunar Surface Exploration," with the University of California, Berkeley, California.

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LUNAR SOIL ENGINEERING AND ENGINEERING GEOLOGY

By

T. William Lambe[1] and James K. Mitchell[2]

Position Paper Prepared for NASA 1967 Summer Conference on
Lunar Exploration and Science,
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July 31 - August 13, 1967

I. INTRODUCTION

This paper sets forth objectives and recommendations for the development of a long-range program in soil engineering and engineering geology for support of lunar exploration and science. It was intended to serve as a basis for discussions at the 1967 NASA Summer Conference on Lunar Exploration and Science, University of California, Santa Cruz, July 31 - August 13, 1967 which would lead to formulation by the working groups of a sound working plan for guidance of soil and rock engineering studies. This paper is brief and many items are covered only in outline form. It is believed, however, that the major problems of lunar exploration that require attention by soil engineers and engineering geologists are noted. Types of measurements and analyses that may be used for their solution are suggested where appropriate. It is important to note that this paper was prepared prior to the Santa Cruz Conference, and, consequently, does not reflect any of the decisions or priorities established as a result of the Conference.

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II. RECOMMENDATION

A coordinated program in Lunar Soil and Rock Engineering should be initiated and developed by NASA. It is recommended that NASA establish an in-house soil and rock mechanics laboratory equipped and staffed so that sophisticated soil tests and analyses can be made. The primary function of this laboratory should be to attack the short range problems related to all lunar missions, both manned and unmanned.

Long-term support should be provided to two or three universities already strong in soil and rock mechanics and with some experience in the space program. Space science capability in related areas within the universities should be considered. The roles of the university laboratories should be to conduct basic research on lunar soil and rock properties, develop new methods for solution of lunar surface materials problems, back up the NASA in-house laboratory, train students for positions in the space program, and help define and solve the many unforeseen, but inevitable problems that will arise.

A relatively small but high quality program of this type should result in savings of money, time, and possibly life, far in excess of the investment.

III. GOALS

The ultimate goals of the Lunar Soil and Rock Engineering Program should be:

A. To develop the capability of predicting, at least in a semi-quantitative manner, soil conditions at any point on the moon on the basis of remote measurements.

B. To develop the capability for detailed quantitative determination of soil and rock properties at any chosen site where scientific or engineering work is contemplated.

C. To develop methods of analysis suitable for solution of soil and rock mechanics problems on the moon.

D. To utilize the special environmental conditions on the moon, particularly vacuum, temperature, and radiation, to obtain data that will aid in the understanding of soil and rock behavior on the earth.

IV. LUNAR SOIL AND ROCK PROBLEMS

The following are some of the major problems in lunar exploration that depend on soil and rock mechanics for solution.

A. Dynamic bearing capacity for spacecraft landing.

B. Rocket blast erosion problems.

C. Contamination of systems by eroded surface material.

D. Trafficability for roving vehicles and walking astronauts.

E. Slope stability during landing, traversing, and constructing.

F. Sampling.

G. Stability of laboratories and emplaced scientific stations.

H. Drilling.

I. Underground excavation.

J. Underground construction.

K. Underground storage.

L. Waste disposal.

M. Radiation shielding.

N. Thermal insulation.

O. Construction materials.

P. Mineral resource location.

Problems A through H are of immediate concern in the Apollo and Apollo Applications Programs. Problems I through P will become important should post-AAP development of the moon be undertaken.

V. LUNAR SOIL ENGINEERING PROGRAM

First priority in the Lunar Soil and Rock Engineering Program should be the determination of engineering parameters of lunar soils. Laboratory tests on returned samples will be needed, coupled with tests run on lunar soil in-situ. For the conduct of soil and rock tests on the lunar surface the testing equipment should be simple, rugged, adaptable to the harsh lunar environment, and automated to the extent practicable. The test methods should yield data which can be interpreted meaningfully in terms of the parameters needed for soil and rock mechanics analyses. Existing and proven theories and methods of analysis should be used wherever possible. Selection of test methods and development of apparatus should begin immediately.

As test results become available they should be correlated with remote sensing data so that the reliability of analyses based on remote measurements can be improved. Remote sensing, provided reliable methods can be developed, may prove to be the most economical means for determination of general surface material properties.

Of second priority is the development of improved analytical techniques for such problems as dynamic bearing capacity, slope stability and trafficability. Methods of analysis, except possibly in the area of trafficability of soils and mobility of vehicles, are reasonably well advanced, provided the appropriate soil data can be obtained. The results of Surveyor I and III have been encouraging in providing improved estimates of pertinent soil properties; however, the ranges of possible values must be narrowed and the variability from location to location determined. As of this time the number of variables still exceeds the number of independent direct measurements that have been made so that unproven assumptions remain in all quantitative estimates of soil properties.

Meaningful evaluations of in-situ soil strength and compressibility properties from the results of tests on returned specimens requires securing suitable undisturbed samples. Thus the development of appropriate sampling techniques must be given high priority.

Astronaut training is an essential component of a sound program in soil and rock engineering. Since the astronauts will be the "engineers in the field," they should be educated to some minimum level of proficiency in these areas. It should be noted that soil and rock engineering are far from precise quantitative disciplines and experience and judgment factors play an important part in development of optimum solutions to problems.

VI. NECESSARY SOIL PROPERTY DATA FOR SOLUTION OF SPECIFIC PROBLEMS

Table 1 has been prepared, based on the major problem areas listed in Section IV, to indicate specific properties of lunar materials that must be known if reasonable solutions to the problems are to be expected. Also listed are the authors' assessments of the suitability of existing analytical methods for handling the problems.

VII. PROPERTY MEASUREMENT

Table 1 relates soil and rock properties to specific problems associated with the scientific and engineering aspects of lunar exploration. Table 2 is concerned with methods for measuring the different properties. An indication (which in many cases is an opinion) is given for each of the following factors wherever possible.

A. Whether measurement can be made by remote sensing (RS), tests-in-situ (TIS), tests on samples at a lunar base (LBS), or tests on earth returned samples (ERS).

B. A recommendation as to which of the four possible approaches listed in A should be used for

   1. Gathering data for classification purposes (C).
   2. Preliminary mission planning (PMP).
   3. Final mission planning (FMP).
   4. Determination of design parameters (DP).

Table 3 presents a listing of some specific test methods which might be used for acquisition of the necessary data for property evaluations. An indication is given (again an opinion in most cases) as to the suitability of existing test methods, that are widely used for studies of terrestrial soils and rocks, for use in determination of lunar material properties. Useful techniques already developed for study of lunar surface materials are noted where appropriate. Of particular importance in the development of testing methods and apparatus for in-situ lunar soil tests and tests performed at lunar bases is consideration of the harsh lunar environment, the necessity to keep payloads to a minimum, the limited dexterity of a space-suited astronaut, and the desirability for techniques that are simple, reliable, and rapid.

VIII. CONCLUSION

Tables 1-3 represent but a crude first attempt to classify problems, soil and rock properties, and test methods in a form which may be helpful in formulation of research efforts for a systematic program of lunar exploration. Much further refinement of all aspects of the topics covered is needed and most of the interrelationships presented require critical examination in detail. It should be noted that emphasis throughout has been on determination of properties for use in solution of specific engineering problems. Data obtained from measurements of the type suggested, however, may be expected to be of great scientific value as well. It is hoped that this paper will serve as a stimulus for study by the rest of the Working Group and that a sound program in soil mechanics and engineering geology will emerge.

TABLE 1

SOIL AND ROCK DATA NEEDED FOR SOLUTION OF ENGINEERING PROBLEMS RELATED TO LUNAR EXPLORATION

Problem	Property values needed for solution	Suitability of Existing Analytical Methods
1. Dynamic bearing capacity (landing)	Strength, compressibility, elastic constants, density, penetration resistance	Apparently adequate, based on results from Surveyor I and III
2. Static bearing capacity	Shear strength (in terms of friction and cohesion), density, compressibility	Adequate
3. Rocket blast erosion	Density, porosity, cohesion, adhesion of soil to other materials, particle size and shape	Probably adequate
4. Contamination of systems by eroded material	Density, particle size and shape, cohesion, adhesion properties	Analytical Methods Not Needed
5. Trafficability	Density, strength, compressibility, stress-strain characteristics, penetration resistance	Probably need improvement
6. Slope stability	Unit weight, shear strength (in terms of friction and cohesion), subsoil profile, strength under transient and cyclic loading	Adequate
7. Sampling	Density, hardness, grain size and size distribution, strength, adhesion properties, penetration resistance	Analytical Methods Not Needed
8. Stability and settlement of laboratories and emplaced scientific stations	Compressibility, rate of compression, susceptibility to densification under dynamic loads, relative density	May be inadequate in case of cohesionless materials
9. Drilling	Hardness, grain size and shape, fracture patterns, adhesion characteristics, density, lubricating characteristics, thermal properties	Semi-empirical correlations on drillability available
10. Excavation and blasting	Unit weight, porosity, strength, stress-strain characteristics (brittleness), sizes and size distribution, adhesion characteristics, knowledge of absolute stresses	Semi-empirical laws for blasting available

Note: Time-dependency of stress-strain and strength characteristics may be important.

TABLE 1 (Continued)

Problem	Property values needed for solution	Suitability of Existing Analytical Methods
11. Underground construction	Unit weight, porosity, strength, stress-strain characteristics, elastic constants, in-situ stress, susceptibility to change in properties under changed environment.	Probably adequate
12. Underground storage	Thermal properties, permeability, plus those for underground construction	Probably adequate or appropriate solutions can be developed fairly easily
13. Waste disposal (underground)	Same as underground storage plus interaction characteristics of wastes and in-situ materials	Don't know
14. Radiation shielding	Density, porosity, adsorption properties	Adequate (?)
15. Thermal insulation	Thermal conductivity, density, specific heat	Adequate
16. Construction materials (Evaluation of)	Density, durability, strength, composition, stress-strain characteristics, grain size and size distribution, grain shape, texture, fabric	Analytical Methods Not Needed
17. Mineral resources (Location of)		Analytical Methods Not Needed? Geophysical methods for mineral location
18. Soil classification (engineering)	Mineralogy, texture, grain size and size distribution, relative density	Adequate
19. Rock classification	Mineralogy, strength parameters, elastic constants, structure and jointing	Adequate

TABLE 2

GENERAL CONSIDERATIONS ON THE MEASUREMENT OF LUNAR SOIL AND ROCK PROPERTIES

Property	Approach For Determination[1]	To Be Used For[2]
1. Visual classification and general description of material	All	C, PMP
2. Grain size, shape and size distribution	RS	C, PMP
	LBS	C, FMP, DP
	ERS	C, FMP, DP
3. Compressibility	RS(?)	C, PMP
	TIS	DP
	LBS	FMP, DP
	ERS	FMP, DP
4. Penetration Resistance	RS	C, PMP
	TIS	C, DP
5. Strength, including friction and cohesion	RS	C, PMP
	TIS	DP
	LBS	DP
	ERS	PMP, FMP, DP
6. Unit weight, density	RS	C, PMP
	TIS	C, DP
	LBS	DP
	ERS	PMP, FMP, DP
7. Relative density	TIS	MP, DP
	LBS	C, DP
	ERS(?)	C, DP

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[1]RS - remote sensing
TIS - tests in-situ
LBS - tests on sample at lunar base
ERS - tests on earth returned sample

[2]C - classification data
PMP - preliminary mission planning
FMP - final mission planning
DP - determination of design parameters

NOTE: Working Group should establish priority ratings.

TABLE 2 (Continued)

Property	Approach For Determination[1]	To Be Used For[2]
8. Elastic constants	RS	PMP
	TIS	DP
	LBS	DP
	ERS	PMP, FMP, DP
9. Adhesion properties	RS	C, PMP
	TIS	DP
	LBS	C, DP
10. Porosity	RS	C, PMP
	TIS	DP
	LBS	C, DP
	ERS	C, PMP, FMP
11. Thermal Properties	RS	C
	TIS	C, DP
	LBS	C, DP
	ERS	C, PMP, FMP
12. Durability	RS	PMP
	LBS	FMP, DP
13. Permeability	TIS	DP
	LBS	DP
	ERS	PMP, FMP, DP
14. Composition	RS	C, PMP
	TIS	C
	LBS	C, FMP
	ERS	C, PMP, FMP
15. Stress-strain characteristics	TIS	DP
	LBS	DP
	ERS	PMP, FMP, DP
16. Absolute stresses	TIS	FMP, DP

TABLE 3

TEST METHODS FOR LUNAR SOIL AND ROCK PROPERTIES

Property	Possible Test Methods	Suitability of Existing Methods
1. Visual classification and general description	Direct observation of samples and photographs	Adequate
2. Grain size, shape, and size distribution	Direct observation	Adequate for coarse particles
	Photographs	Limited by camera resolution and to surface material
	Sieving	ERS* only
	Light microscope	Adequate
	Electron microscope	ERS only
3. Compressibility	Remote sensing-photographs of surface features	Obtain only crude data
	Spacecraft landing records	May require assumptions about other properties
	Plate Load Tests	May be difficult on moon
	Penetration tests; e.g. cone	Potentially useful if properly interpreted
	Consolidation tests	Apparatus redesign for lunar environment
4. 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
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 4
	Direct shear tests	Good for ERS,may be difficult on moon
	Triaxial shear tests	Good for ERS,may be difficult on moon
	Vane shear tests	Probably useful in fine-grained, weak materials
	Transient and cyclic loading	Good for ERS, difficult on moon

* Earth-returned samples

TABLE 3 (Continued)

Property	Possible Test Methods	Suitability of Existing Methods
6. Unit weight, density	Remote sensing - (a) penetration records (b) thermal properties (c) slope analyses (d) Surveyor scoop type experiments	(a)(b)(c) require assumption of other soil parameters Not known
	(e) Nuclear density meters	Give variable results
	Sampling - various field density methods	Should be adequate
	Bore hole probes with nuclear units	Under development
7. Relative density	Penetration tests Sampling	Large experience factor needed to develop classification Unsatisfactory for cohesionless materials
8. Elastic Constants	Records of landing dynamics	Requires assumption of other soil properties
	Plate load tests	May be difficult on moon
	Data from strength tests	Adequate, but requires undisturbed sample
	Seismic surveys - wave propagation	Depends on complexity of soil and rock profile
	Vibration and cyclic load tests	May be useful, at least on ERS
9. Adhesion Properties	Shear along contact surface between unlike materials Observation of material sticking to instruments, etc.	Not known
10. Porosity	Remote sensing - (a) Albedo (b) Thermal Properties (c) Radar, radio wave, etc (d) Photographs	(a)(b)(c) require assumptions
	Direct determination in-situ or on samples	Adequate
11. Thermal Properties	Remote sensing - (a) Infrared (b) Other	(a)(b) require assumptions
	Direct - (a) Borehole Probe	Under development
	(b) Thermal conductivity tests	Adequate
	(c) Emplaced temperature sensors	Adequate

TABLE 3 (Continued)

Property	Possible Test Methods	Suitability of Existing Methods
12. Durability	Visual observation Response to changes in environmental conditions Standard degradation tests	 Adequate for ERS
13. Permeability	Calculation from grain size and porosity Direct measurement on samples In-situ bore hole test-gas	Fair for sand sizes, unsatisfactory for finer material Adequate for ERS Should be developed
14. Composition	Remote - (a) Photographs (b) Thermal, electrical, magnetic properties Direct - (a) Borehole camera (b) Visual observation (c) Microscope (d) X-ray diffraction (e) Chemical analysis (f) Electron microscope	(a)(b) require assumptions
15. Stress- strain characteristics	Strength tests Plate load tests Landing dynamics Instrumented penetrometers Seismic response characteristics	Adequate Adequate Requires assumptions Unknown
16. Absolute Stresses	Borehole convergence Overcoring Flat jack Empirical, based on (a) sonic velocity (b) resistivity	Still being worked on To be adapted (satisfactory on earth) Cannot use in bore hole Questionable (unreliable)