Permeability Tensors of Anisotropic Fracture Networks

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Analytical models are presented to provide enhanced capabilities for modeling fluid flow through natural fractures nested in parallel plate type configurations. The modeled fractures may be arbitrarily positioned, but subgrouped according to the consistent parallel sequences. The derived analytical expressions for fracture permeability can be considered as an extension to those in which flow within fractures is uniform and isotropic. This modification offers a correction for the traditional permeability calculations whenever fractures are oblique to the flow orientation. For the fracture flow scenarios, the graphical solutions show the permeability envelope normal to any arbitrary planes within the calculated domain. Consideration of rock anisotropy may significantly improve the accuracy in determining the formation permeability in cases where natural fractures exhibit a dominant control in regional fluid flow.

KEY WORDS: fracture flow, permeability tensor, anisotropy.

INTRODUCTION

Characterizing hydraulic properties for single and network fractures has been a research focus for a few decades. This is mainly the result of groundwater utilization and subsurface remediation, where the nature of the dominant fractures appears to govern flow processes. This is also partially a consequence of complications inherent to fracture investigations, in which our understanding and associated approaches in revealing the fracture characteristics seems to be far from satisfactory.

As the location of the investigation deepens, the mechanical influences on fracture behaviors attract more focal interest. Simple, but physically sensible theoretical models to evaluate characteristic fracture permeability were first pro-

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posed by Snow (1968, 1969), based on the parallel plate flow concept and some statistical observations of fracture patterns. He described their relation to certain influential parameters such as anisotropy, aperture, spacing, and porosity. Under the simplest assumption of a smooth fracture topological surface, the concept of flow in the fractures is analogous to the flow between parallel plates (Bear, 1972), and was proven experimentally by Witherspoon and others (1980). The so-called “cubic law,” as implied in the parallel plate analogue, warrants flow domination within the fractures, compared with the flow in the porous matrix blocks. In view of the related issues, a concise literature summary of the flow and transport in fractures can be found in Wang (1991).

Determination of the anisotropic permeability for homogeneous and fractured media has attracted significant interest from many hydrogeologists and petroleum engineers. The importance of this investigation may be reflected in the understanding of fluid flow channeled by the major fractures (Hsieh and Neuman, 1985; Hsieh and others, 1985); or the determination of the direction in which a well should be drilled to intercept the most permeable flow orientations (Vaziri and Byrne, 1990). Interest was also expressed in the permeability anisotropies of fractured media and their relation to the statistical configurations of the fractures (Oda, 1985; Sagar and Runchal, 1982). In the case of modeling using the continuum theorem, the associated research has been restricted to fractures with simple configurations due to the complications in the analysis. For the more general case of the oblique fractures, solutions are scarce. This paper is aimed at providing models and solutions for arbitrarily oriented fractures. The solutions are not only general but also easy to be implemented. The detailed derivation is also given to assist in comprehension of the physical fracture geometric settings.

PERMEABILITY OF A SINGLE HORIZONTAL FRACTURE

From the Navier-Stokes equations (Lamb, 1932; Muskat, 1937; Schlichting, 1968) for slow laminar single phase flow of an incompressible Newtonian fluid, equations have been derived for the average velocity and discharge per unit width of a parallel plate conduit or a single fracture. The simplest characterization of the flow in an individual rock fracture is by analogy with that between two parallel flat plates (Snow, 1969), i.e.,

\[ v_f = -\frac{b^2}{12\mu} \frac{\partial p}{\partial x} \]  \hspace{1cm} (1)

where \( v_f \) is the mean flow velocity, \( b \) is the separation between the plates or fracture aperture, \( \mu \) is the dynamic viscosity, and \( p \) is the fluid pressure.

If Equation (1) is expressed in a two-dimensional coordinate system \((x_1, x_2)\), mean velocity \( v_f \) can be decomposed as