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EXPLOSION EFFECTS IN HOGGAR GRANITE WITH
EXPERIMENTAL MEASUREMENTS

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COMPARISON OF COMPUTER MODEL PREDICTIONS OF NUCLEAR EXPLOSION EFFECTS IN HOGGAR GRANITE WITH EXPERIMENTAL MEASUREMENTS*

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1. INTRODUCTION

A reliable predictive capability now exists at the Lawrence Livermore Laboratory which allows the calculation of effects produced by shock wave propagation in rock. This capability has been achieved through the use of the numerical code SOC,¹ with input parameters established by appropriate measurements of material properties.^{2,3,4} Calculations of cavity radius, peak shock stress, particle velocity and chimney height (as predicted by the extent of rock fracturing) have been confirmed by data from various experiments involving underground nuclear detonations. Using this technique, predictions were made of the explosion effects for Wagon Wheel,⁵ a proposed gas stimulation experiment in Sublette County, Wyoming. The failure envelope measured for Wagon Wheel sandstone indicated a shear strength similar to strengths measured for granites, and much greater than those measured to date for other sandstones. It was found that a SOC calculation using the Wagon Wheel material properties agreed with many of the field

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measurements carried out in conjunction with nuclear detonations in the Hoggar Granite Massif.* Because of inherent differences between the stress-strain relationships of granite and sandstone these somewhat surprising results indicated the need for further study of the material properties of Hoggar granite, as well as a review of the calculational procedures used.

Samples of Hoggar granite were obtained through the generous cooperation of the Commissariat á l'Energie Atomique, and laboratory studies of the properties of the granite have just recently been completed by Schock, Heard, and Abey.⁶

This paper presents an analysis of those material property measurements as used in SOC, focusing on both the differences and similarities between results obtained by the use of material properties of the Hoggar granite (HG) and the Wagon Wheel sandstone (WW).

II. THE MATERIAL PROPERTIES

A. Compressibility

One of the basic input requirements for SOC is the hydrostatic compressibility curve relating the mean applied pressure to the resulting volumetric strain. Since the reference state for a particular time cycle in SOC is the previous cycle, the volumetric strain is used in the form of

$$\mu = \frac{V_0}{V} - 1$$

* Located in the southern part of the Sahara Desert.

where V_0 is the volume at the beginning of the current calculational cycle. The volume V is measured as a function of pressure, usually for pressures up to 40 kbar. Above 40 kbar, the curve is merged into shock Hugoniot measurements. Figure 1 shows the compressibility curves measured for HG and WW in terms of P versus μ . Discrete points are picked from the curve and tabulated for use in SOC. The calculations perform a linear interpolation between the input data points. HG is much less compressible than is WW, but both curves deviate only slightly from a straight line. One of the primary mechanisms for stress attenuation which is employed in the physics of SOC is represented by the difference between the shock loading path and the slope of the compressibility curve. Thus, on the basis of the compressibility curves, both WW and HG should have similar stress attenuation properties.

Although SOC does not consider any shear stress effect on material compressibility, laboratory measurements show that samples under shear stress may dilate or compact more efficiently because of microfracturing. Uniaxial strain tests on WW show considerable compaction with increased shear stress. Triaxial tests on WW show compaction until the shear stress reaches 90% of the failure stress; at this point, dilatation occurs. Granites in general do not compact in triaxial shear tests but exhibit dilatation at shear stresses between 30-50% of the failure stress.

Figure 2 compares the bulk modulus for HG measured by three different experiments. The results obtained using hydrostatic compressibility and uniaxial strain test data show excellent agreement, while the bulk modulus determined by acoustic velocity is much higher. (This is a normal

effect observed in most other rocks.) Of all the static measurements, the uniaxial strain tests are the most representative of the stress state on shock loading. Since the SOC program does not consider dilatancy which might be induced at high strain rate, no effect on the bulk modulus due to strain rate will be taken into account at present.

B. The Rigidity Modulus and Poisson's ratio

The SOC program requires two coefficients to relate the applied stress to the strain manifested in the rock. The first coefficient is the bulk modulus (k) as determined from the compressibility curve (shown in Fig. 2). The bulk modulus varies with pressure. The second coefficient must be a constant with respect to pressure, and may approximate either the rigidity modulus (G) or Poisson's ratio (ν). The relationship between these coefficients depends on the bulk modulus and is given by

$$G = \frac{3}{2} k \frac{(1 - 2\nu)}{(1 + \nu)} \quad \text{or} \quad \nu = (3k - 2G)/2(3k + G)$$

Figure 3 shows how G varies with pressure as determined by (1) acoustic velocity, (2) assuming various values of ν in the above equation, and (3) as measured in the uniaxial strain test. Surprisingly, there is good agreement between the acoustically derived values and the uniaxial strain values below 0.5 kbar of applied pressure. At pressures above a few hundred bars, the rigidity modulus as determined from the uniaxial strain is approximately constant at 300 kbar.

Figure 4 shows the variation of Poisson's ratio for the previously discussed experiments. The calculated ν using a constant $G = 300$ kbar

is in excellent agreement with the value of Poisson's ratio obtained from the uniaxial measurements. Thus, using $G \approx 300$ kbar involves the assumption that there is no strain rate effect on the elastic modulus.

C. Shear Failure Envelopes

Figure 5 shows the measured failure envelopes for both HG and WW. Also shown as dashed curves are the shear stress limits allowed after the rock has fractured. The most important region of the failure envelopes where HG can be seen to differ from WW is between 1 and 12 kbar of applied pressure, where HG is considerably stronger. For a zone that does not fail on shock loading, the hoop stresses developed by the radial divergence of the zone maintain the shear stress above the loading path as the pressure in the zone drops. This means that HG will allow much higher hoop stresses to develop before failure than will WW. The higher hoop stresses result in higher peak particle velocities with slightly less attenuation with distance than would result from the use of the WW failure envelope. The curves for both fractured materials are developed by noting the stress drop after failure of the virgin rock. These are shown as (x) in Fig. 5 for HG.

III. THE CALCULATIONAL RESULTS

A. Wagon Wheel Material Properties

The results of the WW calculation are presented in Ref. 5; however, a condensed review will be given here. The WW calculations used the

compressibility curve indicated in Fig. 1 and the failure envelopes indicated in Fig. 5. A constant Poisson's ratio of 0.2 was used as the second coefficient. For Wagon Wheel, the use of the constant ν implied a strain rate effect which increased the elastic moduli above those measured by uniaxial strain. This procedure was justified on the basis of calculations of Gasbuggy and Rulison which required a similar Poisson's ratio to match the experimental data.

Figures 6 and 7 show the calculational results for the WW material properties, assuming a 1 kt explosive source. A least squares fit of the HG data points in Fig. 7 agrees well with the dashed WW curve. Table 1 compares the cavity radius and various fracture radii as obtained both from the WW calculation and the actual measurements from the nuclear explosions in Hoggar granite.

Table 1

Radius	Calculation WW meters	Measurements HG meters
Cavity (R_c)	7.2	7.3
Rubble zone (R_b)	10.5-12	10-14
Compressive failure (R_p)	26	26
Tensile failure (R_T)	38-48	35

B. Hoggar Granite Material Properties

In this section, we present a series of calculations to investigate the differences between HG and WW material properties and to determine what

modifications and assumptions are required to obtain agreement with the experimental data. For this initial study, we try to match the cavity radius, fracture radius and peak particle velocity as a function of distance. All these calculations use a source term equivalent to 1 kt, a constant overburden pressure of 100 bars, and the compressibility curve indicated in Fig. 1 for Hoggar granite. Input modifications are confined to variation in the failure envelopes and the second elastic constant.

Calculation No. 1

The first calculation uses the material properties as measured and interpreted in the previous section. It uses the failure envelopes for virgin and fractured Hoggar granite from Fig. 5, and a constant rigidity modulus of 300 kbar (Figs. 3, 4) as a best fit to the uniaxial strain data. The results are collected in Table 2.

Table 2

Radius	Calculation No. 1 meters	Measurements HG meters
R_c	6.3	7.3
R_f	25	26
R_r	74	35

Particle velocity as a function of distance is shown in Fig. 8.

The calculated limit of compressive failure is in good agreement, but the cavity radius is too small and tensile failure occurs much farther out than either the WW calculation or the HG measurements. Particle velocity

attenuates with distance as $R^{-1.3}$, in agreement with Hoggar measurements and WW calculations; however, absolute values are approximately 40% higher.

To decrease the peak particle velocity requires either reduction of the compressibility, or adjustment of either the failure envelope or the loading path to bring them closer together. The first alternative is unrealistic; compressibility measurements are inherently reliable. Adjusting the failure envelope requires the assumption that the rock contains many natural fractures. Adjusting the loading path requires the assumption that the rigidity modulus increases with higher strain rates.

Calculation No. 2

For this calculation we assume that the rock contains enough natural fractures to reduce the strength of the rock. Byerlee⁷ investigated the variation in shear stress vs normal stress for sliding friction between ground surfaces of Westerly granite. The results are shown in Fig. 5, where the open triangles represent the static friction and the solid triangles represent the kinetic friction. It is interesting to note that the points for static friction lie just above the failure envelope for virgin WW and the kinetic points lie just below the fractured WW failure curve.

For the second calculation, all parameters remain the same as in the first calculation except that the failure envelope for virgin WW is lowered to agree with the static friction point between pressures of 1 kbar and 10.5 kbar only. Table 3 presents the results.

Table 3

Radius	Calculation No. 2 meters	Measurements HG meters
R_c	6.5	7.3
R_f	30	26
R_r	71	35

The peak particle velocity as a function of distance is shown in Fig. 8. The magnitude of the velocity is in good agreement with the data; however, the velocity attenuates as $R^{-1.7}$. This is within the scatter of the data, and on this basis the calculation would be acceptable. However, the cavity radius is still too small and now the limit of compressive failure is slightly too large.

A close examination of the points (x) in Fig. 5 (indicating the stress drop after failure), shows that a curve such as that representing the fractured WW envelope of the kinetic sliding friction is well within the scatter of the points (x). Reduction of the fractured shear stress below 5 kbar of pressure would significantly increase the cavity radius.

Calculation No. 3

For the third calculation we again use the virgin HG strength as in the first calculation. Also, we use the fracture failure envelope for WW shown in Fig. 5 as in the second calculation. To lower the particle velocity we assume a strain rate effect by using a constant Poisson's ratio of 0.15, which increases the shear modulus with increasing pressure as shown in Fig. 3. Table 4 shows the result.

Table 4

Radius	Calculation No. 3 meters	Measurements HG meters
R_c	6.9	7.3
R_f	27	26
R_r	75	35

The peak particle velocity as a function of distance is shown in Fig. 8. The calculated points agree identically with the experimental curve. The cavity radius and limit of compressive failure are both well within the range of the experimental error.

IV. CONCLUSION

The calculation that best fits the observed data is calculation No. 3; this calculation assumes that the rigidity modulus is strain rate dependent. There is some experimental support for using this assumption for granite. Green and Perkins⁸ measured large increases in the elastic moduli at high strain rates for unconfined samples of Westerly granite. However, Handin⁹ found that this effect vanished at a few kilobars of confining pressure.

It is reassuring, however, that the SOC calculation using the HG material properties did match the data obtained from nuclear explosives in this material. This also indicates that the "pattern" of WW material properties fortuitously produced calculational results that agreed with the Hoggar experimental data. There is, however, one rather disturbing point.

The permanent displacements calculated by SOC for Hoggar granite in all cases were almost exactly an order of magnitude lower than the reported absolute displacements for distances beyond the fractured region. Further investigation of this discrepancy is continuing.

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FIGURE CAPTIONS

- Fig. 1. Compressibility, Hoggar granite and Wagon Wheel sandstone.
- Fig. 2. Bulk modulus vs pressure, Hoggar granite.
- Fig. 3. Rigidity modulus as a function of pressure, Hoggar granite.
- Fig. 4. Poisson's ratio as a function of pressure, Hoggar granite.
- Fig. 5. Failure envelopes for Wagon Wheel sandstone and Hoggar granite.
- Fig. 6. Calculated Wagon Wheel cavity radius, compressive failure limit, fracture initiation, and shock front as a function of time for 1 kt.
- Fig. 7. Calculated Wagon Wheel particle velocity at shock front vs scaled range, comparison with Hoggar granite data.
- Fig. 8. Peak particle velocity as a function of distance in Hoggar granite, comparison of calculations with experimental results.

Ternune - Fig. 1

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Terhune - Fig. 6

Terhune - Fig. 7

Terhune - Fig. 8