

INFLUENCE OF FLUID INJECTION ON STRESS IN THE EARTH'S CRUST

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SYNOPSIS

A coupled stress flow method is described for analyzing the steady state effect of injecting fluid into rock systems where the flow is governed by the behavior of deformable fractures. The method employs two finite element techniques, one for fluid flow and the other for stress analysis, and a converging iteration process. Examples of fracture systems with simple geometries are analyzed to demonstrate some subsurface conditions underwhich injected fluids are able either to attenuate or to concentrate stresses in the earth's crust as distance from the point of injection increases.

INTRODUCTION

Recent evidence of a possible connection between the triggering of earthquakes and the increase of fluid pressures in fracture systems in the earth's crust indicates a phenomenon that needs much investigation. Low to medium earthquakes have been reported in connection with the filling of reservoirs [Richardson and Glover, 1947; Housner, 1969]. Events at the Rocky Mountain Arsenal well near Denver, Colorado, suggest that injection into a fractured system has been able to trigger earthquakes [Evans, 1966; Healy, et al., 1968; Lane, 1969]. More recently considerable evidence of such effects has also been gathered at the Rangely, Colorado oil field [Dietrich et al. 1972]. Thus, the concept is now developing that if earthquakes can be made by man injecting fluids into the subsurface, then perhaps the appropriate control of fluid pressures in the earth's crust can lead to a method of earthquake control [Handin and Raleigh, 1972].

A fundamental problem in any attempt to inject fluid into the underground will be the influence of such injection on the state of stress in the earth's crust. If the flow is restricted to porous media, the calculation of the induced pressure distribution due to injection can follow well established procedures. However, there are many situations, especially in the vicinity of faulted systems, where the fluid flow will be largely governed by discontinuities in the rock system. Such discontinuities can deform with changes in hydraulic pressure and this can lead to a significant change in permeability and a highly nonlinear behavior. A numerical technique has recently been developed [Noorishad et al., 1971] to handle such behavior and has led to a stress-flow method of analyzing the coupled effect of tectonic stresses and the forces produced by injected fluids.

COUPLED STRESS-FLOW METHOD

In order to determine the steady-state distribution of pressures when fluids move through a deformable mass of fractured rock, it is necessary to consider the coupled action of flow forces, body forces and boundary loads. The pressure distribution must, of course, be compatible with the

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state of stress within the total system. The discussion that follows is restricted to the two-dimensional steady-state case, but the approach can be extended to three dimensions.

The method employs two finite element techniques and a converging iteration process. One must first describe the geometry of the fractured system. This requires carrying out sufficient field work so that the fracture geometry, i.e. orientation, spacing and distribution of apertures, can be defined in space. One must also know the strength characteristics of both the intact rock and the fractures.

The behavior of the fractured rock mass can be described by two equations

$$\frac{1}{\gamma} [K_f(\delta)]\{P\} - \{Q\} = 0 \quad (1)$$

$$[K]\{\delta\} - \{F(P)\} = 0 \quad (2)$$

The first equation is the numerical formulation for the finite element flow analysis where γ is the specific weight of the fluid, $[K_f(\delta)]$ is the flow conductivity matrix that is dependent on fracture deformations, $\{P\}$ is the pressure vector for the entire fracture network, and $\{Q\}$ is the flux vector at those boundaries where flow has been prescribed. The second equation is the numerical formulation for the finite element structural analysis, in which $[K]$ is the assembled structural stiffness matrix for both continuum and fractures, $\{\delta\}$ is the displacement vector for the fractures, and $\{F(P)\}$ is the force vector that includes the flow forces, body forces and boundary loads.

It is evident that these two equations are coupled implicitly by $\{P\}$ and $\{\delta\}$. Furthermore, it should be realized that $[K_f]$ varies nonlinearly with fracture deformation, i.e. $[K_f]$ is a function of δ^3 . As a result, the two equations cannot be solved simultaneously, and an iterative scheme is required.

A convenient starting point is to set $P=0$, which is equivalent to having no flow forces initially in the system. By solving (2) with this assumption, we obtain the first approximation for $\{\delta\}$ which gives the deformations in the rock mass due to the effects only of the engineering structure. These deformations can then be used to modify the conductivity matrix $[K_f]$ and (1) can be solved to obtain the first approximation for $\{P\}$.

In the second iteration, $\{F(P)\}$ is first modified to include these new values of $\{P\}$, and the above two-step iteration is repeated to obtain the second approximation for $\{P\}$. This sequential process is continued until successive values of P at any node are less than some arbitrary limit. When this limit is reached, the fluid pressure distribution is compatible with the state of stress within the deformable rock body, and the effects of seepage throughout the fractured rock mass can be quantitatively evaluated. The rate of convergence to an acceptable solution for this iterative process has been found to be quite rapid. Details of the method are given by Noorishad et al. [1971].

SOME PRELIMINARY RESULTS

Several numerical models of fractured rock systems have been analyzed using the coupled stress-flow method. Before attempting to analyze complex arrangements of fractures, we have first carried out preliminary studies on relatively simple models. These cases have enabled us to examine the influence of joint orientation, permeability of the system, and material properties of the rock mass.

One of the first questions we have examined is the distribution of stresses that are likely to be generated in the vicinity of the injection well with the simplifying assumption that the role of residual tectonic stresses can be disregarded for the moment. Obviously, the residual stresses may play a dominant role in the overall behavior of fractured rock masses especially if the components in the horizontal plane are not the same magnitude. However, by ignoring these forces in the preliminary work, we have been able to get some idea of the effects that are due only to the injection of fluid into symmetrical arrays of vertical fractures where the strength characteristics of the rock matrix and fractures are not necessarily the same.

One model that has been examined is a mutually perpendicular system of vertical fractures that is intersected by an injection well at the center. In this model, the joints were spaced 10 ft apart and were assumed to have a normal stiffness equal to that of the intact rock blocks, viz. 10^8 psf. The rock matrix was assumed to have a Young's modulus of 10^8 psf and a Poisson ratio of 0.25. The angle of friction in the joints was set at 20° and the joint tangential stiffness was 10^6 psf, or two orders smaller than the normal stiffness.

By fixing only the pressure at the point of injection so as to be 200 psi in excess of the outer boundary value, we obtained an excellent measure of the way in which fluid pressures and rock stresses are attenuated away from this point. As might be expected, the central pair of fractures that is intersected by the injection well plays a dominant role in controlling the fluid flow. The slight shifting of rock blocks along fracture planes resolves the rock stresses into two orthogonal sets that line up with their maximum stresses normal to the outside confining boundary. Since the joint is much weaker in shear than in compression, the rock block simply accommodates itself to the stress level imposed and in so doing, the stress directions remain orthogonal to the fracture planes. It is apparent that the orientation of joints in a fractured rock mass must be carefully determined if one is to obtain a realistic representation of stress distribution.

In another model, the effect of fracture orientation was investigated by arranging the orthogonal network of fractures so as to intersect at 45° with the outer confining boundary. A significant change in the results was obtained when the same conditions were assumed as had been used in the first model. A stress concentration was found at each corner of the model with stresses being about 60% higher than that used at the point of injection. These results demonstrate that the angle of intersection between the joint system and its boundaries is another important factor that must be known if one is to develop a complete understanding of the effects of injecting fluids into fractured rock systems.

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