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TECHNIQUES FOR MEASURING STRESSES IN ROCK ON THE EARTH

ADAPTABILITY TO A LUNAR EXPLORATION PROGRAM

Prepared under Contract No. NSR 05-003-189 by
F. E. Heuze and R. E. Goodman

UNIVERSITY OF CALIFORNIA, BERKELEY

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INDEX

THE MEASUREMENT OF STRESSES IN ROCK

I. INTRODUCTION

1. The following constitutes an extensive review of techniques used for the determination of stresses in a rock mass on the earth. The theory of these techniques and a detailed listing of instruments are presented. The purpose of this study is to guide appraisal of the adaptability of such measurements to a Lunar Exploration Program. It will serve as a basis for recommendations and preliminary design of a probe to measure the absolute state of stress in the moon's crust. The value of such an experiment has been emphasized in a previous publication[*] on this contract from both a scientific and engineering standpoint.

Rock differs from many other engineering materials in being under significant initial stress. The range in possible values of initial stresses is great due to the unknown influence of topographic and geologic factors. Excavation at the surface or underground disturbs this stress field and induces a new one. The final stress state consequently is directly dependent on the initial state of stress which must therefore be determined for any rational analyses of a rock structure.

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[*] Mitchell, J. K., and Lambe, T. W., "Lunar soil engineering and engineering geology," Summer Conference on Lunar Exploration and Science, U. C. Santa Cruz, July 31 - August 13, 1967, NASA CR-61178.

TABLE I

METHODS OF MEASURING STRESSES IN ROCK

METHOD	KEY REFERENCES
1. Complete stress relief by overcoring	
(a) Measure diametrical displacements	Merrill (1967), Panek (1966), Leeman (1967), Merrill et al. (1964)
(b) Measure stresses in a stiff inclusion	Wilson (1961), Hult (1963), Hast (1958), Leeman (1964), Coutinho (1949)
(c) Measure strains on bottom or walls	Leeman (1964), Leeman and Hayes (1966), Hoskins (1967)
2. Partial stress relief by excavation	
(a) Measure displacement on cutting a slot, and pressure in slot to cancel displacements (flat jack method)	Tincelin (1958), Alexander (1958), Hoskins (1966)
(b) Measure displacement of points inside a hole on drilling a contiguous hole	Kawamoto (in preparation)
(c) Measure diametrical displacement of points inside a hole on deepening it	De la Cruz and Goodman (in preparation)

METHOD	KEY REFERENCES
3. Calculations from structural behaviour	
(a) Measure displacement of tunnel walls, or roof, or invert on advance of face	Obert, Merrill and Duvall (1958, 1967)
(b) Measure strain or stress in tunnel walls resulting from new mining	Morgan and Panek (1963)
4. Rock fracture stress	
(a) Measure pressure to fracture rock with borehole jacks	Jaeger and Cook (1963)
(b) Measure water pressures to initiate and propagate fracture in a hole	Fairhurst (1965)
(c) Core discing	Obert and Stephenson (1965)
5. Indirect methods	
(a) Seismic velocity	Marsh and Thurston (1951)
(b) Seismic frequency	none
(c) Electrical resistivity	Sen (1962)
(d) Gamma ray	Borecki and Kidybinske (1966)

II. METHODS FOR MEASURING ABSOLUTE STRESSES IN ROCK

The methods available for assessing the state of stress in rock masses are listed in Table I. A discussion of the methods based on complete or partial stress relief follows. These are the overcoring and flat jack methods.

1. Methods Based on Complete Stress Relief by Overcoring

Overcoring refers to the relief of stress in the rock around an instrumental hole by drilling a larger concentric hole. The method was initiated for stress measurement in boreholes by Hast in 1951, who first used trepanning (drilling of overlapping drill holes) to execute the outer hole. Olsen overcored rosettes on the surface of a gallery in rock as early as 1932 (Olsen, 1957).

Overcoring brings about a virtually complete removal of stress in the rock around the inner borehole. The methods based on overcoring are therefore severely affected by nonlinear and inelastic mechanical behavior. Overcoring may be accomplished by diamond-drilling a hole three to four times the radius of the instrumented hole. In the U. S. Bureau of Mines method, for example, the inner hole is EX (1.5") and the outer hole is 6 inches. Rocha has proposed overcoring EX with NX (3"). Overcoring has also been accomplished by overdrilling the bottom of a hole, instrumented in its center (Leeman, 1964).

a. Determination of stresses by measurement of diametrical displacements as a result of overcoring.

This method has recently become widely used because of the excellent deformation gages developed by the U. S. Bureau of Mines. The latest version of this gage (Merrill, 1967) has 3 cantilever beams allowing simultaneous measurement of displacements across three diameters during overcoring.

The displacement measurements are related to the in situ stresses by means of the Kirsch solution (Merrill and Peterson, 1961). If P and Q are the maximum and minimum stresses (compression positive) in the plane perpendicular to the drill hole, the displacement across a diameter (d) inclined at θ to P is

$$U_\theta = (P + Q)\frac{d}{E} + (P - Q)\left(\frac{2d}{E}\right)(\cos 2\theta) \qquad (1)$$

where E is Young's modulus for the rock. It is therefore accurate if the measurement is made at shallow depth in a borehole drilled perpendicular to a free face. If the measurement is conducted at such a depth that the longitudinal stress (parallel to the borehole) is not negligible, or if the borehole is inclined so that it does not follow a principal stress direction, the displacements will be affected by longitudinal stress and shear stress in the plane normal to the hole.

Adopting local coordinates X_1 X_2 X_3 with the drill hole parallel to X_2, the displacement across a diameter making an angle θ with X_1 (θ is positive measured from (+)X_1 toward (+)X_3) is (Panek, 1966):

$$U(\theta) = \sigma_1 f_1 + \sigma_2 f_2 + \sigma_3 f_3 + \tau_{13} f_4 \qquad (2)$$

where $$f_1 = \frac{d}{E}(1 - \nu^2)(1 + 2\cos 2\theta) + \frac{d\nu^2}{E}$$

$$f_2 = -\frac{d\nu}{E}$$

$$f_3 = \frac{d}{E}(1 - \nu^2)(1 - 2\cos 2\theta) + \frac{d\nu^2}{E}$$

and $$f_4 = \frac{d}{E}(1 - \nu^2)(4\sin 2\theta)$$

Note that the shear stress components parallel to the borehole axis (τ_{23}, τ_{21}) do not contribute to the displacement across a diameter.

By making measurements across several diameters in a minimum of 3 different holes (Gray and Toews, 1967) the complete stress tensor may be determined. Panek (1966) demonstrates how the best fit to redundant data may be determined using the method of least squares. In the case of a shallow measurement in a hole perpendicular to a free surface, Equation 1 may be used to determine P, Q, and θ if measurements are made in 3 different directions. For a 60° configuration, with measurements at: (a) θ; (b) $\theta + 60°$; and (c) $\theta + 120°$, superposition yields the following result (Obert and Duvall, 1967)

$$P + Q = \frac{E}{3d}(U_a + U_b + U_c)$$

$$P - Q = \frac{E}{\sqrt{2}\,3d}\left[(U_a - U_b)^2 + (U_b - U_c)^2 + (U_c - U_a)^2\right]^{1/2}$$

and $\tan 2\theta = \dfrac{-\sqrt{3}\,(U_b - U_c)}{2\,U_a + U_b - U_c}$

In these formulas, θ is measured counterclockwise from U_1 to P, and if

$U_b > U_c$ and $U_b + U_c < 2\,U_a$, then $0 \leq \theta \leq 45$

$U_b > U_c$ and $U_b + U_c > 2\,U_a$, then $45 < \theta < 90°$

$U_b < U_c$ and $U_b + U_c > 2\,U_a$, then $90 < \theta < 135°$

$U_b < U_c$ and $U_b + U_c < 2\,U_a$, then $135 < \theta < 180°$

Rocha (paper in preparation) has developed equipment and procedures for measuring displacements in off diameter as well as diametrical directions in a borehole. His equipment allows complete solution for the stress tensor at any point in a single borehole.

b. Measurement of stress changes in a solid inclusion as a result of overcoring.

This approach, first suggested by Coutinho (1949), is based on the stresses induced in the center of an elastic inclusion in a stressed elastic material. If the inclusion is "welded" into a circular hole in rock whose stress is then relieved by over coring, it will develop stresses σ_{1_i} and σ_{2_i} by virtue of the rock stresses σ_{1_r} and σ_{2_r}, the relation being

$$\sigma_{1_r} = K_1 \, \sigma_{2_i} + K_2 \, \sigma_{2_i}$$

$$\sigma_{2_r} = K_1 \, \sigma_{2_i} + K_1 \, \sigma_{1_i}$$

where

$$K_1 = \frac{(1 + \nu_i)\,(3 - 4\,\nu_i)}{8\,(1 - \nu_r)\,(1 + \nu_r)} \cdot \frac{E_r}{E_i} + \frac{5 - 4\,\nu_r}{8\,(1 - \nu_r)}$$

$$K_2 = \frac{(1 + \nu_i)\,(1 - 4\,\nu_i)}{8\,(1 - \nu_r)\,(1 + \nu_r)} \cdot \frac{E_r}{E_i} + \frac{4\,\nu_r - 1}{8\,(1 - \nu_r)}$$

K_1 and K_2 are practically constant for $E_i/E_r > 4$ and are insensitive to ν_i and ν_r.

A solution corresponding to the boundary condition of an elastic inclusion fit into a hole in the rock was obtained by Muskelishvili and reported by Leeman (1964). The results are similar to those given above. Hult (1963) considered the stresses in inclusions in viscoelastic material. As an alternate to using formulas of the type given above, interpretation of field data may be based on calibration of the gage in rock from the test site, e.g. the hollow cylinder obtained in overcoring.

Instruments based on this method were developed by May (1958), Potts (1957), Salamon (1962), Wilson (1961), Hast (1958), and Nichols et al. (1967). Good results of tests with Wilson's device were recently reported by Hobbs and Clarke (1966). Hast (1958) developed a fine instrument and refined technique for rigid inclusion type measurements and has accumulated great experience. A variety of the rigid inclusion method is the photo elastic method developed by Roberts et al. (1964). A glass cylinder is prestressed inside a small hole and overcored. The glass acts as a rigid inclusion and develops photo elastic fringes, which are counted with a hand held analyser by the observer.

An advantage of the rigid inclusion approach is its relative insensitivity to the value of the modulus of elasticity of the rock. A disadvantage is that the inclusion must be prestressed in the hole and the rock may break under the prestress during overcoring.

c. Measurement of stresses by means of strain gages glued to the rock inside the borehole and overcored

Leeman (1964) introduced a method of stress measurement by overcoring a rosette glued on the bottom of a drill hole. He developed apparatus for grinding the bottom flat and affixing the gage rosette. The rosette output allows calculation of the magnitude and direction of principal strains at the bottom of the borehole. There is no published analytical solution to the stresses at the bottom of a borehole, but Gaille and Wilhoit (1960) published the results of a 3 dimensional photo elastic investigation of this problem. The stress along any radius at the center of the hole bottom was found to be 1.56 times the free field stress parallel to the same radius, and - 1.04 times the free field stress parallel to the borehole. This may be written

$$\sigma_x = \sigma_x' K_1 + \sigma_y' K_2 + \sigma'_z K_3$$

$$\sigma_y = \sigma'_y K_1 + \sigma'_x K_2 + \sigma'_z K_3$$

where σ'_x, σ'_y, and σ'_z are the primary stresses and

$$\begin{Bmatrix} K_1 \\ K_2 \\ K_3 \end{Bmatrix} \begin{matrix} = \\ = \\ = \end{matrix} \begin{Bmatrix} 1.56 \\ 0 \\ -\,1.04 \end{Bmatrix}$$

Applying Hooke's law

$$\varepsilon_x E \;=\; (\sigma'_x K_1 + \sigma'_y K_2 + \sigma'_z K_3) - \nu\, (\sigma'_y K_1 + \sigma_x K_2 + \sigma'_z K_3)$$

$$\varepsilon_x E \;=\; \sigma'_x (K_1 - \nu K_2) - \sigma'_y (\nu K_1 - K_2) + \sigma'_z K_3 (1 - \nu)$$

leads to the following expression for the strain ε_x at the bottom of the hole

$$\varepsilon_x E \;=\; 1.56\, \sigma'_x - 1.56\, \nu\sigma'_y - 1.04\, (1 - \nu)\, \sigma'_z$$

with a similar equation for ε_y.

Hoskins (1967) pointed out this unfortunately large dependence of the strains on the generally unknown longitudinal stress σ_z'. Berents and Alexander (1965) and Hoskins (1967) suggested grinding the hole bottom into a hemisphere and overcoring a rosette placed thereon. The formulas for stresses in a sphere (e.g. Timoshenko and Goodier, 1951) could then be used to reduce the data,

with

$$\begin{Bmatrix} K_1 \\ K_2 \\ K_3 \end{Bmatrix} = \frac{1}{2\,(7 - 5\nu)} \begin{Bmatrix} 27 - 15\,\nu \\ 15\,\nu - 3 \\ -\,(3 + 15\,\nu) \end{Bmatrix}$$

Substitution in Hooke's law yields in this case:

For $\nu = 0$

$$\varepsilon_x E = 1.93\,\sigma_x' - 0.24\,\sigma_y' - 0.24\,\sigma_z'$$

For $\nu = 0.2$

$$\varepsilon_x E = 2.00\,\sigma_x' - 0.4\,\sigma_y' - 0.4\,\sigma_z'$$

with a similar equation for ε_y. The smaller dependence of the results on the unknown stress σ'_z means smaller errors when data are interpreted using the assumption that $\sigma'_z = 0$, as has been customary.

Hoskins suggested alternating measurements with flat and hemispherical bottoms, allowing calculation of the longitudinal stress σ_z'. When σ_z' is known, the stresses σ_x' and σ_y' can be determined accurately from the strain data. Leeman and Hayes (1966) developed instruments for measuring sufficient strain data inside a borehole to calculate the complete stress tensor in one overcoring operation. An instrument was developed to fix three strain gage rosettes to the walls of the borehole. This method is so new that little is known yet about its general applicability.

2. Partial Stress Relief Methods: The Flat Jack Method

If the rock exhibits nonlinear stress-strain relations or hysteresis on cyclic loading, methods of stress measurement by complete stress relief are subject to error. Another approach would be to cause a relatively small change in the stresses at reference points and relate the magnitude of the induced change to the primary stress field. The best known method of this type is the flat jack technique, originally developed by Tincelin (1958), in which the induced change is related to the primary stress by stress compensation. Another approach, the interference of one hole on another, is under study by Kawamoto (personal communication). Talobre (1967) described a similar approach conducted at the end of a borehole.

a. Flat jack method

In this method one measures the average pressure normal to the plane of a slot cut in a rock wall. A slot cut into the wall by overlapping drill holes or, better, a diamond saw (Rocha, Lopes, and Silva, 1966), causes deformations in the rock toward the slot, which are measured by a Whittemore or Huggenberger gage or a vibrating wire. A flat hydraulic jack is embedded in the slot and the displacements of the rock, away from the slot, are recorded as the jack is pressured. The pressure required to restore the deflections from slot cutting is an estimate of the primary rock pressure. A detailed analysis of the flat jack test was made by Alexander (1960) and Hoskins (1966).

The flat jack method generally yields a value only for the pressure perpendicular to the plane of the jack, not the complete stress tensor. In the past it has been performed at shallow depth beneath the surface, whose generally disturbed stress field detracts from the usefulness of the results. However Rocha, Lopes, and Silva (1966) have introduced a diamond-saw slot countersinking technique that extends the method in depth. Also, the method has several distinct advantages: in the course of testing one determines the modulus of elasticity, the stresses are determined without need for accurate knowledge of E; finally, the jack measures average rock pressures over a large area, reducing the influence of small inhomogeneities.

b. Analysis of data from flat jack test

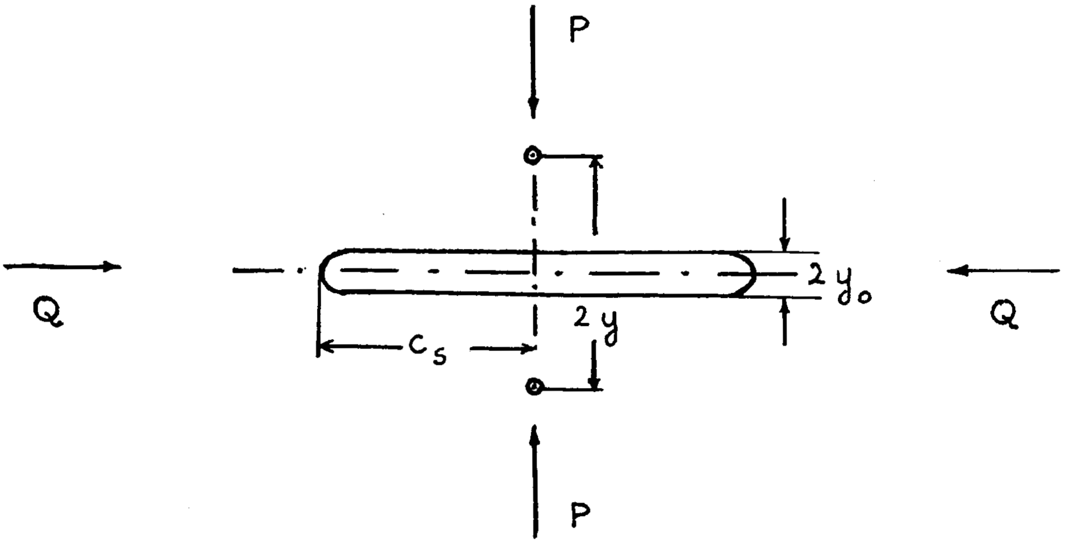
In the conduct of a flat jack test, two distinct operations are performed:

(1) a slot of finite width is excavated and the resulting displacements across the slot between preset gage points are measured;

(2) a jack of small width in grouted contact with the rock, is pressured until the pins are restored to their former position.

The cancellation pressure of (2) is often taken as the pressure preexisting in rock perpendicular to the jack before slot cutting. There are two reasons why this is not exactly true: 1) the slots are of different width and length in (1) and (2) and therefore equal displacements in the two cases must signify unequal pressures; 2) pressure parallel to the slot axis also has an effect on the displacement.

Displacements on slot cutting. The displacement between pins 2 y distant symmetrically located across a slot 2 y_o thick and 2 c_s long is



$$\omega_1 = \frac{P\,c_s}{E}\left[(1-\nu)\left(\sqrt{1+y^2/c_s^{\,2}}-\frac{y}{c_s}\right)+\frac{1+\nu}{\sqrt{1+y^2/c_s^{\,2}}}\right]$$

$$+\ y_o\,(P-Q)\left[-2\,\nu\left(\sqrt{1+y^2/c_s^{\,2}}-\frac{y}{c_s}\right)+\frac{(1+\nu)}{\sqrt{1+y^2/c_s^{\,2}}}\right]$$

Displacements on pressuring flat jack. The displacement caused by a thin jack c_j long with internal pressure P_j is

$$\omega_2 = \frac{P_j c_j}{E}\left[(1-\nu)\left(\sqrt{1+y^2/c_j^{\,2}}-\frac{y}{c_j}\right)+\frac{(1+\nu)}{\sqrt{1+y^2/c_j^{\,2}}}\right]$$

ω_2 is measured as a function of P_j so that for any given P_j, E can be calculated if ν is assumed.

If ω_1 is measured in two tests at right angles, P and Q may be calculated from the two equations for ω_1. Typical dimensions are

$2\ y_o$ = 1-7/8" to 2"

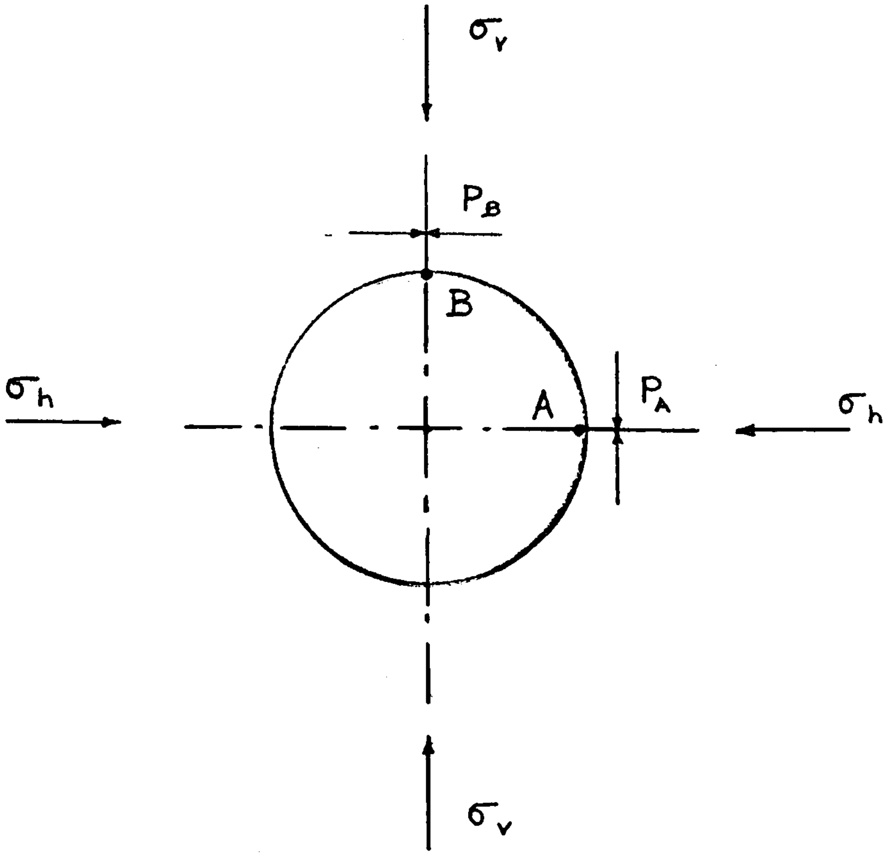
$2\ c_s$ = 13"

$2\ c_j$ = 12"

2 y may be 6" or 12" depending on the extensometer available.

Evaluation of initial free field stresses. P and Q represent wall rock stresses that have been caused by concentration of initial stresses in the free field upon excavation of the test chamber. Frequently it is the free field initial stresses that are wanted.

For example, in the circular tunnel shown, P_A represents a combination of stress concentration factor k_1 acting on σ_v and k_2 on σ_h.



$$P_A = k_{11}\,\sigma_v + k_{12}\,\sigma_h$$

$$P_B = k_{21}\,\sigma_v + k_{22}\,\sigma_h$$

k_{ij} are the stress concentrations at a distance inward of 1/3 jack width.

for a circular tunnel, $k_{12} = k_{21}$ and $k_{11} = k_{22}$.

Solving for σ_v and σ_h, and letting $k_{11} = k_1$ and $k_{12} = k_2$ one obtains

$$\sigma_v = \frac{P_A k_1 - P_B k_2}{k_1^2 - k_2^2}$$

$$\sigma_h = \frac{P_B k_1 - P_A k_2}{k_1^2 - k_2^2}$$

k_1 and k_2 may be determined by photoelasticity, analytical solution, or finite element analysis.

3. Remarks

The above presentation of data interpretation from overcoring and flat-jack tests is based on the assumption of rock isotropy and linear elasticity. It has been emphasized that these methods are quite sensitive to nonlinear and inelastic rock mechanical behavior and data interpretation would be difficult in such a case.

However rock anisotropy can be accommodated in the reduction of overcoring data (Becker and Hooker, 1967). The introduction of anisotropic instead of isotropic equations in the proper cases has proved to yield results significantly different for the stress tensor values thus warranting their use.

III. REVIEW OF PROBES

1. Definitions

For the reader's convenience some definitions are presented or repeated here.

Overcoring: The so-called overcoring technique of stress measurement consists in drilling a first bore hole at depth in a rock body and inserting the measuring probe in it. A first reading is taken of the gage output while subjected to an initial arbitrary prestress.

The first hole is then overdrilled with a bit of much larger diameter (4 times for instance). This brings about complete relaxation of a thick wall cylinder of rock in whose central hole the probe has been placed. This relaxation monitored by the probe is assumed to be elastic. The probe's output has been previously calibrated in terms of stresses or deformations in the laboratory.

Calibration Curves: Curves obtained beforehand in the laboratory and relating the gage output to deformations (soft inclusions), stresses (rigid inclusions), or change in rock properties (resistivity, wave velocity) with applied pressure.

Soft Inclusion: A probe in which measuring parts are subjected to significant deformations, play a passive role in the measurements, and are calibrated in terms of deformations. They can be termed displacement gages. Stresses can then be computed from the theory of elasticity if the rock's elastic constants are known, assumed or otherwise measured.*

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*Related publications on this contract include:

Heuzé, F.E., and Goodman, R.E., Investigation of rock behavior and strength - In situ and laboratory techniques - Adaptability to a lunar exploration program. Department of Civil Engineering, U.C. Berkeley. February 1968.

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

Rigid Inclusion: A probe requiring laboratory calibration in terms of stresses and subjected to much smaller deformations. Rigid inclusions are generally undirectional and some required calibration in the same type of rock as the one tested. They must be such that the ratio (gage modulus)/(rock modulus) is greater than 2.

Restoration of an Initial Stress Condition: An opening (slot or borehole) is made in a rock mass, whose deformation is monitored during and after drilling. A pressure cell is inserted in the opening and pumped up until the initial reading of monitoring instruments (pins, pressure cell) is restored. The initial stress in rock is then assumed to be the one in the pressuring cell at cancellation. Thus there is no need for complementary determination of the elastic constants. Moreover they can be obtained from the deformation curves (pin displacement).

Component: A bore hole gage at one location will measure 1, 2, or 3 diametral deformations and will be called 1, 2, or 3-component gage. In order to get the complete state of stress in a plane perpendicular to the bore hole axis at any location, three deformations upon relaxation have to be measured. If not, the result of measurements at several depths will have to be interpolated at some central position hence reducing the accuracy.

2. Listing of Probes

Each instrument is presented separately according to the following outline:

Name:

Reference: (see attached list of references)

Principle: one of the following

Overcoring of soft inclusion
of rigid inclusion
of photoelastic material
of strain gage on bottom of hole

Restoration of initial stress condition

Changes of rock properties with stress level

Location: In a borehole (and minimum number of holes required for experiment)

On the rock's surface

In a slot

Instrumentation: (only those parts directly involved in the measurement of stress)

Quantity measured:

Comments:

PROBE 1

Name: Maihak Strain Cell
References: 1,2,3,4,5,6
Principle: Overcoring of a soft inclusion
Location: Used in a bore hole

Instrumentation: Vibrating wire, electromagnetic plucker, oscilloscope or frequency counter

Quantity Measured: Vibration frequency of the string; thus bore hole diameter from calibration curves and stresses from elastic theory.

Comments: Measures deformation across one diameter only. Could be extended to 3 simultaneous diametral measurements. Good sensitivity. Oscilloscope is cumbersome. E must be known.

PROBE 2

Name: CSIR Strain Cell, Mark I
References: 7,8,9
Principle: Overcoring of a soft inclusion
Location: Used in a bore hole

Instrumentation: Circular elastic rings upon which a strain gage is mounted. Strain gage potentiometer.

Quantity Measured: Strain on rings. Thus deformation of bore hole diameter from calibration curves and stresses from elastic theory.

Comments: Deformations measured across 2 orthogonal diameters (2 rings) can be extended to 3 diameters. However, measurements not in the same plane. E must be known.

PROBE 3

Name: CSIR Strain Cell, Mark II
References: 3, 10
Principle: Overcoring of a soft inclusion
Location: Used in a bore hole

Instrumentation: LVDT's (linear variable differential transformers) and recording system

Quantity Measured: Voltage outputs; thus deformation of bore hole diameter from calibration curves and stresses from elastic theory.

Comments: It is a three component gage. Good accuracy. E must be known.

PROBE 4

Name: Sibek's Cell
Reference: 11
Principle: Overcoring of a soft inclusion
Location: Used in bore hole

Instrumentation: LVDT's and recording system

Quantity Measured: Voltage output; thus deformation of bore hole diameter from calibration and stresses from elastic theory.

Comments: Single component gage. Can be extended to 3 components. E must be known.

PROBE 5

Name: U.S. Bureau of Mine Gage
References: 12, 13
Principle: Overcoring of a soft inclusion
Location: Used in a bore hole

Instrumentation: 1 gaged cantilever beam and strain gage potentiometer

Quantity Measured: Strain on gages, cantilever deflection and bore hole deformation from calibration curves and stresses from elastic theory.

Comments: Single component gage
Rugged
Good sensitivity
E must be known

PROBE 6

Name: U.S. Bureau of Mines Gage
Reference: 14
Principle: Overcoring of a soft inclusion
Location: Used in a bore hole

Instrumentation: 3 gaged cantilever beams
strain gage potentiometer

Quantity measured: Strain on gages
Cantilever deflection and borehole deformation through calibration curves
Stresses from elastic theory

Comments: 3 component gages
Measurement in a single plane perpendicular to borehole axis
Rugged
Good sensitivity
E must be known

PROBE 7

Name:	Griswold's Cell
Reference:	15
Principle:	Overcoring of a soft inclusion
Location:	Used in a bore hole
Instrumentation:	4 transducer rings or cantilever beams All gaged Strain gage potentiometer
Quantity Measured:	Voltage output Ring deformation or cantilever deflection thus bore hole diameter Stresses from elastic theory
Comments:	3 component gage Relatively low sensitivity for this particular gage E must be known

PROBE 8

Name:	Surface rosette gage
Reference:	16
Principle:	Overcoring of a strain gage rosette
Location:	On the surface of a rock mass
Instrumentation:	Strain gage rosette Strain gage potentiometer
Quantity Measured:	Strain on rosettes Stress relief on overcoring from calibration curves in the laboratory.
Comments:	Gage is not recovered Surface masurement Rosettes are fragile Good bonding to rock surface is a problem E need not be known but the reliability of biaxial calibration is difficult to evaluate.

PROBE 9

Name:	Bottom rosette gage
References:	17, 18, 19, 20
Principle:	Overcoring of a strain gage rosette
Location:	Bottom of a bore hole, prepared flat or hemispherical
Instrumentation:	Strain gage rosettes Strain gage potentiometer
Quantity Measured:	Strain on gages upon stress relief Stress from calibration curves in the laboratory
Comments:	Gage is not recovered Rosettes are fragile Good bonding to rock surface is a problem No theory exists at present for the state of stress at the bottom face of a bore hole, which is of a highly complex nature. Calibration is not thought to be very reliable because of effect of unknown stress parallel to hole.

PROBE 10

Name:	Pott's Stressmeter
Reference:	21, 22, 23, 24
Principle:	Overcoring of a rigid inclusion
Location:	Used in a bore hole
Instrumentation:	Steel cell filled with oil and closed by a gaged diaphragm
Quantity Measured:	Strain on diaphragm gage from change in cell's volume. Stress from laboratory calibration in uniaxial compression
Comments:	Measurement in only one direction Can be also used without overcoring to monitor long term stress changes E need not be known Uniaxial calibration not satisfactory High prestress required Recoverable through overcoring

PROBE 11

Name: May's Stressmeter

Reference: 25, 26, 27, 28

Principle: Overcoring of a rigid inclusion

Location: Used in a bore hole

Instrumentation: Steel cell filled with oil and closed by a gaged diaphram

Diferent thickness of diaphram will give different sensitivities

Quantity Measured: Strain on diaphram gage

Stress from laboratory calibration in uniaxial compression

Comments: Measurement in only one direction

Can be also used without overcoring to monitor long term stress changes

E need not be known

Uniaxial calibration not satisfactory

High prestress is required

Recoverable through overcoring

PROBE 12

Name: National Coal Board Borehole Gage

Reference: 29, 30

Principle: Overcoring of a rigid inclusion

Location: Used in a bore hole

Instrumentation: Split brass cylinder gaged along an inside diameter

Quantity Measured: Strain on gage

Stress from laboratory calibration under uniaxial compression

Comments: Measurement in only one directon

Can be also used without overcoring to monitor long term stress changes .

E need not be known

Uniaxial calibration not satisfactory

High prestress required

Recoverable through overcoring

PROBE 13

Name: Hast's Stressmeter

References: 31, 32

Principle: Overcoring of a rigid inclusion

Location: Used in a bore hole

Instrumentation:
Nickel alloy spool
Coil
Screening tube

Quantity Measured: Changes in impedance of the coil changes in stress through calibration

Comments:
Measurement in only one direction
Can be also used without overcoring to monitor long term stress changes
E need not be known
Uniaxial calibration not satisfactory
High prestress is required
Recoverable through overcoring

PROBE 14

Name: Salamon's Cell

References: 33, 34

Principle: Overcoring of a rigid inclusion

Location: Used in a bore hole

Instrumentation:
Hydraulic cell
8 wire strain gages
4 legs (one for temperature compensation)

Quantity Measured:
Strain on gages
Stresses from laboratory calibration

Comments:
Measurement in only one direction
Can be also used without overcoring to monitor long term stress changes
E need not be known
Uniaxial calibration not satisfactory
High prestress required
Recoverable through overcoring

PROBE 15

Name: USGS Solid Inclusion Probe

Reference: 35

Principle: Strains developed on spherical inclusion

Can be overcored

Location: Grouted in place in a borehole

Quantity Measured: Output of 3 strain gage rosettes

Comments: Applicable particularly for monitoring long term change in stress

Very rugged

PROBE 16

Name: Robert's Stressmeter

Reference: 36

Principle: Overcoring of a photoelastic gage

Location: Used in a bore hole

Instrumentation: Glass cylinder light source

Polarizer

Analyser

$\lambda/4$ plate

Quantity Measured: Fringe pattern

Directions and magnitude of change in stresses from laboratory calibration

Comments: A borehole camera can be used to monitor changes in the fringe pattern

The equipment is rather cumbersome and fragile

Gives a CHANGE IN STRESS but not the absolute STRESS TENSOR

PROBE 17

Name:	Photoelastic rosette
References:	37, 38, 39, 40
Principle:	Overcoring of a photoelastic strain rosette
Location:	On the face of an opening or at the bottom face of a bore hole
Instrumentation:	Photoelastic strain rosette Polariscope
Quantity Measured:	Fringe pattern Direction and magnitude of the change in stresses from laboratory calibration
Comments:	A borehole camera is used to monitor changes in the fringe pattern The equipment is rather cumbersome and fragile Gives a change in stress but not the absolute stress tensor

PROBE 18

Name:	Flat Jack
References:	41, 42, 43, 44
Principle:	Restore initial stress conditions
Location:	Used in an elliptical shallow slot
Instrumentation:	Flat hydraulic cell Reference pins
Quantity Measured:	Reference pins displacement upon rock relaxation and restressing Stress level at pins displacement cancellation
Comments:	Surface measurement (depth 1 foot) 1 Component of stress only for one cell thus need for 2 orthogonal cells emplaced close to each other Not used in a bore hole E can be computed from pin displacement (reference 63)

PROBE 19

Name: Jaeger's Curved Jack

Reference: 45

Principle: Restore an initial stress condition

Location: Used in the ring cut by a thick wall drilling bit

Instrumentation: Thin quadrantal hydraulic cells

Two series:
- Inner ones for reference
- Outer ones for pressurization

Quantity Measured: Pressure in inner cells for references (drops on overcoring and is restored by pressurization in outer cells); thus initial stress in rock is restored.

Comments: The theory has been worked out but the instrument has not so far been used in actual testing.

PROBE 20

Name: Seismic Gage

References: 46 to 53

Principle: Change of properties with stress level (wave velocity)

Location: Surface impact and surface pickup
or
Borehole charge and borehole pickup

Instrumentation: Sledge hammer or seismic charge

Triggering circuit

Geophones

Oscilloscopes

Quantity Measured: Wave Travel Time

Wave velocity and elastic constants

Comments: The elastic constants change with the state of stress

Results are compared to laboratory movements

Indicates a PRESSURE LEVEL but does not give the STRESS TENSOR

PROBE 21

Name:	Resistivity Gage
References:	47, 54 to 59
Location:	Can be used in a bore hole
Instrumentation:	Electrodes Ohmmeter
Quantity Measured:	Loss of potential Rock resistivity
Comments:	The rock's resistivity changes with the state of stress Results are compared to laboratory measurements Indicates a PRESSURE LEVEL but does not give the STRESS TENSOR

PROBE 22

Name:	Nuclear Probe
Reference:	60
Principle:	Change of properties with stress level (attenuation of a radiation)
Location:	Can be done in bore holes (1 for source and 1 for pick up)
Instrumentation:	Gamma radiation sources Gamma counter
Quantity Measured:	Input radiation and absorption with distance
Comments:	The absorption varies with the rock's PRESSURE LEVEL but the STRESS TENSOR cannot be obtained

TABLE II

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 AT I LOCATION	E NEEDED TO REDUCE DATA	OVERALL RATING FOR EARTH OPERATION
1	1 to 6	South Africa	Mechanical Soft	Borehole	Overcoring	Frequency and Strain	Yes	1	Yes	B
2	7,8,9	South Africa	Mechanical Soft	Borehole	Overcoring	Strain	Yes	2	Yes	B
3	3,10	South Africa	Mechanical Soft	Borehole	Overcoring	Strain	Yes	3	Yes	A
4	11	Czechoslovakia	Mechanical Soft	Borehole	Overcoring	Strain	Yes	1	Yes	B
5	12,13	U.S.A.	Mechanical Soft	Borehole	Overcoring	Strain	Yes	1	Yes	B
6	14	U.S.A.	Mechanical Soft	Borehole	Overcoring	Strain	Yes	3	Yes	A
7	15	U.S.A.	Mechanical Soft	Borehole	Overcoring	Strain	Yes	3	Yes	A
8	16	U.S.A.	Mechanical Soft	Surface	Overcoring	Strain	Yes	2 or 3	Yes	C
9	17 to 20	U.S.A. South Africa	Mechanical Soft	Borehole Bottom	Overcoring	Strain	No ?	2 or 3	Yes	C
10	21 to 24	Great Britain	Mechanical Rigid	Borehole	Prestress and Overcoring	Stress	Yes?	1	No	B
11	25 to 28	Canada	Mechanical Rigid	Borehole	Prestress and Overcoring	Stress	Yes?	1	No	B
12	29,30	Great Britain	Mechanical Rigid	Borehole	Prestress and Overcoring	Stress	Yes?	1	No	B
13	31, 32	Sweden	Mechanical Rigid	Borehole	Prestress and Overcoring	Stress	Yes?	1	No	B
14	33,34	South Africa	Mechanical Rigid	Borehole	Prestress and Overcoring	Stress	Yes?	3	No	B
15	35	U.S.A.	Mechanical Rigid	Borehole	Overcoring	Strain	Yes	6	No	C
16	36	Great Britain	Photo Elastic Plug	Borehole	Prestress and Overcoring	Stress	Yes?	2 or 3	No	B
17	37 to 40	Canada	Photo Elastic Rosette	Borehole Bottom	Overcoring	Stress	No	2 or 3	No	C
18	41 to 44	France	Mechanical Soft	Slot	Restore Initial Stress	Pressure	Yes	1	No	B
19	45	Australia	Mechanical Soft	Ring	Restore Initial Stress	Pressure	Yes	3	No	B?
20	46 to 53	Several Countries	Electronic	Boreholes (2)	Change in Rock Properties with Pressure Level	Wave Velocity in Rock	No	0	No	C
21	47,54 to 59	Canada	Electrical	Borehole		Rock Resistivity	No	0	No	C
22	60	Poland	Nuclear	Boreholes (2)		Radiation Absorbtion	No	0	No	C

IV. CONCLUSION

1. The major features of the reviewed probes are summarized in Table II. The following should be considered when rating the devices for adaptability to a lunar exploration program.

   1. Has the technique been used satisfactorily on earth?
   2. How rugged is the probe?
   3. Are any fluids used in operating the probe?
   4. How good is its sensitivity?
   5. What is the overall accuracy of the measurement towards determination of the absolute stress tensor? How many components of stress are measured at one location?
   6. Is knowledge of the rock's elastic constants required to interpret the measurement or can a direct stress reading be obtained?
   7. What is the possibility of automatic recording and remote control?
   8. Is there a requirement for high initial prestressing of the probe thus endangering its retrieval?
   9. Is the calibration very sensitive to temperature and pressure variations?
   10. What is the essential measuring device? (LVDT, cantilever, wire, ring, pressure cell, photoelastic material, strain rosette, etc.)
   11. How cumbersome is the total measuring and monitoring instrumentation?
   12. How easily can a stress measurement be integrated into a complex bore hole experiment on the moon?

Based upon these considerations a rating of reviewed probes has been made for their adaptability to lunar measurements. (Table III)

2. It is concluded here that in order to measure stresses in rocks on the moon efforts should be directed towards the design and/or lunarization of a "three-component" gage to be used in an overcoring process. Automatic recording will be refined for data analysis to be performed on earth. LVDT's seem to be best fitted as displacement monitoring instrument, to a lunar environment.

Of all the devices known to the authors it appears that Probe No. 6 (U.S. Bureau of Mines - Grosvenor's system*) would be the best suited to undergo miniaturization and lunarization. It is interesting to note that this conclusion has been reached independently by Kaarsberg (see ref. 69).

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*A very similar probe has been designed by Dr. Niles Grosvenor, Colorado School of Mines, Golden.

TABLE III

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

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