STRESS AND FLOW IN FRACTURED POROUS MEDIA

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INTRODUCTION

The purpose of the present study is to develop a method for simultaneous solution of stress and flow in a deformable fractured isotropic porous medium saturated with a single phase slightly compressible fluid. The system defined as such can be under the effect of body forces, boundary loads, initial stress, and influenced by some fluid pressure disturbance. The method involves application of the theory of elasticity for plane strain systems, Darcy's law for porous medium, and Biot's constitutive equations for the mixture of fluid and solid skeleton. The resulting initial boundary value problem is then numerically formulated into finite element equations using the calculus of variations.

A'computer program has been developed by modifying existing programs to consider interactions between fracture:; and porous medium when both flow and stress fields are coupled. The program is capable of handling problems in rock masses where fractures extend from one boundary to another, intersect each other, or arc isolated in the porous medium. The fractures may have random orientations and the rock matrix can be permeable or impermeable. The region under investigation may be two dimensional or axially symmetric. Solutions can be obtained for either a steady-state flow field under static equilibrium or a non-steady flow field in conjunction with quasi-static equilibrium conditions.

Results obtained for certain typical examples are generally in close agreement with analytical solutions available for rigid systems. In addition, some new features on the response of deformable rock masses under the influence of a flow field have been studied. The present development can be extended to handle coupled stress and heat flow problems in rock masses. Such modification requires new sets of constitutive equations and the application of realistic thermomechanical material properties.

DISCUSSION AND CONCLUSIONS

The method described here has been developed to provide a means to understand in a broader sense, the behavior of a system consisting of a porous deformable rock mass saturated with a single phase liquid which is under the combined influence of fluid pressure, boundary flux, and boundary loads. Darcy's law for flow through porous rock and the parallel plate model for flow in fractures have been used to define flow in the porous rock mass. The theory of elasticity together with a non-linear fracture model is used to define deformations in the porous skeleton as well as in the fracture network. In order to provide an interrelation between fluid flow and structural deformations in the rock mass, two constitutive relations introduced by Biot (1941) have been used. In addition, an interconnection between flow in fractures and in the adjacent porous rocks was developed by writing mass balance relations.

A finite element numerical procedure was adopted in this analysis because obtaining analytical solutions for stress and flow problems in porous rock masses with complicated geometries and boundary conditions is a difficult, if not impossible, task. Through proper use of calculus of variations, the governing equations and boundary conditions are cast into discrete finite element equations--the solution of which gives fluid pressure and structural displacements at all nodal points specified within. the region under investigation.

The application of finite element procedures in this study has been quite advantageous. It has provided flexibility in discretization of the region and has offered freedom to describe the geometry in two dimensions. The use of two-dimensional isoparametric elements for defining the porous medium and onr-dimensional isoparametric elements which define fracture segments has further contributed to the efficiency of the numerical procedure. Furthermore, the numerical method developed in this study enables one to obtain stresses and flows within each element very efficiently.

The present numerical development has also proved to be capable of handling a wide range of problems from steady-state flow under static equilibrium conditions to transient flow under quasi-static equilibrium conditions. The rock may be porous and permeable or impervious. The rock mass can be deformable or structurally rigid. The pressure or flux source may be located in the porous medium and its boundaries, in a fracture segment or at the intersection of fractures. In addition, isolated or nonintersecting sets of fractures can be incorporated into the region under study.

In the analysis of rigid fractured systems simulated by the present method, it has been shown that the flow into the well is proportional to the total length of the fractures intersecting the well. This has been shown for either one or two fractuxes that intersect the well.

The study of the response of a deformable fractured porous medium subject to fluid withdrawal from a well intersected by the fractures has revealed that the fractures close more rapidly at early time, while at later time the rate of closing reduces due to the subsequent pressure drop in the porous medium. Such behavior is not expected to occur in fractures in impermeable systems where the deformations will continue with further changes in fluid pressure.

The nonlinear behavior of joints in fractured systems during fluid flow with changing stress can be studied more quantitatively using the present method. It should be possible to use this approach to obtain the variation of fracture stiffness due to fluid pressure. Fluid injection cannot be expected to reduce the stiffness of fractures in a porous medium when highly compressive initial stresses exist. Only where a rock system is subject to small initial compressive stresses will the fracture network be more susceptible to a reduction in stiffness. The variation of the normal stiffness of the fractures due to fluid injection can be approximated by logarithmic functions.

Although the present method is able to handle a wide range of flow problems in rock masses, certain limitations concerning the use of the method should be kept in mind. The existing computer program developed in this study can be used for cases in which gravitational acceleration is negligible. This assumption is valid in most reservoir engineering problems where the aquifer thickness is very small compared to the height of the overburden material. However, further improvements can be made in the program to account for the influence of gravity. Also it is assumed that changes in both the flow and stress fields take place at constant temperature.

Applicability of the present method depends on the availability of geological information on rock mass structures. The geometry of the system including the length, orientation, and initial fracture aperture openings should be known. The fact that these data are not easily accessible for rock mass structures at depth further restrlcts'the use of the method. Such restrictions have directed the attention of some investigators towards statistical approaches.

It should be emphasized that understanding the behavior of fractured rock masses under the combined effects of flow and stress is a complicated process. The numerical method developed in this work represents a first step toward handling this problem. Further complications .can be expected if one is concerned with the flow of heat in such systems. However, the present work may be helpful in suggesting a possible approach to non-isothermal problems associated with fractured rocks.

Extension of the present investigation in future work by others is recommended in such areas as:

(A) Development and application of new fracture models that can help one to simulate the behavior of discontinuities in rock masses more efficiently.

(B) Further generalization of the present computer program to include an option for the solution of coupled stress and heat conduction problems in rock masses. Such modification will require new sets of constitutive equations and the application of realistic thermo-mechanical material properties.

(C) If the present method is to be used as a practical tool rather than remaining as a purely idealized simulation technique, it should be applied to field problems where realistic physical data can be obtained on the behavior of rock masses.

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