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# Letters

## Comments on Paper by R. F. Favreau, 'Generation of Strain Waves in Rock by an Explosion in a Spherical Cavity'

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Although *Favreau*'s [1969] attempt to define more explicitly the phenomena of explosively generated elastic strain waves in rock utilizes equations and boundary conditions to define the behavior of a high-pressure gaseous-rock system, it has two primary faults that obviate the usefulness of calculated values for behavioral parameters in actual wave propagation. First, Favreau's model prescribes that the forcing function at the rock-explosive interface be applied to the surface of a cavity in an elastic material that must remain elastic and unfractured for all magnitudes of pressure applied. That is, neither the elastic limit of the material nor its strength may be exceeded if the elastic wave equation is to be applicable. Second, the residual strains obtained by Favreau are due to a continuous pressure in the cavity, whereas the residual strains obtained by *Atchison and Tournay* [1957] and others in field experiments were often caused by permanent deformation of the rock after explosive gases had escaped from the cavity.

Before considering the details of the above, it might be noted that the use of displacement potential simplifies the solution of the differential equations involved, particularly if transform calculus is employed. Expressions for displacement, stress, strain, etc. can be easily derived from the displacement potential. The mathematics of the model proposed by Favreau is more easily handled by transform calculus if a forcing function is chosen as

$$p(t) = P_0[1(t) - (3\gamma/a)u]$$

where $a$ is the radius of cavity, $\gamma$ is the heat capacity ratio, $u$ is the displacement, $1(t)$ is a unit step function, and appropriate boundary conditions are defined.

Favreau's method requires a knowledge of the solution of the wave equation. Methods of transform calculus do not require a foreknowledge of the solution, and they constitute an elementary problem in evaluating a transform function by use of poles in the complex plane.

Experience has shown that in Favreau's model neither the forcing function nor the boundary conditions represent the conditions that exist when a confined explosive is detonated in rock in field experiments. Both model conditions assume that the rock immediately around the explosive behaves elastically. Favreau's assumed 80,000-$\mu$ strain in tension and 150,000-$\mu$ strain in compression sustained by the rock are at least two orders of magnitude greater than the elastic range to which the wave equation can be applied for most rocks. Hence, the elastic wave equation cannot be applied to the material (which does not behave in an elastic manner) immediately around the cavity. It was this fact that lead *Sharpe* [1942] to define a 'radius of equivalent cavity' at some distance into the rock away from the explosive, at which elastic behavior might be assumed. This distance, which would vary for each rock-explosive combination, has not been measured or approximated.

In the field experiments of *Atchison and Tournay* [1959] the detonation gases escaped from the cavity a very short time after the explosion took place. In Favreau's model they remain completely confined; this would cause a 'permanent' strain that would be released only if the gas pressure were to go to zero.

The high-speed photographic studies of *Duvall and Atchison* [1957] showed that the stemming and gases begin to escape from a borehole (charge depth 0.93 meter) well within 1 msec. The strain records also show that for granite and marlstone the residual strain persists only for about 3 msec at about 1.6 meters from the charge. Sandstone exhibits a permanent strain that remains after the gases have been released. Thus Favreau's residual strain has no counterpart in the permanent strain reported by Atchison and Tournay, which was due to nonrecoverable movement of the rock near the strain gages or to a nonelastic recovery after the passage of the pulse.

It is apparent, therefore, that the elastic equation, the boundary conditions, and the forcing function cannot be applied to actual rock as Favreau has applied them. This is demonstrated by the radial strain curves presented by Favreau. Also, the ratio of the crushed volume of rock to the charge volume [*Atchison and Tournay*, 1959] varies from about 8 to 18 for the explosives used as examples. Thus the radius of the crushed zone varies from almost 3 to more than 4 times the charge radius. The fracture zone and nonelastic zone extend some distance beyond the crushed zone. This would drastically affect the value of the cavity radius employed in calculations as well as the character of the pressure function at the (unknown) elastic boundary.

For a given model to be applicable, the curves for stress, strain, velocity, displacement, and acceleration in both the radial and the circumferential directions should be similar to curves obtained from field measurements. That is, the shape (frequency distribution) of the curves change in shape with time and distance, and the attenuation and dispersion for each curve should be similar, as should the travel times. Thus there is a minimum of about fifteen parameters that should be reasonably satisfied. Favreau's model approximates only two of these: the arrival time and the attenuation of peak radial strain. However, arrival times in rock are only approximately elastic, and the agreement in peak strain attenuation is obviously fortuitous.

The proposed model curves for radial strain show little similarity to curves for observed waves. Observed waves become less sharp and lengthen with travel distance. The proposed rock-explosive model behaves in the opposite manner. An examination of Favreau's equation 30 shows that the time-independent term does not decrease as rapidly as the other terms, which results in a wave with a vertical front at large distances. Velocity, acceleration, stress, and displacement all demonstrate a persistent finite jump at the wave front. It is a well established fact that high frequencies are attenuated with the greatest rapidity in natural rock, and finite jumps are usually observed only in shock waves.

A complete rock-explosive model would necessarily require the inclusion of an equation of state for the rock crushed or strained beyond the elastic limit, whose volume has been found to be at least from 8 to 18 times that of the explosive charge.

Thus, the proposed rock-explosive model has the following deficiencies:

1. It assumes total elastic behavior of the rock around the cavity. The observed nonelastic behavior of the rock obviates the application of the elastic wave equation and the assumed pressure function.
2. The model pressure function assumes that the detonation gases remain confined. This produces a fictitious residual strain which has no counterpart in actual field tests, where gases quickly escape. Thus, Favreau's Figures 6*a* and 6*e* are not applicable unless explosive gases remain completely confined.
3. The model, in ignoring the effect of the nonelastic behavior of the rock immediately around the cavity, also ignores the attenuation, dispersion, and energy losses caused by flow, fracture, and other processes. Field experimentation utilizing from less than a pound of explosives to several kilotons of explosives indicates that nonelastic behavior is a dominant factor in determining the pulse shape at the radius of equivalent cavity.
4. For most commercial explosives the factor $\gamma$ is almost constant and, hence, is an insensitive parameter.
5. Rock will not elastically sustain the strains prescribed by this model in order that it be applicable.

The above criticisms are confirmed by the fact that calculated wave forms approximate

only two of a large number of parameters that should be simulated if the model is indeed to be representative.

## References

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