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INVESTIGATION OF ROCK BEHAVIOR AND STRENGTH IN SITU AND LABORATORY TECHNIQUES ADAPTABILITY TO A LUNAR EXPLORATION PROGRAM

Prepared under Contract No. NSR 05-003-189 by
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UNIVERSITY OF CALIFORNIA, BERKELEY

For

NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

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INVESTIGATION OF ROCK BEHAVIOR AND STRENGTH

I. INTRODUCTION

Sound planning of Apollo Application Programs (AAP) and extended lunar exploration programs call for a preliminary formulation of desirable rock mechanics studies on-site as well as on Earth Returned Samples (ERS). Two aspects of this problem have been dealt with in other publications on this contract*, namely, measurement of stresses and rock deformability in boreholes. The bulk of rock testing techniques, still to be appraised, is the object of the present report.

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 whose use appears vital for sound engineering practice. As expressed by Deere[17], four steps are involved in the design of any structure:

1. Determination of the boundary conditions of the problem, i. e., its dimensions and geometry and the magnitude of the loads which are to be resisted. This includes the initial state of stress of the in situ rock.

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*Heuzé, F. E., and Goodman, R. E., "Techniques for measuring stresses in rock on the earth. Adaptability to a lunar exploration program," Department of Civil Engineering, University of California, Berkeley, February 1968.

Goodman, R. E., Van, T. K., and Heuzé, F. E., "Devices for measuring rock deformability in boreholes on earth. Adaptability to a lunar exploration program," Department of Civil Engineering, University of California, Berkeley, February 1968.

2. Determination of the engineering properties of the materials involved. Unlike metals or concrete, rock varies to such an extent that an extensive program of in situ and laboratory testing subject to engineering judgment should be required to insure selection of pertinent design parameters.

3. Selection of a tentative design and prediction of the behavior in terms of stability and deformations using equations from theoretical and applied mechanics. Rock behavior, however, does not always agree with continuum theories, this being the most delicate problem, so far, to be tackled.

4. Assessment of the predicted behavior in terms of acceptability of performance for the particular problem at hand followed by redesign if necessary. Indeed, Step 2 investigated in this report is of utmost importance. The design and prediction of engineering behavior will be no better than the material properties used in the equation relating load and deformation properties (Step 3) even though the relations are correct and applicable, and the geometry and loading values of the first step are correct.

Following is a critical evaluation of the most significant techniques currently used in the investigation of rock behavior and strength.

II. IN SITU TESTING*

1. Seismic Testing

The field seismic technique is frequently utilized in exploratory work to sound out the variations in quality of an in situ rock mass, i. e., number and type of discontinuities, layering, overall fracturation, etc. It can also apply to the detection of surface subsidence, to investigation of ore deposits,

*The reader is referred to a List of References, a List of Symbols, and Table I for complementary information on this subject.

etc. Seismic wave velocity may be measured from a refraction seismic survey by surface impact and recording, up-hole shooting, continuous 3-D logging in drill hole or cross hole seismic recording. Despite the fact that it does not yield information immediately related to rock strength and deformability, this test should be given highest priority in a lunar exploration program for scientific reasons. It is another kind of remote sensing technique. As discussed later, subsequent engineering use can be made of the available data even though the computed dynamic modulus corresponds to transient loading and very low stress levels generated by the pulse.

2. Static Testing

Behavior and possibly strength parameters of a rock mass are better investigated through so-called static tests not concerned with the vagaries of transient loading. They more closely approximate the actual response of the body to engineering works as follows:

a) Plate Bearing Test

Deere states[17], "A relatively large volume of rock deforms as the result of the change in stress imposed by structures built upon or within it. The frequency and nature of the geological discontinuities within the zone of influence are significant factors which determine to a great extent the behavior of the rock mass. The only method that can be used to provide a reasonable estimate of the effect of these discontinuities and of the numerical values of the deformation modulus is large-scale field load tests." However valuable this technique in earth rock engineering, the considerable bulkiness of the apparatus involved does not make it appropriate for lunar programs owing to payload constraints. Moreover, new borehole techniques[68, 72] seem to provide equally reliable data and in a much faster way.

b) Pressure Chamber Test

This very large scale loading test has limited use even on earth and should not be considered for lunar exploration.

c) Field Shear Test

Little has been achieved in the field of large scale in situ shear testing. However valuable data it can yield on earth, this test cannot take place in a lunar program because of its complexity and cumbersome character.

d) Flat Jack Test

Originally a stress measurement technique, the flat jack designed by Freyssinet has been improved by Rocha[32]. The instrument can also be used as a deformability measuring instrument[33]. This technique remains basically one of surface investigation.

e) Field Compression

Even less is known of the actual value of this extension to large scale specimens (pillars, etc.) of the uniaxial compression laboratory test. It should be pointed out here that the previous two techniques are the only ones so far known to the authors to be true in situ strength tests making them most valuable in earth engineering, however expensive.

f) Rock Deformeters

Equally important to the deformation under applied load is the relaxation of a rock mass upon removal of stresses which take place on the surface of and around underground openings. The "quality" of the rock usually increases with distance to the open surface, the "skin" being usually of poor strength owing to high gradient of stresses, blasting, and other effects. Hence there is need for investigation of strain from the surface to the undisturbed zone. This is achieved through the use of rock deformeters[16, 36, 37] (down-the-hole extensometers, floating rock-bolt clusters, transit surveys, etc.). This technique should be a compulsory complement to any stress survey or surface load deformation study in earth rock engineering. Unfortunately room and payload constraints will very probably prohibit its use in lunar exploration.

g) Log of Borings

Careful logging of the products of drilling can give valuable data on rock quality. From any exploratory drilling the following information should be gathered in order to relate these factors to subsequent testing in the laboratory: total length drilled, fracture frequency, and length, position and orientation of specimens retrieved. Careful logging will provide a quantitative quality index, the Rock Quality Designation (RQD) developed by Deere[17], which can be compared to other quality indexes as discussed further on. Drilling and logging shall be done at the site of any other in situ test and this is true on the moon as on earth. Salient features and rating of the above tests are summarized in Table I.

III. LABORATORY TESTING*

The following does not constitute an exhaustive list of known laboratory tests on rock. This would be beyond the scope of this investigation. Emphasis is placed, rather, on those tests which are most commonly used to provide information relevant to rock strength and mechanical behavior as opposed to chemical, isotopic, mineralogic, petrographic, thermal, electrical or magnetic behavior[70]. Nor does it constitute a proposal for

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*The reader is referred to a List of References, a List of Symbols, and Table II for complementary information on this subject.

TABLE I

IN-SITU TESTING OF ROCK BEHAVIOR AND STRENGTH

	TESTS	REFERENCES	STRENGTH PARAMETERS ϕ	STRENGTH PARAMETERS Others	BEHAVIOR PARAMETERS Elasticity	BEHAVIOR PARAMETERS Linearity	BEHAVIOR PARAMETERS Fracturing	INTERPRETATION FORMULAE	USEFULNESS IN EARTH ROCK ENGINEERING	ADAPTABILITY TO LUNAR EXPLORATION
DYNAMIC	SEISMIC (surface and subsurface)	1 to 17	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	4 15 to 25 75	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.
STATIC *	PRESSURE CHAMBER	17	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
STATIC *	FLAT JACK	4, 15, 16 26 to 32	No	No	Yes	Yes	No ?	see ref. 26 for E, ν	B Surface only is investigated. Severe edge effects.	C
STATIC *	SHEAR	7, 33, 34	Yes	C	Yes	Yes ?	Yes ?	$\tan \phi = \frac{F_S - C}{F_N}$	A ? Very cumbersome. Little experience.	C Too bulky
STATIC *	COMPRESSION	35	Yes ?	No	Yes	Yes	Yes ?	$E_t = \frac{\Delta \sigma_1}{\Delta \epsilon_1}$ $\sigma_3 = 0$	? Very little experience.	C
STATIC *	ROCK DEFORMETERS	16, 36, 37, 74, 76, 77	No	No	Yes	Yes	No ?	$E_t = \frac{\Delta \sigma}{\Delta \epsilon}$ at depth	A Most valuable for deep investigation.	B ?
STATIC *	LOG OF BORINGS	17, 38	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. 68)

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.

testing of Lunar Returned Samples. This will be, possibly, the subject of a further study.

1. Dynamic Testing

a) Pulse Velocity

As in the field, the travel time, amplitude variation and energy absorption of pulses have been used extensively in an effort to characterize, mainly through the dynamic Young's modulus, the elastic properties of a rock mass. This technique shall be called indirect since E_d is not directly usable for engineering purposes but through empirical correlation laws[40, 71].

b) Resonance

The resonant frequency of a rock specimen from which E_d can be computed is neither a "first-order" parameter of strength nor behavior. However, owing to their non-destructive character, the two previous dynamic tests would rank with high priority in a program of testing on Returned Lunar Samples.

2. Static Testing

a) Compression Tests

Uniaxial and triaxial compression tests are among the most widely performed strength tests. Their data should be analyzed in a statistical way to put into evidence not only the average value of strength parameters (compressive strength, angle of friction, cohesion) but also the distribution (scattering) and anisotropy. Despite the fact that they are destructive tests they should be performed on Returned Lunar Samples.

b) Shear Tests

Following recent developments in the simulation of rock joints behavior[73], direct shear test data can be used in a new application of the Finite Element Method. When one is interested only in joint angle of friction and not in joint stiffness, the multi-stage triaxial test provides required information. Results will apply to the stability of structure presenting major discontinuities (slopes in jointed rock, openings in bedded rock, etc.)

c) Tension Tests

The stability of structures in rock masses also very heavily depends, in most cases, upon the rock's tensile strength. In the past few years, much research has been devoted to the investigation of tensile strength. It appears that for practical purposes, two tests (direct unconfined tension and rupture of a beam) would give the best answers. Their results are different but complementary so that both should now be considered as standard tests.

d) Creep Test

Their purpose is to find out which percentage of the maximum compressive load can be applied onto a rock over a sustained period of time without it undergoing excessive strain. A common procedure of soil testing, it finds its application in rock engineering, too[55, 56] (deformation of dam abutments, creep of mine pillars, etc.). Moreover, to be significant, results must be obtained over a rather long period of time.

e) Permeability

Standard permeability tests in the laboratory have been recently modified[34] to provide very promising "second order" parameters of strength and behavior. The main features and rating of the techniques discussed above are shown in Table II.

IV. CONCLUSION

This study draws attention to two very important features of rock testing:

1. In the present state of the art, design of structure upon or in rock relies mostly on in situ behavior analysis and laboratory strength studies. Little has been done in the in situ testing of rock strength. The major obstacle appears to be the bulkiness of the equipment used in order to investigate as wide a site as possible, hence the difficulty of repetition at many different sites.

2. "First-order" parameters of strength will be defined as those values obtained directly from laboratory tests (σ_c, σ_t, R, ϕ_r, ϕ_j, etc.). However, owing to the non-homogeneity of rock, these data are often characterized by a wide scattering of values. Several investigators have in the past few years attempted either to define "second-order" parameters of strength and quality[17, 34] or to build up empirical correlation laws[44, 64, 71] between first order parameters. To be mentioned are the Rock Quality Designation[17] (RQD) based upon the degree of recovery of pieces of sound cores in a drill hole, the Velocity Ratio[17] $(V_f/V_\ell)^2$ where V_f and V_ℓ are respectively the seismic velocities in the field and in laboratory testing of specimens, the ratio $\delta_e/(\delta_p+\delta_e)$[17] in a plate bearing test where δ_e and δ_p are respectively the elastic and permanent rock deformations, the coefficient of variation[34] σ/M in uniaxial compression tests where σ is the standard deviation and M the average value of the compressive strength, and the permeability ratio[34] R_{-1}/R_{-50} where R_{-1} and R_{-50} are respectively the diverging permeability under 1 bar and converging permeability under 50 bars differential pressure in a thick wall cylinder specimen. One can also define the ratio[17] E_r/E_{lab} of the field deformation modulus and

laboratory dynamic modulus as a second order parameter of behavior.

However severe the constraints can be in a lunar program of rock engineering studies, the above discussion lends hope that a very comprehensive and reliable investigation of lunar rock engineering properties can be conducted. Instruments will be designed[68] which can operate in boreholes on the moon, and meaningful laboratory tests can be performed on a limited amount of returned samples, to ultimately 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.

TABLE II

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	4, 15 to 17 39 to 43	No	E_d , ν	Yes	see Table I seismic	C	A non destructive
		RESONANCE	4	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, 15 to 17 44 to 48	ϕ_r , σ_c	E_t , ν	No	$\sigma_c = \sigma_{1max}$ $E = \Delta\sigma_1/\Delta\epsilon_1$	A	A
		Biaxial	16, 54	No ?	E , ν need not be known	No	$E_t = -\frac{4ab^2 P_o}{(b^2-a^2)U}$	B	B
		Triaxial	4, 15 to 17 47, 49 to 53	ϕ_r , σ	E_t , ν	No	$\sigma_1 = C + \sigma_3 \tan\phi$ $E_t = \frac{\Delta(\sigma_1-\sigma_3)}{\Delta\epsilon_1}$	A	A
	SHEAR	Direct shear	7, 33 to 35 61 to 63	ϕ_r , ϕ_j Smax , Sr , C	No	No	—	A	B heavy apparatus
		Multi-stage triaxial	4, 47	ϕ_j from fracture envelope	No	No	—	A	A can be done in any triaxial test
	TENSION	Direct tension	4, 16, 58, 60	σ_t	E_t , ν (tensile)	No	$\sigma_t = [\sigma_1]max$ $E = \Delta\sigma_1/\Delta\epsilon_1$	A	A
		Brazilian	57, 59	σ_t	No	No	$\sigma = \frac{2P}{\pi DH}$	B	B simple - check on σ_t
		Rupture	4, 47	R	E	No	$R = 8PH/\pi D^3$ $E = 4PH^3/3\pi D^4 d$	A	A simple
		Torsion	4	S	No	No	$S = \frac{T \times D}{2J}$	C	C
	OTHERS	Creep	55, 56	No	$\epsilon = f(time)$	Yes	—	B	B time consuming
		Permeability	34	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.

LIST OF SYMBOLS

a	inner diameter of thick wall cylinder or tunnel (in)
b	outer diameter of thick wall cylinder or tunnel (in)
c	cohesion (psi)
d	deflection of beam (in)
D	diameter of specimen (in)
E_{tot}	static deformation modulus (psi)
E_t	static tangent modulus of elasticity (psi)
E_d	dynamic modulus of elasticity (psi)
F_N	normal stress (psi)
F_S	tangent stress (psi)
G	shear modulus (psi)
H	length of specimen (in)
J	moment of inertia
k	permeability (in/sec)
K	correction factor
n	resonant frequency
P_i	internal pressure in chamber
P_o	applied hydrostatic pressure (psi)
P	applied load, lbs (plate bearing, Brasilian, rupture)
R	modulus of rupture (psi)
S	shear strength (psi)
S_r	residual shear strength (psi)

S_{max}	peak shear strength (psi)
T	torque (in x lbs)
U	variation in a (in)
V_{ℓ}	longitudinal wave velocity ft/sec
V_s	shear wave velocity ft/sec
α	radius of loading plate (in)
γ	unit weight of rock lbs/ft^3
δ	rock deflection under plate (in)
δ_r	displacement at distance r from tunnel center
ε_1	longitudinal strain (in)
ν	Poisson's Ratio
ρ	γ/g
σ_1	longitudinal stress (psi)
σ_3	confining pressure (psi)
σ_t	tensile strength (psi)
σ_c	uniaxial compressive strength (psi)
ϕ_r	friction angle rock (degrees)
ϕ_j	friction angle joint (degrees)

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