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Evolution of permeability in sand injectite systems

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ABSTRACT

Sand injectite complexes comprise kilometer-scale clastic intrusion networks that act as effective conduits for the migration, accumulation and then recovery of hydrocarbons and other fluids. An equivalent continuum model is constructed to represent a sand injectite reservoir, coupling stress and fluid flow in fractured rock using the continuum simulator TOUGHREACT coupled with FLAC3D to follow deformation and fluid flow. A permeability model, which uses staged percolation models, is proposed to improve permeability estimation of fracture networks by accommodating four different levels of fracture connectivity. This permeability model is confirmed against field and laboratory data, corresponding to the different connectivities of fracture networks. The new constitutive permeability model is incorporated into the coupled hydro-mechanical simulator framework and applied to sand injectites with the analysis of permeability evolution mechanisms and mechanical sensitivity. The results indicate that when the magnitudes of principal stresses increase in a constant ratio, normal closure is the dominant mechanism in reducing fracture aperture and thereby permeability. Conversely, the evolution of stress difference can accentuate aperture and permeability due to an increase in shear dilation for critically or near-critically oriented fractures. Also, the evolution of aperture and related permeability of fractured rock are more sensitive at lower stress states than at higher stress states due to the hyperbolic relationship between normal stress and normal closure of the fractures.

1. Introduction

1.1. Geological background and significance

Sand injectite systems are increasingly common in outcrop and subsurface studies of shallow crustal processes. They are typified by complex geometries and can accommodate commercial volumes of hydrocarbons.[1,2] Such reservoirs are formed from sand, sourced from an overpressured sandstone parent unit, remobilised as a fluidised slurry and injected by hydraulic fracturing into an otherwise impermeable unit.[3–5] One such reservoir is the Panoche Giant Injection Complex (PGIC) within the San Joaquin Basin, California. Tectonically-induced basin-scale fluid overpressures have propagated fractures upward to form fracture networks.[6,7] These fracture networks typically communicate between reservoirs, sometimes separated by low permeability seals spanning hundreds of meters[8] and potentially destroying seals and traps.[9–11]

In sand injectites, fractures with a lower dip generally have greater initial lengths and apertures than fractures with a higher dip. Besides, after the sand intruded into the fractures across horizontal formations, the sand intrusions with a higher dip are relatively poorly sorted, more tightly packed with low porosity than sand intrusions with a lower dip.[12] In contrast, the sand intrusions with a lower dip are usually moderately sorted and loosely packed, and with moderate porosity. These characteristics make the permeability pervasively lower for the intruded fractures with a higher dip than those with a lower dip. Overall, the average permeability of sand dikes in the PGIC is $\sim$ 220 mD, whereas the sand dikes of higher ($> 40°$) and lower dips ($\leq 20°$) have an average permeability of $\sim$ 81 mD and $\sim$ 529 mD, respectively.[12]

Sand injectites are unique in which small-scale vertical permeability often exceeds horizontal permeability, making thin pay zones very productive.[13] Basin-scale sand injectite complexes can significantly change fluid migration routes and fluid flow behaviors. Hydraulic fractures and sand dikes may dramatically increase field-scale vertical permeability and enable regional-scale inter-reservoir communication.[14] However, such positive effects of improved access to hydrocarbons may be offset by deleterious impacts of early water breakthrough.[15] Therefore, it is important to investigate and improve the estimation of fluid flow behaviors within fractured reservoirs.

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Each set of the intruded dykes / fractures are intersected with each other at particular orientations. Due to the shallow sedimentary lithology formation including unconsolidated and consolidated layers, it is very essential to develop a new permeability model, which includes connectivity of dyke / fracture networks, with consideration of matrix permeability influence. According to the proposed permeability model developed in this work, it would be more accurate to assess the evolution of permeability of sand injectites, and predict the flow path in the dykes / fracture networks.

1.2. Applicable permeability models

Permeability models to represent the equivalent permeability of fractured rock originally assumed ubiquitous fractures of infinite lateral extent[16,17] Such characterizations typically incorporate the cubic law[18] with the presence of truncated fractures representing more reasonable estimations of permeability.[19] Ignoring fluid exchanges between fractures and matrix[20] renders estimated permeability lower than true permeability where matrix permeability is significant.[21] A variety of approaches have refined permeability models for fractured media.[22,23,26,27] For fracture networks of nested scales, fractal characteristics[28] have been applied by representing fractal dimensions of multiple physical parameters,[29] including the implementation of checkerboard approaches.[30]

None of those previously discussed references consider percolation. Nevertheless, percolation theory[31] is able to determine the degree of connectivity of fracture networks. Permeability models based on percolation theory have been useful in analysing transport properties of disordered systems.[20,24,25] The classical concept of percolation theory describes the percolation probability of connected clusters in a random system. The concept of percolation theory for a fractured medium makes extensive use of dimensionless density to quantify the degree of fracture connectivity and increases permeability estimation[32] in both two and three dimensional fractured media with various local permeability for fractures.[24,25,37] Equivalent permeability is critically controlled by fracture network connectivity[33] with dimensionless densities recovered from field data, e.g. outcrops.[34]

The onset of percolation of fracture networks greatly increases the permeability of the fractured rock. This percolation threshold may be estimated theoretically based on the fracture density, length, and shape of fractures.[35–37] With fracture geometry recovered from field data and outcrops, fracture network permeability can be estimated analytically.[32,38,39] Overall, after determining the dimensionless density, density, fracture distribution and percolation threshold of fractured rock, fracture network connectivity can be measured, and permeability of fractured rock may be derived based on different connectivity levels of the fracture networks – this is the approach followed later in this work.

1.3. Coupled modeling approaches

Fractures increase the complexity of fluid flow behavior and stress response within fractured media. To better represent the response of fractured rock, constitutive relationships which couple stress and fluid flow are crucial. For example, laboratory data and some field data have found that aperture and subsequent permeability can be at least partly controlled by in-situ stresses and fluid pressures,[28] and that percolation methods typically do not consider these effects. Thus, aperture model is derived as a constitutive model depending on the in-situ stresses and fluid pressures, which is then combined into percolation methods. There are two primary approaches that are widely implemented for the characterization of fractured rock, *viz.*: discontinuum and equivalent continuum approaches.[40]

Discontinuum approaches assume that the rock mass consists of individual blocks delimited by fractures. These fractures can be defined either as explicit discrete elements by matrix blocks with interfaces between them.[41] The advantage of the discontinuum approach is that this approach is more suitable in evaluating small-scale response in detail and over the short term. However, the computational complexity required for modeling flow in a dual system of fractures and matrix, and the exchange between the two systems, demands more advanced software and hardware configurations, and requires more computational time.[42]

In contrast, the equivalent continuum approach seems more suitable for long term simulation of large-scale fractured rock. The major assumption of this approach is that the macroscopic behavior of fractured rock and their constitutive relationships can be characterised by the laws of continuum mechanics.[40] Fracture properties are implicitly embedded in the equivalent continuum model and included in modulus parameters.

In the work presented here, the continuum simulator TOUGHREACT[43] is used to couple fluid flow with deformation response of the rock mass represented by the code in FLAC3D.[44] Constitutive models used in the simulator represent the coupled mechanical deformation and poroelastic response of the fractured rock, and characterize aperture and permeability evolution.[45]

Based on the constitutive models, the workflow of the equivalent continuum simulation begins with equilibration of temperature and pore fluid pressure in TOUGHREACT. Then the fracture information, such as fracture geometries and modulus, is input into a FORTRAN executable. The composite fracture modulus with the equilibrium pore fluid pressure are input into FLAC3D to perform the stress-strain simulation. Then the revised pore fluid pressure field is redistributed based on the dual porosity poromechanics.[40,43] The stress-induced permeability is investigated through two-way implicit coupling in the code. The effective stress state of fractures is updated dynamically. Based on the effective stress state, the fracture aperture will be calculated accordingly. Due to the modification of fracture aperture, the composite modulus of fractured block is also updated simultaneously. The two-way coupling could reflect the influence of mechanical properties evolution in changing pore pressure distribution and flow path.

1.4. Aims and objectives

Regionally-developed giant sand injectite systems affect subsurface hydrocarbon volume and significantly influence fluid migration paths by coupling hydro-mechanical processes. The big research picture is reservoir characterization of sand injectites, which includes three stages: 1. Estimate the permeability of the fracture / dike networks in sand injectites; 2. Model fracture propagation; 3. Characterise sand intrusion. This paper will focus on the fluid transport properties of fracture networks assuming no fracture propagation and before the onset of sand intrusion, which is the first stage for the research of reservoir characterization of the sand injectites. Hence, the implemented assumptions and theory will be related to the permeability estimation of fractured rocks with the background of sand injectites, before coupling fracture propagation and sand intrusion in the future.

2. Permeability models

A model for fractured sand injectite systems is developed as an equivalent continuum model. This equivalent continuum model couples stress and fluid flow, and links constitutive relationships including fracture aperture, porosity and permeability as key elements. The concept of percolation theory is implemented to estimate the permeability of the fractured reservoir where the fracture network connectivity is classified by the degrees of percolation represented by dimensionless density. The permeability model is confirmed by comparing its permeability magnitude against field and laboratory data. Besides, the proposed permeability model, which is based on percolation theory, enables us to account for the fracture connectivity, network percolation and fluid exchange between fractures and matrix.