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SOME STUDIES OF DEEPLY BURIED HIGH EXPLOSIVE ROCK FRACTURING

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SOME STUDIES OF DEEPLY BURIED HIGH EXPLOSIVE ROCK FRACTURING

INTRODUCTION

Rock blasting is the subject of a number of articles and books (e. g. Ref. 1). However, practically all the applications discussed relate to the use of a free surface to take advantage of the fact that rocks are weak in tension. Placement of charges, and the timing of detonations when a charge array is used, has become more scientific as the principles become better understood. The high explosive charges are emplaced in holes drilled behind and parallel to the free surface. When the outgoing compressional wave generated by the explosion is reflected from the free surface it gives rise to tensile stresses which spall the rock near the free surface.

However, the explosive fracturing of rock in deep underground formations in the absence of a free surface and how it may be related to enhancement in permeability is not well understood. Enhancement in permeability can be produced by inducing connected porosity not previously in the rock, or by connecting previously existing unconnected porosity through fracturing. Several processes now undergoing feasibility study contemplate the use of high explosives in deep formations to cause fracture and enhancement of permeability. Various in situ processes such as coal gasification, oil shale retorting, and copper ore leaching all require gaseous or liquid fluids to circulate through large volumes of materials in which permeability has been enhanced.

A study was undertaken to help understand and evaluate the use of high explosives for fracturing rock. The study was done on a high speed digital computer with a one-dimensional code called SOC.² The code is designed to calculate the propagation of a stress wave generated by an underground explosion as well as the accompanying displacement and fracture of the surrounding rock. The calculations were driven by a pressure-specific volume relationship which describes the expansion of the gases generated by the detonation of high explosive. The code uses the isentrope (reversible adiabat) which passes through the Chapman-Jouget (C-J) point (i. e., the pressure and specific volume at the detonation front). In a SOC code calculation done in plane, cylindrical, or spherical geometry, the detonation wave starts on the inside and propagates outward at an input detonation velocity which is a characteristic of the explosive. The pressure at the detonation front is the C-J pressure and can range from about 100 kilobars up to about 400 kilobars for some high specific energy explosives. Behind this front, the HE expands along an adiabat. At the interface between the HE and rock, the rock sees initially a peak pressure more or less than the C-J pressure depending on the impedance match between the HE and the rock. A shock wave is generated and propagates through

the rock, and attenuates until it becomes an elastic wave at some distance from the center of detonation. In the meantime that portion of the rock which sees sufficiently high shear stresses undergoes fracture.

In addition to the HE expansion adiabat, the other input to the SOC code calculation includes a description of the behavior of the rock under consideration. This includes a pressure-specific volume (P-V) relationship derived from rock sample measurements obtained both hydrostatically and under shock compression. Also, a shear strength-mean stress (τ -P) failure envelope was obtained from triaxial shear strength measurements on small samples of the rock.

A lithostatic or overburden stress (ρgh) can be imposed on the medium, where ρ is average overburden density of the rock, g is the acceleration of gravity, and h is the depth below the surface. The factor ρgh can be imposed as a constant value which would represent an imposed stress acting in a horizontal direction at a constant h , or increasing or decreasing away from the center, to represent the change in overburden stress in the vertical direction.

When a portion of the rock medium under consideration undergoes shear failure, the code calculates a total distortional strain which is made up of an elastic shear strain and a failure shear strain, ϵ_f . This is calculated as a function of time and position in the medium. Loosely interpreted, for uniform motion along a hypothetical crack, $\epsilon_f \approx \Delta\ell/\ell$, where ℓ is a length of the crack and $\Delta\ell$ is along the crack. One might expect then, that the observed extent of fracture around an explosion would correlate with ϵ_f . With nuclear explosions, failure radii have been inferred from chimney heights. Unfortunately, at present there is very little hard data available with which to make this correlation. Although experiments of the sort needed are planned, only that obtained for the 5-kiloton Hardhat nuclear event in granite is available. Hardhat was extensively studied in postshot re-entry and exploration near the shot point. Results of a correlation with the Hardhat event with observed failure indicates that the limit of "intense fracture" corresponds to an $\epsilon_f \approx 10\%$, and the limit of "detectable fracture" to an $\epsilon_f \approx 1\%$.³

Although there is no physical model that relates ϵ_f to enhancement in permeability, one might expect that in the "intense fracture" region there would be a significant enhancement in permeability, falling off in some way to where no enhancement takes place beyond a radius where $\epsilon_f \approx 1\%$.

CALCULATIONS AND RESULTS

The primary reason for running the calculations whose results are shown here was to attempt to evaluate certain explosives in terms of which of these would be the most efficient in fracturing rock, and to obtain some understanding of what properties of the explosives are important in these terms. The explosives considered and some of their properties are shown in Table 1.

Table 1. Some properties of explosives considered in study.

Explosive	Density (g/cm ³)	Detonation velocity (m/sec)	C-J pressure (kbar)	C-J density (g/cm ³)	Manufacturer
Tovex 500	1.2	5800	88	1.534	DuPont
Tovex 550	1.3	6267	106	1.640	DuPont
Tovex 600	1.23	5808	91	1.572	DuPont
H. I. 100% Gelatin	1.3	7861	159	1.625	Hercules
HP-196	1.37	5683	85	1.703	Hercules
PTC 4	1.3	7586	164	1.700	Hercules

The isentropes for the expansion of the detonation products are shown in Fig. 1. These were furnished by the manufacturers and appear to be from perfect gas calculations rather than direct measurement. Three of these explosives with different properties were chosen for SOC code calculations: Tovex 550, H. I. 100% Gelatin, and HP-196. The others were considered similar enough to those chosen to produce nearly identical results. The same data shown in Fig. 1 is replotted as P vs V/V₀ for these three explosives in Fig. 2.

An explosion site being considered is at 1800 ft depth in andesite, a dense, low porosity rock which is water saturated at this depth. The measured bulk (ρ_o) and grain densities (ρ_G) are 2.712 and 2.782 g/cm³, respectively. At full saturation, the total porosity (ϕ) is 0.0393 and the weight fraction water (Z) is 0.0144. These values were used to generate a P-V curve and a τ -P failure envelope by a technique devised by Butkovich.⁴ Figure 3 shows the P-V and Fig. 4 the τ -P curves for the andesite developed by this technique and used in the calculations reported here. The failure envelope used is typical for a saturated granite or a low water content, essentially dry lithic tuff, both with water contents Z = 0.01. The data from Terra-Tek also shown in Fig. 3 was not available when the calculations were run. A calculation (Tovex 550) was repeated with the Terra-Tek τ -P data at a later date and these results are also shown.

A series of cylindrical SOC calculations were run with an 8-in. diam (10.16 cm radius) of HE in rock with an imposed constant ρgh of 137 bars to represent the horizontal lithostatic stress at 1800 ft depth. Figures 5a, 5b, and 5c show radial stress pulse shapes at the cavity well (4 in., 1 ft, and 4 ft, respectively, from the center of detonation). The plots were obtained from discrete time edits of the calculation and peak values may have been missed. These curves show the attenuation and the widening of the stress pulse as it propagates away from the detonation center. Figure 6 shows the cavity growth curves as a function of time using the three explosives. The cavities are essentially fully grown in 3 msec, with that produced by the H. I. 100% Gelatin considerably larger than that of the Tovex 550 or HP-196. In each case the final cavity pressure was about 900 bars. That is, the final cavity pressure at full cavity growth has been shown to be related to the

Fig. 1. Expansion isentropes of the detonation products of various high explosives being considered, plotted as pressure vs specific volume.

Fig. 2. Expansion isentropes of the detonation products of various high explosives used in the calculations, plotted as pressure vs volume expansion ratio.

Fig. 3. Pressure-volume relationship for andesite used in the calculations.

Fig. 4. Maximum shear strength-mean stress failure envelopes for andesite used in the calculations. Also plotted is Terra-Tek measured failure envelope not available at the time the calculation was made.

Fig. 5a. Radial stress pulse at cavity wall interface from detonated 8-in. diam cylinder of high explosive with 137 bars overburden stress.

Fig. 5b. Radial stress pulse at 32 cm (1 ft) from center of detonation with 137 bars overburden stress.

Fig. 5c. Radial stress pulse at 123 cm (4 ft) from center of detonation with 137 bars overburden stress.

Fig. 6. Cylindrical cavity radius vs time, 8-in. diam hole with 137 bars overburden stress.

overburden pressure and strength of rock.⁵ These results show that the final cavity pressure is apparently independent of the energy source. Referring to Fig. 2, V/V_0 , the volume expansion of the HE at 900 bars is, for Tovex 550, HP-196, and 100% Gelatin, about a factor of 6, 6, and 10, respectively. Since, for a cylinder, the volume increases as the square of the radius, the radius expansions are $R = \sqrt{6} R_0 = 2.45 R_0 = 24.9 \text{ cm}$, and $R = \sqrt{10} R_0 = 3.16 R_0 = 32.1 \text{ cm}$ as shown in Fig. 6.

Figure 7 shows the radius at which $\epsilon_f = 0.1$ vs time for the three calculations. Based on the Hardhat event experience, this may be interpreted as the radius of "intense fracture" where the enhancement in permeability would be significant. In each case the maximum radius for $\epsilon_f = 0.1$ is about $2.8 R_c$. Figure 8 shows the radius at which $\epsilon_f = 0.01$ vs time for the three calculations. Using the same criteria, this could be interpreted as the maximum radius of detectable fracture beyond which the material is not fractured. The maximum radius for $\epsilon_f = 0.01$ here is about $8.5 R_c$.

One of the surprises which came from this group of calculations was the unexpected high final cavity pressures at which the cavity stopped growing. Experience with nuclear explosion phenomenology indicates that the final cavity pressure is a function of the overburden stress and the strength of the rock surrounding the cavity. It was suspected that the high cavity pressures may be a geometry effect. Consequently a number of calculations using larger cylindrical radii with the same HE, rock, and overburden stress were run. The results (shown in Fig. 9) relate final cavity pressure to hole diameter from 2 to 36 in. These results show a fairly strong relationship between final cavity pressure and charge hole size, which in turn influence the radii to which ϵ_f is a particular value as shown in Fig. 10.

DISCUSSION OF RESULTS

As was stated earlier, the primary reason for doing these calculations was to attempt to evaluate specific explosives to determine which is the most efficient in fracturing rock and enhancing permeability. The other purpose was to help understand which of the properties of the explosive contribute most to these effects. Previous experience, primarily with calculations of the effects of underground nuclear explosives, has given us a quite good understanding of which rock properties are important in terms of shock wave attenuation, cavity growth, and shear failure. Such things as water content, porosity, and degree of saturation of the rock surrounding the explosion are all important to predict the effects of the explosion on its surroundings. The depth of burst (or overburden stress) and energy yield of the explosive are equally important. The literature on measurements and calculations and correlation between the two is too voluminous to cite in this report. However, Ref. 6 contains much pertinent information.

Fig. 7. Cylindrical radius at which $\epsilon_f = 0.1$ vs time, for an 8-in. diam of HE with 137 bars overburden stress.

Fig. 8. Cylindrical radius at which $\epsilon_f = 0.01$ vs time, for an 8-in. diam of HE with 137 bars overburden stress.

Fig. 9. Hole diameter vs final cavity pressure obtained from horizontal cylindrical SOC calculations with 137 bars overburden stress using Tovex 550 high explosive in a "weak" andesite.

Fig. 10. Hole diameter vs radius for $\epsilon_f = 0.1$ and 0.01 obtained from horizontal cylindrical SOC calculations with 137 bars overburden stress using Tovex 550 high explosive in a "weak" andesite.

In this report, we are considering a real rock. However, at the time the calculations were done, measurements of the rock properties had not been made. Therefore, we made approximations based on rocks of similar bulk density, grain density, and water content. In terms of evaluating explosives, approximations are acceptable, since the comparisons are made of the relative results of the calculations.

With regard to the comparisons, the results show that the cavity continues to grow until the final cavity pressure is about 900 bars in the rock whose properties are that of the approximations, and at a depth where the overburden stress is 137 bars. The most important factor in terms of the expansion adiabat of the HE is the volume expansion factor V/V_0 at the final cavity pressure. The reason 100% Gelatin gives a larger cavity with this rock at a depth where the overburden stress is 137 bars is because V/V_0 is greater for the 100% Gelatin at 900 bars than it is for the Tovex 550 or HP-196 at 900 bars. Obviously if the overburden stress were less, then the final cavity pressure would be less and V/V_0 would be greater in a rock with the properties used.

The calculation of the radius at which ϵ_f is 0.1, 0.01, or any other value is very closely related to the final cavity radius in a given type of rock. In the cases shown, the radius for which $\epsilon_f = 0.1$ is $\sim 2.8 R_c$, where R_c is the final cavity radius. The radius for which $\epsilon_f = 0.01$ is $\sim 8.5 R_c$, and these values should be essentially independent of the overburden stress. In other words, lower overburden stress would yield larger cavities; however, the radius at which ϵ_f is a given value is a constant times the final cavity size. These factors may be different in different rock types, but calculations with vastly different rock types indicate that the ratio where $\epsilon_f = 0.1$ does not vary over a large range.

Addressing the unexpectedly high final cavity pressure (i. e., the pressure in the cavity when growth stops at a few milliseconds after detonation), our experience with calculations of nuclear explosion phenomenology has been that final cavity pressures are equal to 1.4-2.25 times the overburden pressure.⁵ It has been shown that the final cavity pressure is equal to the overburden pressure plus an incremental amount which depends on the strength of the rock.⁷ We experience relatively smaller cavities in strong rock than with weak rock. In the rock considered here we have a relatively strong rock as compared to those with which we have nuclear explosion experience, so that we might expect final cavity pressures to be more like two times the overburden pressure. In the cases calculated here, the amounts of energy released and the size of final cavity are orders of magnitude below those obtained with nuclear explosives. One might suspect a geometry effect. The surface-area-to-volume ratio of cylindrical charges go as $2/R$. For small charge holes the ratio is large as compared with large charge holes, which can have an influence. Results relating the final cavity pressure P to hole diameter D show a fairly strong relationship which can be fit to a power law of the form

$$P = C_1 D^{-C_2}$$

where C_1 and perhaps C_2 are materially dependent parameters. Further study of this relationship is required. Figure 10 shows that a near linear fit exists between the radius at which $\epsilon_f = 0.1$ and $\epsilon_f = 0.01$, and initial hole diameter.

An additional calculation was run after the Terra-Tek⁸ shear failure envelope became available (as shown in Fig. 4). The measurements show the rock to have a shear strength about three times that assumed in the earlier "weak andesite" calculations. Consequently, cavity size and failure radii are significantly reduced, as shown in the comparisons on various figures.

SUMMARY

Results of the calculations and previous experience show that the final cavity pressure at which cavity growth ceases is controlled by the strength of the rock, the overburden stress, and to a lesser extent by the size of the shot hole. The final cavity size influences the failure radius, whether it be considered to be intensely fractured or somewhat less fractured but still where there is significant enhancement in permeability. Then, for a given rock at a given depth, the only thing left that will have an effect on cavity size are the characteristics of the explosive used.

The explosives used in the calculation had somewhat different detonation velocities and C-J pressures. There is no significant difference in the failure radii due to differences in these two quantities. The main characteristic of the explosive in terms of HE fracturing is the value of V/V_0 at the final cavity pressure. For example, the 100% Gelatin shows a volume expansion of about 10 at the final cavity pressure while the others show a value of about 6. If we want still larger volume expansions than those of the 100% Gelatin, then we need an explosive that lies to right of its expansion adiabat in Fig. 2. These results also suggest that an explosive with smaller average values of $\frac{d \ln P}{d \ln V}$ would produce larger expansions.

The calculations also show that in a given rock, the failure radius (as characterized by certain values of ϵ_f), is approximately linearly related to the final cavity size. Comparison with other calculations in different rocks, with considerably different properties, shows the radius at which $\epsilon_f = 0.1$ is in the range 2.5-3 R_c .

With regard to using the parameter ϵ_f (as calculated by the SOC code) for determining a fracture radius, it must be stressed that at this time the only data available from which comparisons can be made between measurements and calculation are those for the Hardhat nuclear event. Experiments are planned for the near future to obtain correlations between calculations and measurements in a number of different rocks. High explosive fracturing experiments are planned for both laboratory and field scale. At the same time, hopefully, permeability enhancement may be able to be correlated with the same parameter.

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