PREDICTING EXPLOSION-GENERATED PERMEABILITY AROUND GEOTHERMAL WELLS

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The problem of stimulating geothermal reservoirs has received attention in recent years. Detonating explosives in a borehole is one technique for stimulating them. Explosives may also have an application where precipitation of solids near the producing well has significantly reduced the permeability around it. However, the enhancement of the permeability around the borehole has itself not been well-defined, and hence, the effects of explosive stimulation are difficult to predict. Below, we outline a theory which has correlated well with existing measurements of permeability enhancement. A more complete development can be found in Ref. 1.

Theory

The theory is based on linking the Carmen-Kozeny expression,

$$K \propto \frac{\phi^3}{(1-\phi)^2 S^2} , \tag{1}$$

with the parameters involved in the dynamic explosion process. In Eq. (1), ϕ is the porosity and S is the specific surface area.

To relate this formula to the complex phenomena of an explosive detonation, it is useful to view the explosion process in two stages.[2] The first stage is dominated by a large-amplitude stress wave. The second stage involves an expansion of the cavity by high-pressure gases from the detonation. The effects of the first stage on the media are of a dynamic nature, while those of the second stage extend over a much longer time interval and can be regarded as quasistatic processes. To obtain a description of permeability, we must relate these processes to Eq. (1).

According to Kutter and Fairhurst,[2] the principal role of the stress wave is to initiate fractures. The fracture density n is related to the porosity and specific surface by

$$n = \frac{S}{2w} (1 - \phi) , \tag{2}$$

where w is the crack width. Griffith[3] postulated a failure criterion for real materials. From tensile tests, he learned that the average stress at rupture was small compared with the theoretical strength of the solid.

He concluded that energy in the test piece was not uniformly distributed. At points where the cracks originate, high concentrations of strain energy must exist. We assume that these concentration points are macroscopic flaws in the material. A real geologic medium will contain a distribution of flaws having variations in length and orientation. Flaws may be naturally occurring fractures having a distribution in length and orientation, grain boundary weaknesses, and solution channels.

If similar specimens of a given material are subjected to failure tests, they do not all fail at the same stress, A distribution of breakage strengths will be found.[4] It can therefore be interpreted that the material contains a distribution of flaw strengths. Variation in stress levels from an applied load at flaw tips is proportional to the square root of their lengths.[5] Longer flaws will therefore have a higher probability of extending under a given applied stress.

The dynamic stress wave will cause all flaws whose strengths are less than the magnitude of the locally applied stress to extend. A relation between the growth of flaws or the increase in specific surface and energy can be obtained from comminution theory. Several comminution relations have been proposed. The one most applicable to our situation is Rittinger's Law, which states that an increase in specific surface area is directly proportional to the energy input:

$$S \propto E . \tag{3}$$

Rittinger's law has been substantiated by the general scaling laws of Langefors and Kihlstrom,[6] which have been verified for burden dimensions varying between 0.01 and 10 m with a 10^7 variation in explosive charge.

Creating fractures does not in itself generate permeability. This is because the stress wave propagates at the compressional-wave velocity c_p , while fractures can grow in a rectilinear path at a maximum velocity $1/3\ c_p$, Hence, the stress wave will inevitably outrun the fractures it generates. New fractures will then be initiated on other flaw sites in the material. At this moment in the process, the medium consists of a noninterconnected system of fractures with essentially no new porosity.

The second stage of the essentially continuous explosion process is dominated by the quasistatic expansion of the gas in the cavity. The cavity void space is produced by irreversible pressure-volume work of the explosive gases. Void space is created both by free-surface displacement and by compression of the surrounding rock. This model assumes that the fracture porosity surrounding the cavity is created by irreversible radial compression and the tangential tension of the surrounding rock. The fracture porosity will be proportional to the first invariant of the strain tensor,[6]

$$\phi \propto \Delta , \tag{4}$$

where A is the first invariant and contributes to porosity only when it assumes positive values (dilatation).

If we use the dynamic wave solutions of Selberg,[7] the energy decay laws at the wave front are given by:

$$E \propto 1/r^2 \text{ (dynamic, spherical geometry)} \tag{5}$$

and

$$E \propto 1/r \text{ (dynamic, cylindrical geometry)} . \tag{6}$$

If the static solution for a pressurized cavity is used, dilatation will be identically zero in both cylindrical and spherical geometries. However rock will exhibit bilinear behavior; and hence, the elastic moduli will have different values in tension and compression.[8,9] Following the analysis of Haimson and Tharp,[8]

$$\Delta \propto \frac{(f-a)}{r^{1+a}} , \tag{7}$$

where f = 2 for spherical geometry and f = 1 for cylindrical geometry.

For well stimulation, the following appears to be a good approximation.[1]

$$a = f - \varepsilon , \tag{8}$$

where ε is a small positive number. Substituting (3), (5), (6), (7), and (8) into (1), and assuming the explosively generated porosity to be small, the functional behavior of the permeability in the linear elastic case will be approximately

$$k \sim 1/r^4 \text{ (cylindrical symmetry)} \tag{9}$$

and

$$k \sim 1/r^5 \text{ (spherical symmetry)} . \tag{10}$$

Comparison with Experiment

There are only two known explosive stimulation experiments reporting extensive permeability measurements as a function of distance from the borehole. They are the 5 kt Hardhat nuclear event[10] fired in granite, and the 59 kg chemical explosive detonated in coal near Kemmerer, Wyoming."

Fig. 1 shows the comparison between the theoretical expression [Eq. (10)] and the measured permeability around Hardhat. Fig. 2 shows the comparison between the permeability measured as a function of distance from the cylindrical cavity and Eq. (9) for coal.

Discussion

Despite a large variation in explosive yield and rock type between the Hardhat nuclear event and the Kemmerer coal experiment, the predictions of the theory in both spherical and cylindrical symmetries are in excellent agreement with the experiments. No measurements are available for geothermal reservoirs. However, because of the agreement obtained to date, we believe that reasonable predictions can be made for specific geothermal reservoirs. For very deep applications, overburden stresses must be included to obtain the correct decay laws. Practical implementation will require careful evaluation of existing explosives for suitability and safety in the hot environment of geothermal reservoirs.

References

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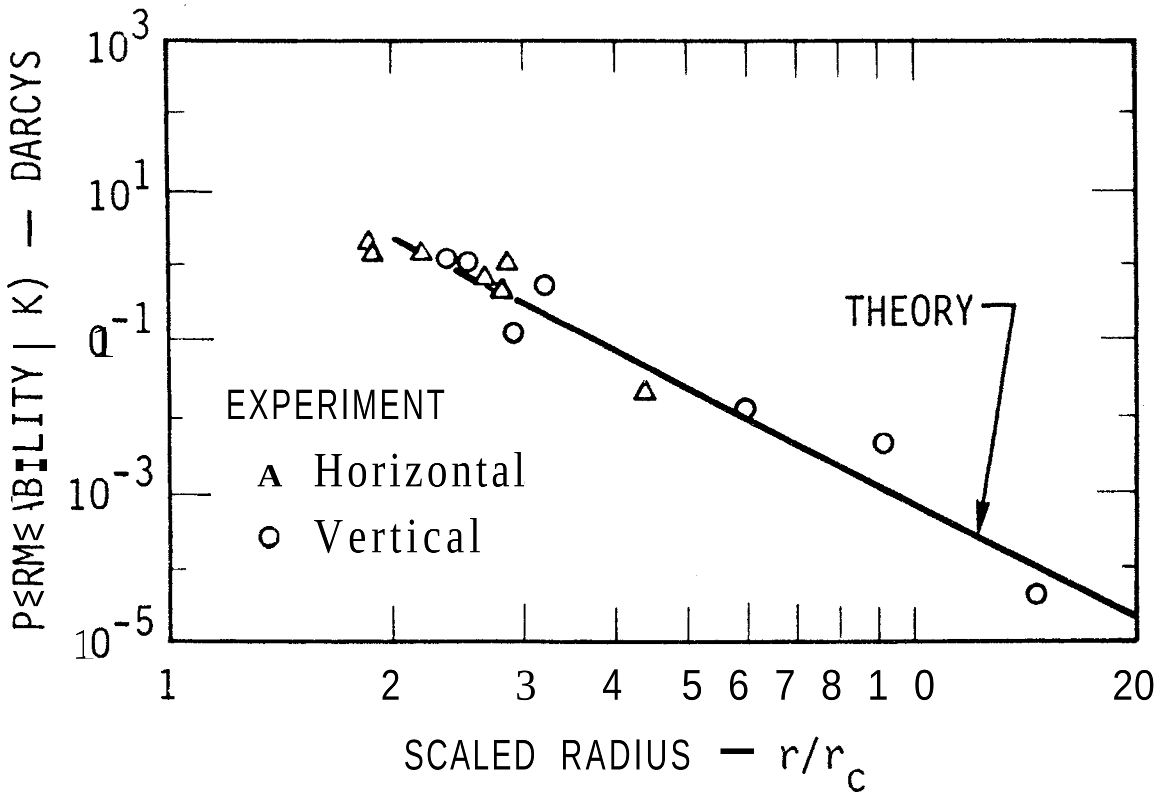

Fig. 1. **Comparison of theoretical and measured permeability values. The log of permeability k is given as a function of distance scaled in terms of the cavity radius r_c. Permeability was measured in both horizontal and vertical holes, and is independent of direction.**

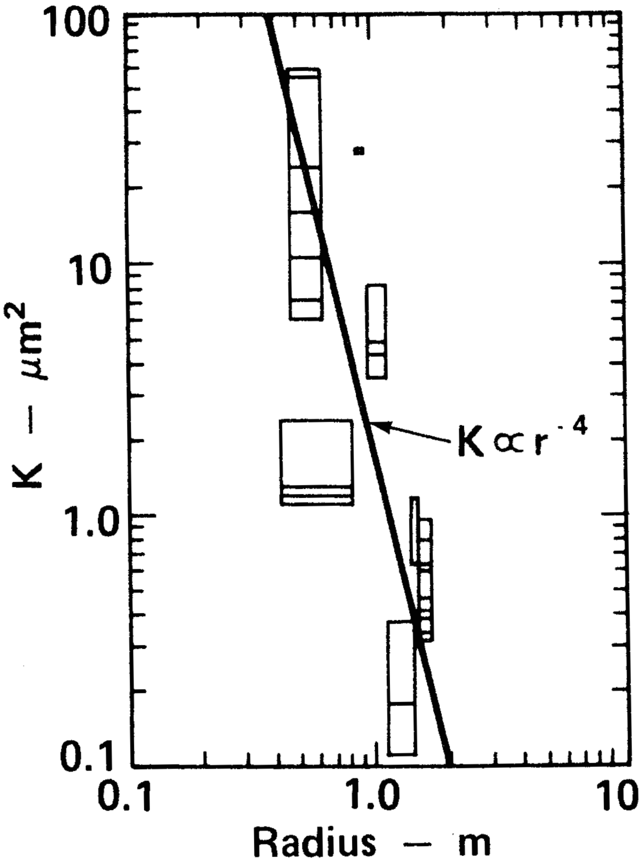

Fig. 2. Coal postshot permeability versus radius for a chemical explosive detonated in a coal seam. The emplacement geometry possessed cylindrical symmetry. Permeability is in Darcies, while the radial distance in meters is measured from the axis of the cavity. The small box on the upper right represents two measurements.