

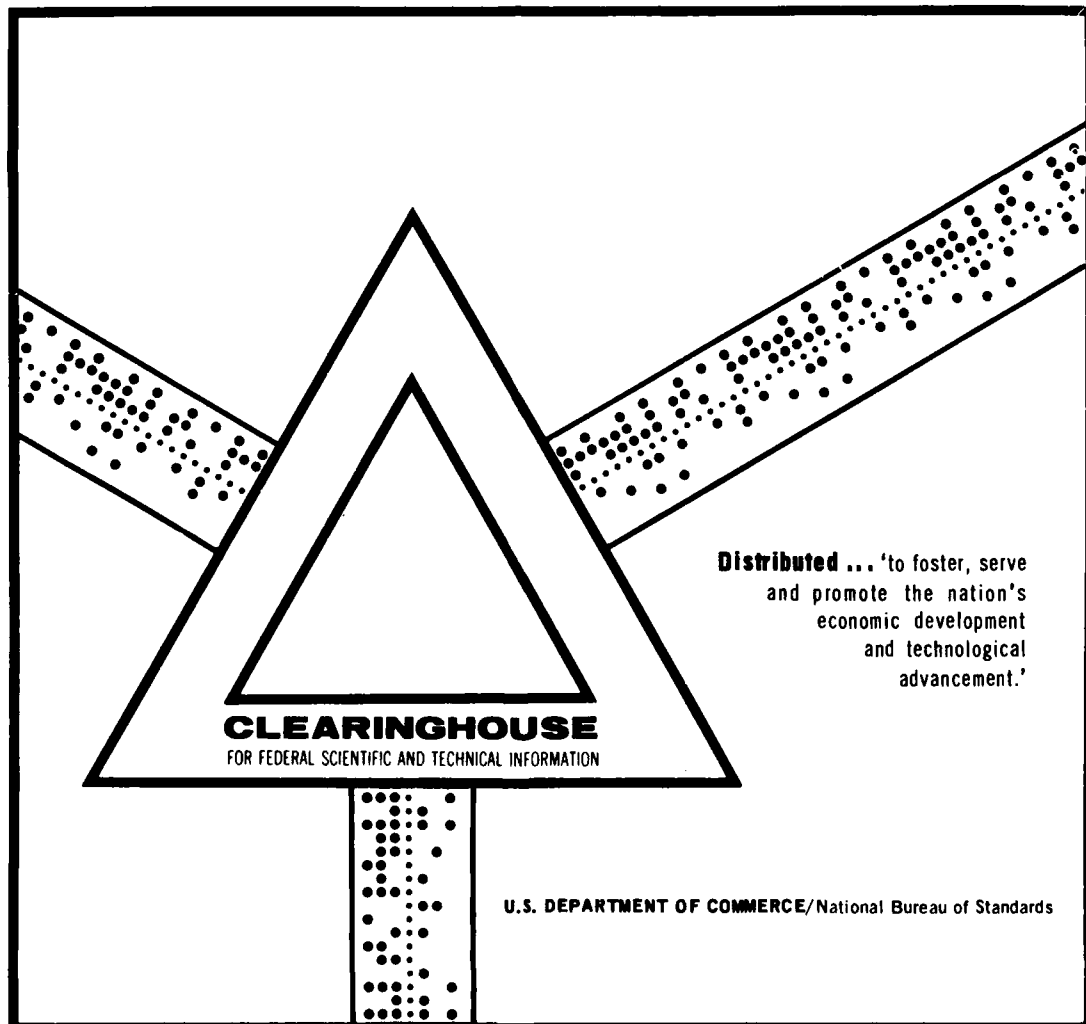
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THE PHOTOELASTIC UNIDIRECTIONAL STRESSMETER.
A BOREHOLE ROCK STRESS GAUGE

Ivor Hawkes

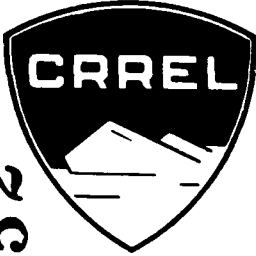
Cold Regions Research and Engineering Laboratory
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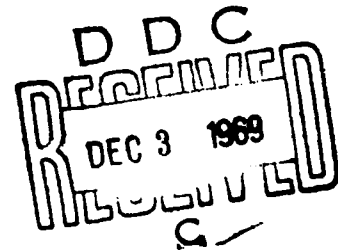
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**THE PHOTOELASTIC
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A BOREHOLE ROCK STRESS GAUGE**

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**THE PHOTOELASTIC
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DA PROJECT 1T061101A91A

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PREFACE

This study was undertaken at the U.S. Army Cold Regions Research and Engineering Laboratory as an In-House Laboratory Independent Research project forming part of the rock mechanics program of the Applied Research Branch (Mr. A.F. Wuori, Chief) of the Experimental Engineering Division (Mr. K.A. Linell, Chief). This report is published under DA Project 1T061101A91A, *In-House Laboratory Independent Research*.

The author wishes to acknowledge the assistance of the following: Mr. R. Perham, Mr. A. George, and Mr. A. Tuthill, who helped design and produce the meters; Mr. R. Atkins and Mr. H. Johnson, who developed the electronic circuitry; and Mr. R. Lange and Mr. P. Kaiser, who assisted in the field trials. Mr. F.J. Sanger performed technical review of the manuscript.

Citation of trade names or manufacturers in this report is for information only and does not constitute official approval or endorsement.

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THE PHOTOELASTIC UNIDIRECTIONAL STRESSMETER

A BOREHOLE ROCK STRESS GAUGE

by
Ivor Hawkes

Introduction

A wide variety of borehole gauges have been developed for measuring rock stress. They all operate on the principle that stress changes around a borehole result in deformations that can be measured by the gauge and interpreted in terms of the stress change either by calculation or calibration. In general terms, gauges that comply with the borehole deformations are referred to as "deformation meters" and those that restrain the deformations by reason of their rigidity are referred to as "stressmeters." The main advantages claimed for stressmeters are that their "stress" sensitivity is much less dependent on the rock modulus than that of deformation meters, and they are clamped firmly in the borehole and therefore relatively unaffected by vibrations.

The use of each borehole gauge developed for stress determinations in rock has been in the main confined to the laboratory responsible for its development. To be generally accepted a gauge must meet the following specifications:

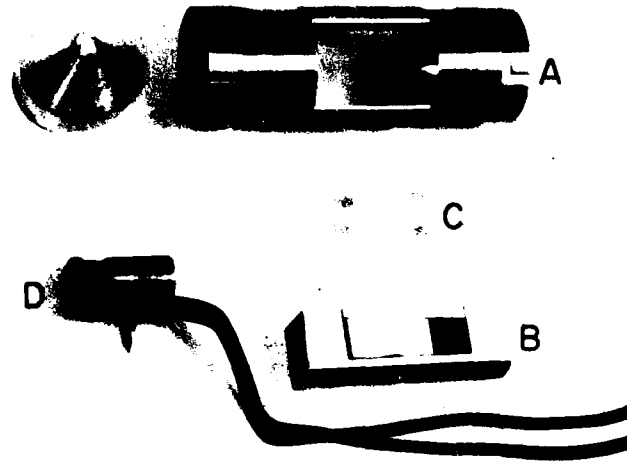
1. Gauges to be left in place to measure stress changes must be relatively cheap, and if possible recoverable, so that large numbers can be used to obtain an overall picture of the changing conditions. This is not necessarily the case for recoverable gauges designed for absolute rock stress measurements where usually only one or two gauges are involved.
2. For use in the adverse environmental conditions encountered underground, it is essential that gauges be robust, stable and unaffected by high humidity, corrosive water or dust.
3. Highly qualified technicians are rarely employed specifically for rock mechanics studies in mines or on civil engineering sites and therefore gauges designed for measuring stress changes must be easy to place and simple to read. Again this does not necessarily apply for absolute rock stress measurements, which can be made only by highly skilled operators.
4. The sensitivity of the gauge must be commensurate with the use to which the results will be put. There is little advantage in designing a highly precise and sensitive gauge at the expense of simplicity or cheapness if its readings are to be interpreted only in general terms.

The photoelastic properties of glass have made possible the development of a wide range of gauges (Roberts, 1966) which in many respects meet the above specifications. This paper describes a photoelastic unidirectional meter with a diametrically loaded glass cylinder as the transducer element which has been developed primarily to measure stress changes. It will be referred to as the P.U. Stressmeter to distinguish it from the biaxial hollow cylinder Photoelastic Stressmeter which has been described in detail elsewhere (Roberts *et al.*, 1964). In modified form the P.U. Stressmeter has been successfully used to measure absolute rock stress (Hobbs *et al.*, 1966). Details of the latest developments of the method are given in this report.

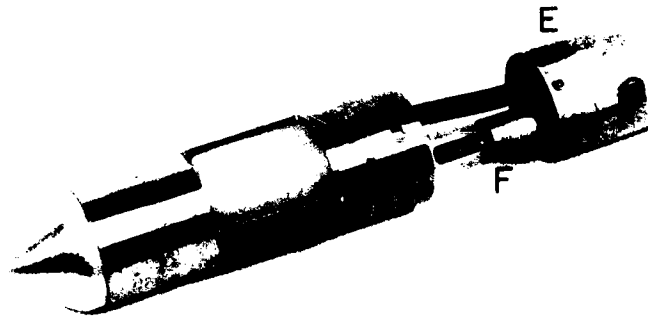
P.U. Stressmeter

The P.U. Stressmeter consists essentially of four components (Fig. 1a): a stainless steel expandable body or housing A, a stainless steel reversible wedge mechanism B, a glass cylinder C,

THE PHOTOELASTIC UNIDIRECTIONAL STRESSMETER



a. Components.



b. Assembled meter and settling tool.

Figure 1. Photoelastic Unidirectional Stressmeter.

and a circularly polarizing light source D. Figure 1b shows the assembled meter and settling tool. The latter consists of a tube with bayonet fittings E, to hold and orient the meter in the borehole and a rod fitted with an allen wrench F, which can be rotated to operate the wedge mechanism. In use (Fig. 2a) the wedge mechanism is expanded to force the glass cylinder diametrically against the inner wall of the tube and load it against the side of the borehole to a predetermined level. Any change in rock stress will produce a change in the preload and is measured in terms of the

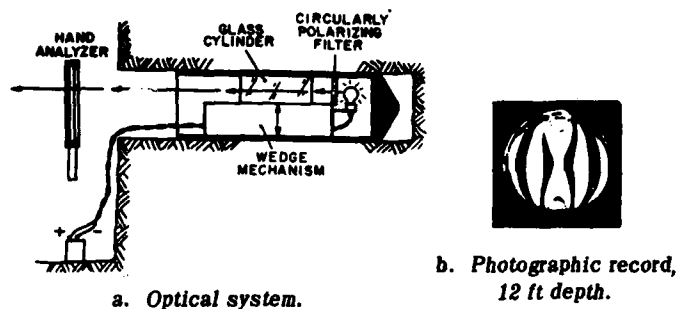


Figure 2. Reading the P.U. Stressmeter.

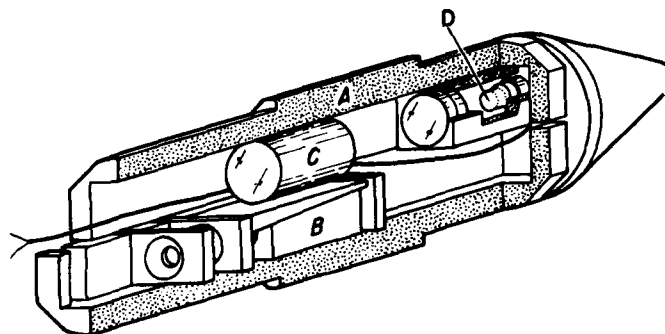


Figure 3. P.U. Stressmeter (modified design).

photoelastic isochromatic fringe order at the center of the glass cylinder made visible when viewed by polarized light (Fig. 2b).

A standard EX diamond reamed hole provides a slide fit for the meter. The wedge mechanism expands up to 0.020 in. to take up any clearance between the meter platens and the inner walls of the borehole. The meter has been subjected to various design changes during its development and Figure 3 illustrates an alternative design which is currently being evaluated. In operation the two forms of gauge are identical but the work reported here was all carried out on the earlier design illustrated in Figure 1.

Glass cylinder transducer

A diametrically loaded glass cylinder forms a very simple, reproducible and reliable load transducer. Glass is extremely stable with time, is perfectly elastic, and is virtually unaffected by water or temperature change.

It is not necessary to have any knowledge of the principles of photoelasticity to use the glass cylinder transducer as incorporated in the P.U. Stressmeter. The full theory can be obtained from standard textbooks, and will only be briefly discussed here.

The optical system used to reveal the isochromatic fringes in the glass cylinder is illustrated in Figure 2a. The circularly polarized light is produced by a combined linear polarizer/quarter wave plate built into the light source. The cylinder is observed through a hand analyzer consisting of two separate filters, a linear polarizer and quarter wave plate. In the analyzer the linear polarizer can be rotated with reference to the quarter wave plate so that Tardy compensation can be carried out to obtain a precise fringe order reading (Frocht, 1948).

THE PHOTOELASTIC UNIDIRECTIONAL STRESSMETER

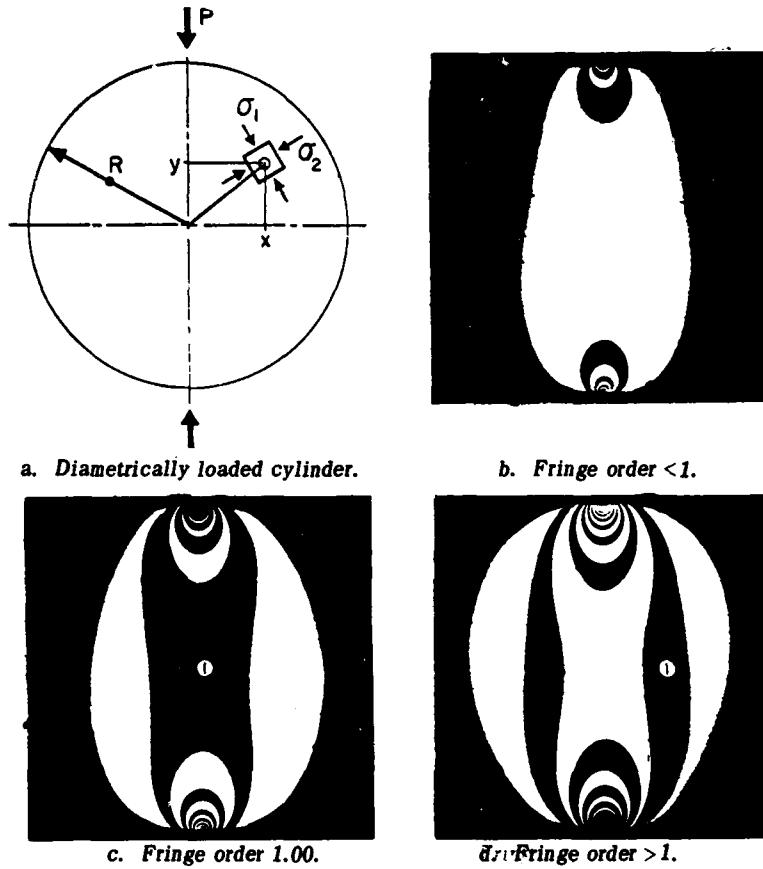


Figure 4. Development of isochromatic fringes in a glass cylinder under a diametrically applied load.

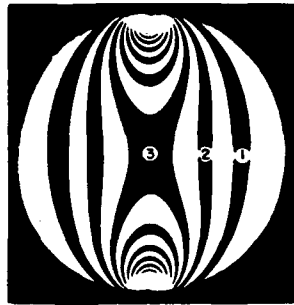
The basic stress optic law for a crossed polariscope system as used in the meter is:

$$N = \frac{t(\sigma_1 - \sigma_2)}{F} \quad (1)$$

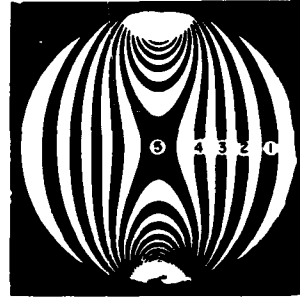
where

- N = isochromatic fringe order
- σ_1, σ_2 = principal stresses normal to the direction of the light path
- F = material unit fringe value
- t = length of the light path through the glass.

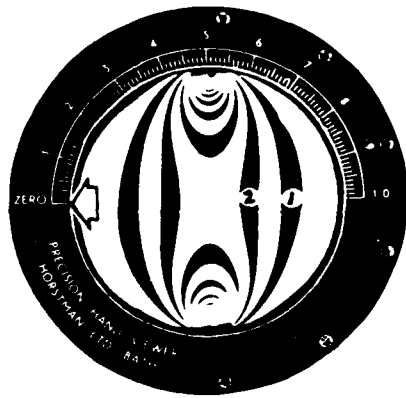
Isochromatic fringes are areas of constant stress difference. They appear as a series of colored lines or fringes separated by easily identified changes of color between blue and red or green and red. These are called "tints of passage" as they mark the boundaries between fringe orders. If a color filter or monochromator is incorporated into the hand analyzer, the fringes will appear as a series of black lines against a light background as in Figures 2b, 4 and 5.



a. Fringe order 3.00.



b. Fringe order 5.00.



c. Fringe order > 2.



d. Fringe order 2.70.

Figure 5. Fringe order measurement.

The distribution of the lines of stress difference in a cylinder under a diametrically applied load is given (Frocht, 1948) with reference to Figure 4a by:

$$(\sigma_1 - \sigma_2) = \frac{4PR(R^2 - x^2 - y^2)}{\pi t(R^2 + x^2 + y^2)^2 - 4R^2y^2} \quad (2)$$

where P = applied load
 R = radius of the cylinder
 t = length of the cylinder
 x, y = rectangular coordinates.

Around the circular boundary of the cylinder $R^2 = x^2 + y^2$, and the stress difference and therefore the fringe order in this region are zero, irrespective of the applied load. At the center of the cylinder the fringe order N is given by

$$N = \frac{4P}{F\pi R} \quad (3)$$

At this point therefore there is a linear relationship between the fringe order and load, which is independent of the length of the cylinder.

The relationship between the fringe order at the center of a glass cylinder of given diameter and the deformation across the diameter is directly proportional to the length. The exact relationship is complicated due to the non-uniform stress field and the flattening of the lines of contact and is best obtained by direct calibration. All the results given in this paper relate to a P.U. Stressmeter fitted with a borosilicate glass cylinder, 0.54 in. in diameter by 1 in. long.

Initially, with no load, the cylinder appears black (zero fringe order). When a load is applied the central region lightens and isochromatic fringes are generated at the points of contact (Fig. 4b) and grow out until they touch at the center to give a fringe order of 1 (Fig. 4c). Further increase in load causes the fringe to split into two continuous lines joining the points of contact, one on each side (Fig. 4d). This process is repeated as the load continues to increase but as the fringe order must always be zero at the edge of the cylinder all fringes remain in the field of view.

Thus it is possible to determine whether the fringe order is 1, 2, 3, etc., by counting the fringes between one side and the center (Fig. 5a, b). When the fringe order is between whole numbers (Fig. 5c) it is necessary to find the fractional fringe order. This is done by making use of the technique of Tardy compensation (Frocht, 1948). The handle of the hand analyzer is aligned with a line joining the points of contact and the scale is rotated until the fringe nearest the center is optically retarded back to form a cross (Fig. 5d). The scale reading is then added to the fringe count to give the precise fringe order. For example, Fig. 5c shows a cylinder loaded to a fringe order > 2 , read with the viewer scale set at zero. The scale is rotated until the second fringe is retarded back to form a cross (Fig. 5d); the scale reading is then 0.70. The fringe order is therefore the original fringe count (2) plus the scale reading (0.70). Using this technique, with a little practice, the average operator can determine the fringe order at the center of the glass cylinder to within $\pm 2\%$. It has been found by experience that the maximum number of fringes that can be counted by the eye alone and without risk of error is five; therefore this is the normally recommended limit. The meter can be read in 6-ft-deep boreholes with the naked eye and at 20 ft using a telescope. Photographic records can of course be made; Figure 2b is a photograph taken with a telephoto lens of the fringe pattern in a P.U. Stressmeter at a depth of 12 ft.

Meter rigidity

The sensitivity of any particular "stressmeter" is a function of the rigidity of the meter relative to that of the rock into which it is inserted. Hult *et al.* (1966) have suggested that this can be defined in terms of a ratio W_m/W_r where W_m and W_r are defined as "resistance to compression" of the meter and rock, respectively, and have units of force/length. The value of W for any particular stressmeter and rock depends on the design of the meter and the way it loads the rock.

For a solid cylindrical inclusion stressmeter, Hult *et al.* (1966) gave the relationship between the W ratio and the modular ratio as:

$$\frac{W_m}{W_r} = \frac{E_m}{E_r} \frac{(1 + \nu_r)}{(1 - \nu_m)} \quad (4)$$

where E and ν are the Young's modulus and Poisson's ratio. From inclusion theory (Coutinho, 1949) when the ratio $(E_m/E_r) > 2$ the sensitivity of the inclusion stressmeter is relatively independent of the elasticity modulus of the rock. Assuming a Poisson's ratio for the inclusion and a rock of 0.2, the same condition may therefore be assumed to apply when the ratio $(W_m/W_r) > 3$.

For a unidirectional stressmeter bearing on the sides of a borehole over diametrically opposed areas, Hult *et al.* (1966) gave the following formulae for W_m and W_r :

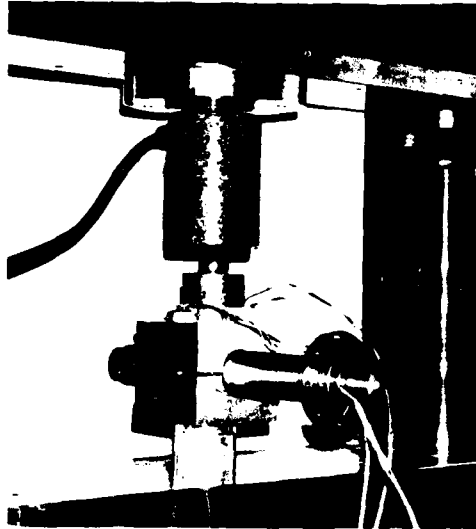


Figure 6. Determination of stressmeter rigidity (modified P.U. Stressmeter under test).

$$W_m = \frac{P}{\Delta_m} \quad (5)$$

and

$$W_m = 0.1 \frac{E_r}{1 + \nu_r} L \quad (6)$$

where L is the active length of the meter (platen length) and Δ_m is the meter deformation.

To obtain the W_m factor for the P.U. Stressmeter the meter was loaded in a split aluminum test block and the load and deformation were recorded continuously on an $x-y$ plotter, as the output signals of a load cell and two displacement transducers (Fig. 6). The fringe order at the cylinder center was also noted at specific loads. The results for a P.U. Stressmeter fitted with a 0.54-in.-diam \times 1-in.-long glass cylinder are shown graphically in Figure 7.

As theoretically predicted, the fringe order/load characteristic is quite linear with a load sensitivity of 182 lb/fringe. The fringe order/deformation characteristic, however, is not completely linear, particularly below a fringe order of $1\frac{1}{2}$ (at \approx 270 lb). This is thought to be due to bedding-in of the platens and gauge components under load. Similar results have been reported by Hast (1958) and Barron *et al.* (1965) for unidirectional stressmeters. Care must be taken when assembling the P.U. Stressmeter to ensure that the glass cylinder is uniformly loaded along the lines of contact with the wedge mechanism and tube. Uneven loading has no influence on the fringe order-load characteristic but it causes the fringe order-deformation characteristic to become very nonlinear at low loads.

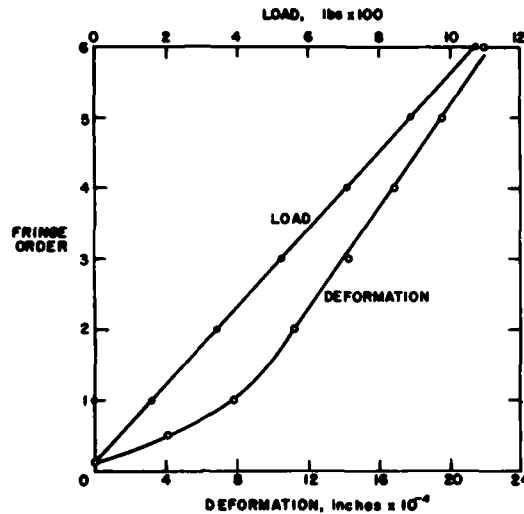


Figure 7. P.U. Stressmeter rigidity.

From Figure 7 the W_m factor is 6.5×10^6 lb/in. and from eq 6 the W_r factor, assuming a Poisson's ratio $\nu_r = 0.2$ and $L = 1.2$ in., is $0.1 E_r$.

For the P.U. Stressmeter the W ratio is therefore

$$\frac{W_m}{W_r} = \frac{6.5 \times 10^6}{E_r} \quad (7)$$

Based on the work of Hult et al. (1966) it may, therefore, be assumed that the meter sensitivity will be largely independent of the rock modulus when this modulus falls below approximately 2.0×10^6 psi [$(W_m/W_r) > 3$]. However, most rocks have a greater modulus and therefore the theoretical meter sensitivity will usually be dependent to some extent on the rock modulus.

Meter sensitivity

The relationship between the fringe order at the center of the cylinder in the P.U. Stressmeter and the stress change in any particular rock type is directly proportional to the length of the glass cylinder and must be obtained by calibration. The problem is that in practice it cannot generally be assumed that the nature of the stresses acting in the rock are known. It must be assumed that any change of stress along the axis of the borehole will not influence the meter readings. This assumption is often made for almost all stress and deformation meters and is not unreasonable for the P.U. Stressmeter which is primarily intended for use close to the surface of excavations where the stress component normal to the surface is very small.

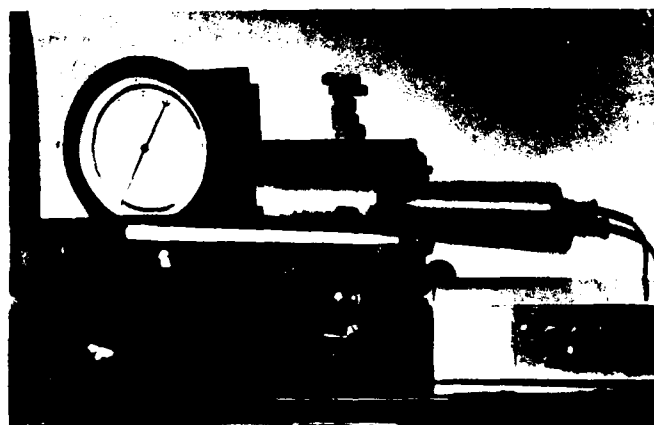
The relationship between the radial deformation of a borehole U and magnitude of the two principal stress components perpendicular to the borehole has been given by Hast (1958) and, with a detailed derivation, by Merrill and Peterson (1961).

For plane stress:

$$U = \frac{D}{E_r} [(\sigma_1 + \sigma_2) + 2(\sigma_1 - \sigma_2) \cos 2\theta] \quad (8)$$



a. Uniaxial stressing (P.U. Stressmeter).



b. Biaxial stressing (modified P.U. Stressmeter).

Figure 8. Calibration techniques.

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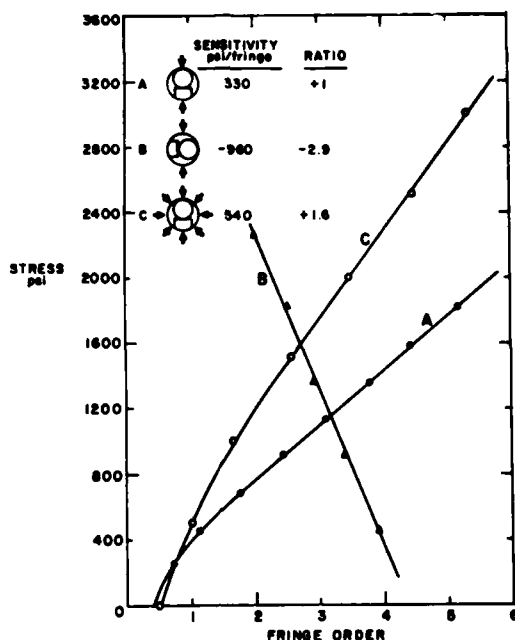


Figure 9. Stressmeter uniaxial and biaxial calibrations - Barre Granite.

where σ_1 and σ_2 = the principal stresses in the plane of the borehole
 θ = the angle to the direction σ_1 (compression + ve)
 D = the diameter of the borehole.

(In practice plane strain usually applies but as the difference between the two cases is very small, plane stress is usually assumed.) Hast (1958) has shown that eq 8 also applies for unidirectional stressmeters if the term D/E_T is replaced by some other constant C which is a function of E_T and the rigidity of the meter. To verify this assumption for the P.U. Stressmeter it was calibrated under uniaxial ($\sigma_2 = \sigma_3 = 0$) and biaxial ($\sigma_1 = \sigma_2$, $\sigma_3 = 0$) stress in Barre granite.

For the uniaxial calibration a 4-in. \times 8-in. \times 12-in. block of granite was cut with its long axis normal to the plane of the "hardway" and an EX reamed hole was drilled centrally through the largest face (Fig. 8a). Particular care was taken to ensure flat, parallel loading faces, and to check uniform stressing a carbon paper impression was made of the platen/rock interfaces. Uniaxial calibrations were made with the meter aligned parallel and at right angles to the direction of loading. The results are given as curves A and B in Figure 9.

For the tests with the meter aligned parallel to the loading direction ($\theta = 0$), the meter was set with an initial preload of 0.5 fringes and the fringe order at the center of the cylinder was measured against applied load (curve A, Fig. 9). Above a fringe order of $1\frac{1}{2}$ the stress/fringe order became linear with a slope of 330 psi/fringe. When the meter was set at right angles to the loading direction ($\theta = 90^\circ$), the fringe order readings fell as the load was increased due to the lateral expansion of the borehole. For this calibration, therefore, the meter was preloaded to around 2 fringes with the block under load and the fringe order increase was measured as the load was removed (curve B, Fig. 9). The sensitivity for this calibration was 960 psi/fringe. There was very little hysteresis

between loading and unloading in both cases and the preload level had no effect on the sensitivity when working within the linear range of the meter.

The biaxial calibrations were carried out in a 6-in.-diam \times 18-in.-long core of granite loaded hydraulically around its peripheral surface (Fig. 8b). The hydraulic calibrator built for this purpose was copied from a design by Fitzpatrick (1962) and is described in detail in this reference. To carry out the test, the core, which had an axial *EX* reamed borehole, was sleeved with latex rubber and positioned inside the steel tube. O-ring seals were then placed over the core at both ends and tightened to the tube to prevent fluid leakage. The stressmeter was then set in the borehole halfway between the ends to avoid the complicated stress field near the sealing points and preloaded to the desired level. The stress/fringe relationship could then be obtained directly by measuring the fringe order against hydraulic pressure. Curve C, Figure 9, shows the results of a typical calibration giving a sensitivity of 540 psi/fringe. As before, there was nonlinearity below $1\frac{1}{2}$ fringes but very little hysteresis and no apparent change in sensitivity with the degree of preload.

From eq 8 the theoretical ratios of the meter sensitivities for the three cases tested ($\sigma_2 = \sigma_3 = 0, \theta = 0$); ($\sigma_2 = \sigma_3 = 0, \theta = 90^\circ$); and ($\sigma_1 = \sigma_2, \sigma_3 = 0$) are $+1 : -3 : +1.5$. The experimental values of these ratios from Figure 9 are $+1 : -2.9 : +1.6$. Within experimental error the form of eq 8 is valid for the P.U. Stressmeter.

To determine the value of the constant *C* and its relationship to the rock modulus, a series of uniaxial calibrations were carried out in different materials with the meter aligned in the direction of loading. Calibrations were made in steel, aluminum and Lucite (acrylic resin) using 8-in. \times 8-in. \times $1\frac{1}{4}$ -in. slabs and in Barre granite, Berea sandstone and Indiana Bedford limestone using prisms roughly 4 in. \times 8 in. \times 12 in. as described earlier. The Young's moduli of the steel and aluminum were taken from standard reference books and the values for granite, sandstone, limestone and Lucite were measured from 1-in.-diam \times 3-in.-long cores. The rock cores were taken from the original block from which the prisms were cut and were oriented so that the loading directions coincided with those in the prisms. The deformations were measured using demountable jigs holding two deformation transducers and the loads, by a strain gauge load cell. A continuous trace of load against deformation both for loading and unloading was obtained by feeding the outputs to an *x-y* plotter. The stress/strain curves for the various materials (Fig. 10) are the average of the loading and unloading cycles, over a stress range of 0 to 2000 psi.

The results of the uniaxial calibrations of the stressmeter are given in Table I and plotted in Figure 11. The results are similar to those described earlier for Barre granite, with initial nonlinearity followed by a more or less linear response. The Berea sandstone was an interesting case in that the sensitivity appeared to be comparatively linear in the range $\frac{1}{2}$ to 4 fringes. It is thought that this is associated with the very great change in the modulus at very low stress levels (Fig. 10). The modulus range for this rock as given in Table I and shown plotted in Figure 10 is the range for 1000 to 2000 psi.

The relationship between the stressmeter sensitivity and the modulus of the material in which it is being used is given in Figure 12. The relationship is quite linear over the range 0.5 to 30×10^6 psi. (The sensitivity in steel is not shown in Figure 12, but it lies close to the relationship shown.) As predicted theoretically, the meter sensitivity is dependent on the rock modulus; the general relationship between the fringe order *N* and stress is:

$$N = \frac{1}{(128 \times 10^6 E_r + 360)} [(\sigma_1 + \sigma_2) + 2(\sigma_1 - \sigma_2) \cos 2\theta]. \quad (9)$$

It is interesting to note, however, that as the rock modulus changes from 1×10^6 to 5×10^6 , a factor of 5, the meter sensitivity only changes by a factor of 2.

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Table I. P.U. Stressmeter sensitivity (uniaxial).

Material	Young's modulus, E_r ($\times 10^6$ psi)	Sensitivity (psi/fringe)	C ($\times 10^{-3}$)
Steel	29.6	1400	0.238
Aluminum	10.2	550	0.606
Granite (axis normal to plane of hard way)	4.7 → 5.2	330	1.01
Limestone	3.2 → 3.5	260	1.28
Sandstone	1.2 → 2.2	210	1.59
Acrylic resin (Lucite)	0.4	140	2.38

$$N = C[(\sigma_1 + \sigma_2) + 2(\sigma_1 - \sigma_2) \cos 2\theta]$$

$$\text{where } C = \frac{1}{(128 \times 10^{-6} E_r + 360)}$$

The stress range of the P.U. Stressmeter depends upon the nature of the stress field and the modulus of the rock and is inversely proportional to the length of the glass cylinder transducer. Assuming a readable range of 2 to 5 fringes in the meter, in uniaxial stress conditions the average stress range of the meter as described will be around 800 psi. This could be increased to 1600 psi and the sensitivity halved by reducing the glass cylinder length to $\frac{1}{2}$ in. Any reduction below this might result in failure of the glass above 5 fringes due to the very high stresses induced. The range however could be increased still further by redesigning the wedge mechanism to accept a larger diameter cylinder.

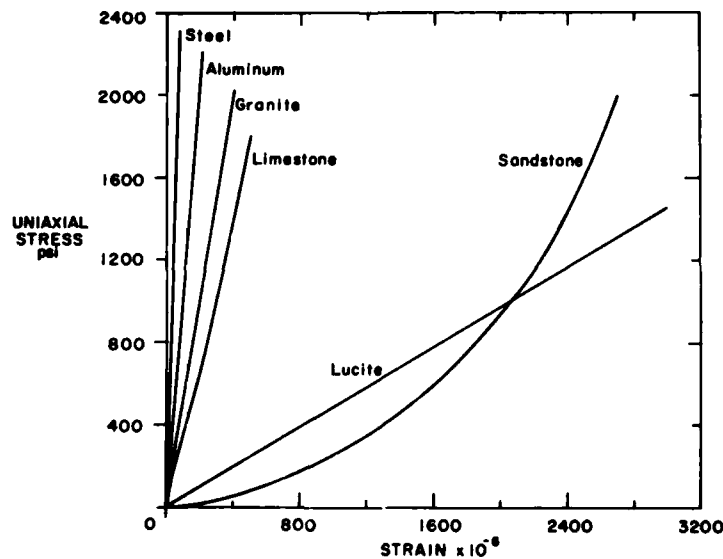


Figure 10. Stress/strain characteristics 0-2000 psi.

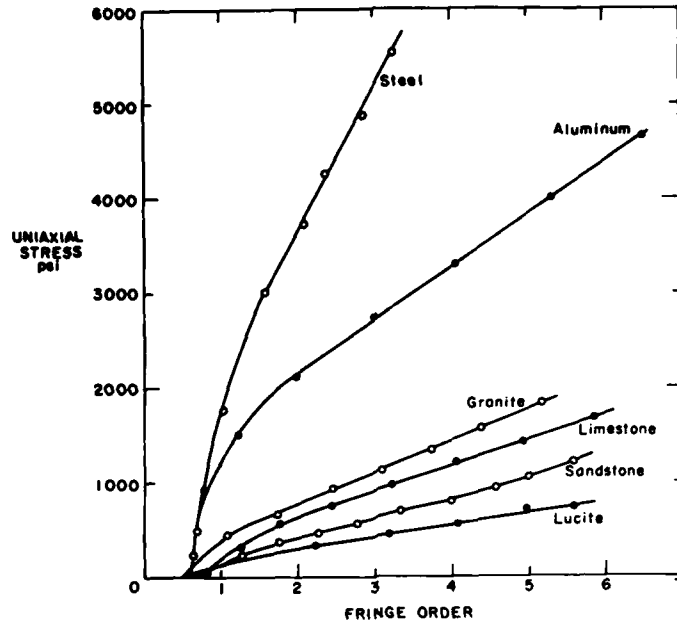


Figure 11. P.U. Stressmeter uniaxial calibrations.

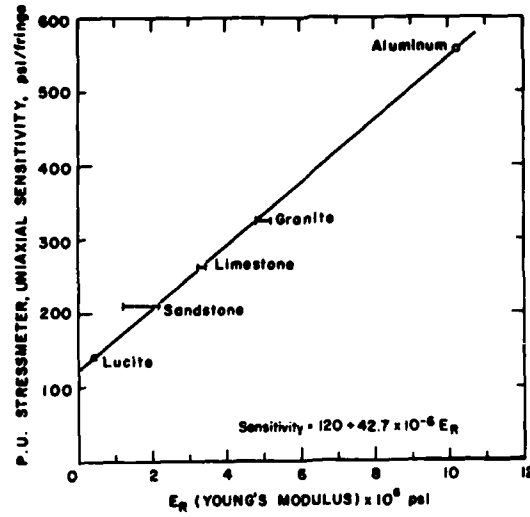


Figure 12. P.U. Stressmeter uniaxial sensitivity.

Temperature effects

Temperature change has no effect on the photoelastic properties of glass over normal working ranges but problems could arise due to differential thermal expansion between the rock and meter. This phenomenon has not been fully investigated but preliminary tests with the meter set into prisms of Barre granite show no appreciable effects over a temperature range of 60F to 120F.

Stress determinations

Field trials have shown that installation of the P.U. Stressmeter presents very few problems. It is, however, important to have a smooth straight hole to enable the meter platens to bear uniformly. When the meter has been positioned and oriented in the hole it is advisable to crank up the wedge mechanism and preload the meter beyond the anticipated stress level change, i.e., to 6 or 7 fringes, so that the platens are well bedded into the walls. Following this operation the meter may be unloaded and left with an initial fringe order reading around 2. When the readings are expected to fall, the initial reading should of course be set higher, at 4 or 5 fringes. If the stress changes increase beyond the working range, it is a fairly simple procedure to reset, or recover, the meter.

The simplest use for the P.U. Stressmeter is the detection of stress buildup in areas where the stress directions are roughly known, i.e., in mine pillars. Under such circumstances satisfactory results will probably be obtained by aligning the meter parallel to the sides of the pillar and using the uniaxial sensitivity applicable to the particular rock. The stress buildup may be more complicated around tunnels and it may be necessary to use two or three meters set into adjacent boreholes to obtain a truer picture of the buildup and the directions. The formulae by which the two principal stress components in the plane of a borehole may be found from three diametral deformation readings made at various angles are well known (Obert and Duvall, 1967). To use these formulae for the P.U. Stressmeter it is merely necessary to replace the factor E_r/D by $1/(128 \times 10^{-6} E_r + 360)$, and the deformations by the fringe order changes. A much simpler technique under such circumstances is to use the meters in conjunction with hollow cylinder photoelastic stressmeters (Roberts, et al., 1964) which, even when incorrectly set, will still give the stress directions in the plane of the borehole in almost all cases. Once these have been generally established the P.U. Stressmeter with its advantage of easier setting, reading and recovery can be used for the actual stress monitoring.

Absolute in-situ rock stress measurements

The P.U. Stressmeter, in the form described, has been used for absolute rock stress measurements using the borehole overcoring technique. Its use, however, is limited to the depth at which the meter can be read and to holes inclined above the horizontal. There are much simpler techniques available for these conditions (Hawkes and Moxon, 1965) and the main interest is in methods suitable for deep vertical holes filled with water or drilling fluid. Because of its basic simplicity the P.U. Stressmeter is potentially attractive for this type of problem, and techniques have been developed to operate the wedge mechanism using an electric motor and to read the fringe order in the glass cylinder by means of a light-sensitive cell. The modified meter is shown diagrammatically in Figure 13 and, being calibrated in a core, in Figure 8b.

The main problem in designing such a meter is to measure the fringe order at the center of the glass cylinder. Figure 14 illustrates the form of the output voltage from a cadmium sulfide, photoresistive cell positioned to accept light passing axially along the center of the cylinder. As the fringe order increases, the voltage output behaves as a damped sinusoidal wave and it is not possible to determine the fringe order from a specific voltage reading. When using the meter for absolute stress measurements, it is necessary to use the photoresistive cell only to enable the initial preload to be set precisely. The change in fringe order can be read after the core and meter

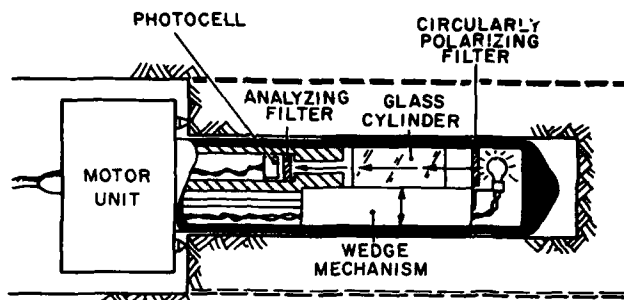


Figure 13. Modified P.U. Stressmeter for absolute rock stress measurements.

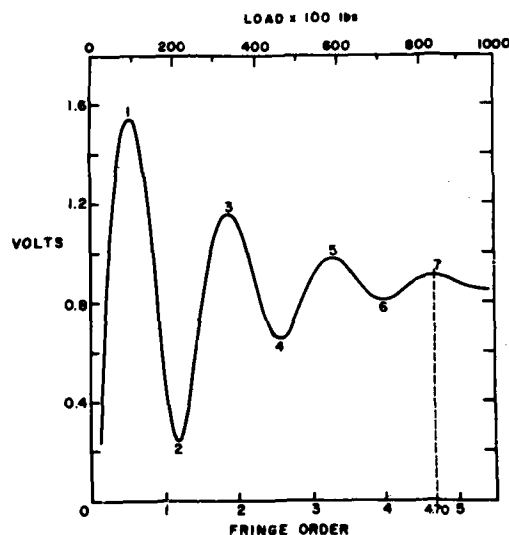


Figure 14. Photoresistive cell output (isochromatic fringes at center of glass cylinder).

have been removed from the hole and the glass cylinder made visible. The most distinct characteristic of the voltage output from the cell is the peaks, 1 to 7 (Fig. 14); these always occur at the same fringe order irrespective of the intensity of illumination. Figure 15 shows a circuit designed to detect very precisely the maximum or minimum voltage peaks and to switch off the current to the motor at any predetermined peak. The repeatability of the preload using this technique is better than can be detected by the eye, i.e. within ± 0.01 fringe.

Field trials of the instrument are currently underway in the quarries of the Rock of Ages Corporation, Barre, Vermont. The technique being used is as follows: A 6-in. hole is drilled vertically to the desired depth and the core is removed. A blank bit holding an 18-in.-long EX core barrel, reamer and bit is then fitted to the 6-in. core barrel and an EX hole is drilled in the middle of the bottom of the larger hole. The modified P.U. Stressmeter is then positioned and oriented in the EX hole by means of a tube connected at the rear of the motor housing of the meter. The electrical control cables pass through the center of this tube. To preload the meter the motor is switched on and the voltage peaks associated with the development of the fringe pattern noted by following the swing of the volunteer needle. To preload the meter at a fringe order of 4.70 corresponding to voltage peak 7 (Fig. 14) the circuit is set to cut out on maximum peak voltages and

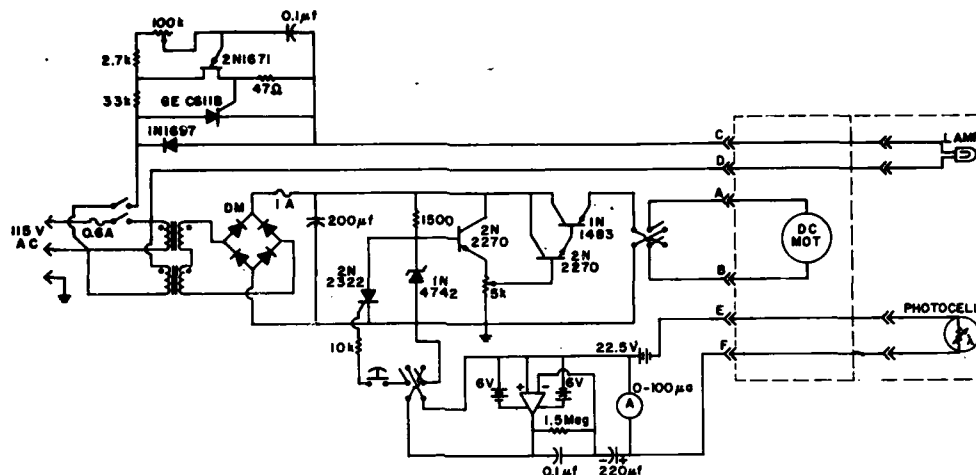


Figure 15. Control circuit for modified P.U. Stressmeter.

the automatic motor cutout circuit activated following voltage peak 5. When voltage peak 7 is reached the meter automatically switches off and the meter is left with the specified preload. The setting rod and the lead wires can then be removed prior to overcoring. There are advantages in leaving the lead wires connected and fed through the water swivel, so that the change in preload can be followed during overcoring and if necessary the meter can be reset during the operation. Following overcoring the core is broken off and the core and meter brought to the surface. The motor unit and photoresistive cell housing are designed for easy removal from the stressmeter body, to enable the change in fringe order to be read with the hand analyzer as described. To calibrate the meter as it lies in the core and to allow for anisotropy the core is then placed in the hydraulic calibrator (Fig. 8b) and calibrated biaxially over the range indicated by the fringe order change. The whole operation has to be repeated twice more to enable the two principal stress components in the plane of the borehole to be obtained.

The technique appears to have promise and there appears to be no reason why three P.U. Stressmeters cannot be set one behind the other at various angles and all of them overcored together. The problems involved in attempting to measure absolute rock stress at depth are, however, formidable (Fairhurst, 1968) and the main objection to the technique described is that a comparatively large hole is required and no account can be taken of the stress component acting axially along the borehole.

Accuracy

The accuracy of rock stress measurements depends primarily on the chosen conversion factor for the meter readings. Strictly speaking the P.U. Stressmeter is not a "stressmeter" as its sensitivity is dependent to some extent on the properties of the rock in which it is used. Rock is such a variable material that to guarantee any degree of accuracy is nearly impossible without calibration on the actual rock piece into which the meter is set. Obert (1967) states that "for most engineering purposes an absolute stress determination within $\pm 25\%$ is generally adequate" and measurements made with the P.U. Stressmeter should fall within this range. The meter however is intended primarily for measuring stress changes, and a relatively high degree of reproducibility, i.e. within 10% should be possible in any given rock type. The main factors however in this respect are sensitivity and stability as it is more important to determine if stress changes are occurring rather than to know the absolute values of the stresses.

Literature cited

- Barron, K.; May, A.N.; and Cross, H.E. (1965) The Mines Branch Stressmeter. Department of Mines and Technical Surveys, Mines Branch, Ottawa, Canada, Divisional Report FMP65/172-MRL.
- Coutinho, A. (1949) Theory of an experimental method of determining stresses not requiring an accurate knowledge of the modulus of elasticity. 9th Congress, International Association for Bridge and Structural Engineering, p. 83-103, Paris.
- Fairhurst, C. (1968) Methods of determining in situ rock stresses at great depths. Missouri River Division, U.S. Army Corps of Engineers, Omaha, Technical Report No. 1-68.
- Fitzpatrick, J. (1962) Biaxial device for determining the modulus of elasticity of stress relief cores. U.S. Bureau of Mines, Report of Investigations 6128.
- Frocht, M.M. (1948) *Photoelasticity*, vol. 2. New York: John Wiley and Sons, Inc.
- Hast, N. (1958) The measurement of rock pressure in mines. *Sveriges Geologiska Undersökning, Arsbok*, vol. 52, no. 3.
- Hawkes, I. and Moxon, S. (1965) The measurement of in situ rock stress using the photoelastic biaxial gauge with the core-relief technique. *International Journal of Rock Mechanics and Mining Science*, vol. 2, no. 4, p. 405-419.
- Hobbs, N.B. and Clarke, D.A. (1966) Residual stress measurements by the drillhole prestressed meter and the rigid brass plug. 1st International Congress on Rock Mechanics, Lisbon, Portugal, vol. 2, p. 3-7.
- Hult, J.; Kvapil, R.; and Sundkvist, H. (1966) Function and scope of stress meters in rock mechanics. *International Journal of Rock Mechanics and Mining Science*, vol. 3, no. 1, p. 1-10.
- Merrill, R.H. and Peterson, J.R. (1961) Deformation of a borehole in rock. U.S. Bureau of Mines, Report of Investigations 5881.
- Obert, L. (1967) Determination of the stress in rock - a state of the art report. American Society for Testing and Materials STP 429.
- _____ and Duvall, V. (1967) *Rock mechanics and the design of structures in rock*. New York: John Wiley and Sons, Inc.
- Roberts, A. (1966) Photoelastic instrumentation for strata control and rock mechanics. 1st International Congress on Rock Mechanics, Lisbon, Portugal, vol. 2, p. 441-446.
- _____; Hawkes, I.; Williams, F.T.; and Dhir, R.K. (1964) A laboratory study of the photoelastic stressmeter. *International Journal of Rock Mechanics and Mining Science*, vol. 1, no. 3, p. 441-458.

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13. ABSTRACT The development, calibration and use of a simple and robust, unidirectional borehole rock stressmeter is described. Readout is in terms of the photoelastic isochromatic fringe order in a glass cylinder built into the meter. The meter, which is preloaded in the borehole, is intended for both stress change and absolute rock stress measure- ments.		
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