A three-dimensional coupled thermo-hydro-mechanical model for deformable fractured geothermal systems

A fully coupled thermal-hydraulic-mechanical (THM) finite element model is presented for fractured geothermal reservoirs. Fractures are modelled as surface discontinuities within a three-dimensional matrix. Non-isothermal flow through the rock matrix and fractures are defined and coupled to a mechanical deformation model. A robust contact model is utilised to resolve the contact tractions between opposing fracture surfaces under THM loadings. A numerical model has been developed using the standard Galerkin method. Quadratic tetrahedral and triangular elements are used for spatial discretisation. The model has been validated against several analytical solutions, and applied to study the effects of the deformable fractures on the injection of cold water in fractured geothermal systems.

Results show that the creation of flow channelling due to the thermal volumetric contraction of the rock matrix is very likely. The fluid exchanges heat with the rock matrix, which results in cooling down of the matrix, and subsequent volumetric deformation. The cooling down of the rock matrix around a fracture reduces the contact stress on the fracture surfaces, and increases the fracture aperture. Stress redistribution reduces the aperture, as the area with lower contact stress on the fracture expands. Stress redistribution reduces the likelihood of fracture propagation under pure opening mode, while the expansion of the area with lower contact stress may increase the likelihood of shear fracturing.
Thermoporoelastic effects during heat extraction from low-permeability reservoirs
Thermoporoelastic effects during heat extraction from low permeability geothermal reservoirs are investigated numerically, based on the model of a horizontal penny-shaped fracture intersected by an injection well and a production well. A coupled formulation for thermo-hydraulic (TH) processes is presented that implicitly accounts for the mechanical deformation of the poroelastic matrix. The TH model is coupled to a separate mechanical contact model (M) that solves for the fracture contact stresses due to thermoporoelastic compression. Fractures are modelled as surface discontinuities within a three-dimensional matrix. A robust contact model is utilised to resolve the contact tractions between opposing fracture surfaces. Results show that due to the very low thermal diffusivity of the rock matrix, the thermally-induced pore pressure partially dissipates even in the very low-permeability rocks that are found in EGS projects. Therefore, using the undrained thermal expansion coefficient for the matrix may overestimate the volumetric strain of the rock in low-permeability enhanced geothermal systems, whereas using a drained thermal expansion coefficient for the matrix may underestimate the volumetric strain of the rock. An effective thermal expansion coefficient can be computed from the drained and undrained values to improve the prediction for the partially-drained matrix.
Effect of Poroelasticity on Hydraulic Fracture Interactions

This study investigates, by performing finite element-based simulations, the influence of fluid leak-off and poroelasticity on growth of multiple hydraulic fractures that initiate from a single horizontal well. In this research, poroelastic deformation of
the matrix is coupled with fluid flow in the fractures, and fluid flow in the rock matrix, in three dimensions. Effects of the fluid leakoff and poroelasticity on the propagation of the neighboring fractures are studied by varying the matrix permeability, and the Biot coefficient. Simulation results show that the stress induced by the opening of the fractures, and the stress induced by the fluid leak-off, each have the effect of locally altering the magnitudes and orientations of the principal stresses, hence altering the propagation direction of the fractures. The stress induced by the opening of the fractures tends to propagate both of the fractures away from each other in a curved trajectory, whereas the effects of fluid leak-off and poroelasticity (i.e., a higher Biot coefficient) tend to straighten the curved trajectory.

Finite element simulations of interactions between multiple hydraulic fractures in a poroelastic rock
A fully coupled three-dimensional finite-element model for hydraulic fractures in permeable rocks is presented, and used to investigate the ranges of applicability of the classical analytical solutions that are known to be valid in limiting cases. This model simultaneously accounts for fluid flow within the fracture and rock matrix, poroelastic deformation, propagation of the fractures, and fluid leakage into the rock formation. The model is validated against available asymptotic analytical solutions for penny-shaped fractures, in the viscosity-dominated, toughness-dominated, storage-dominated, and leakoff-dominated regimes. However, for intermediate regimes, these analytical solutions cannot be used to predict the key hydraulic fracturing variables, i.e. injection pressure, fracture aperture, and length. For leakoff-dominated cases in permeable rocks, the asymptotic solutions fail to accurately predict the lower-bound for fracture radius and apertures, and the upper-bound for fracture pressure. This is due to the poroelastic effects in the dilated rock matrix, as well as due to the multi-dimensional flow within matrix, which in many simulation codes is idealised as being one-dimensional, normal to the fracture plane.

Multiple hydraulic fractures, Sequential fracturing, Simultaneous fracturing, Linear elastic fracture mechanics

Finite element simulations of interactions between multiple hydraulic fractures in a poroelastic rock
A fully coupled three-dimensional finite-element model for hydraulic fractures in permeable rocks is presented, and used to investigate the ranges of applicability of the classical analytical solutions that are known to be valid in limiting cases. This model simultaneously accounts for fluid flow within the fracture and rock matrix, poroelastic deformation, propagation of the fractures, and fluid leakage into the rock formation. The model is validated against available asymptotic analytical solutions for penny-shaped fractures, in the viscosity-dominated, toughness-dominated, storage-dominated, and leakoff-dominated regimes. However, for intermediate regimes, these analytical solutions cannot be used to predict the key hydraulic fracturing variables, i.e. injection pressure, fracture aperture, and length. For leakoff-dominated cases in permeable rocks, the asymptotic solutions fail to accurately predict the lower-bound for fracture radius and apertures, and the upper-bound for fracture pressure. This is due to the poroelastic effects in the dilated rock matrix, as well as due to the multi-dimensional flow within matrix, which in many simulation codes is idealised as being one-dimensional, normal to the fracture plane.
Three-Dimensional poroelastic effects during hydraulic fracturing in permeable rocks

A fully coupled three-dimensional finite-element model for hydraulic fractures in permeable rocks is presented, and used to investigate the ranges of applicability of the classical analytical solutions that are known to be valid in limiting cases. This model simultaneously accounts for fluid flow within the fracture and rock matrix, poroelastic deformation, propagation of the fractures, and fluid leakage into the rock formation. The model is validated against available asymptotic analytical solutions for penny-shaped fractures, in the viscosity-dominated, toughness-dominated, storage-dominated, and leakoff-dominated regimes. However, for intermediate regimes, these analytical solutions cannot be used to predict the key hydraulic fracturing variables, i.e. injection pressure, fracture aperture, and length. For leakoff-dominated cases in permeable rocks, the asymptotic solutions fail to accurately predict the lower-bound for fracture radius and apertures, and the upper-bound for fracture pressure. This is due to the poroelastic effects in the dilated rock matrix, as well as due to the multi-dimensional flow within matrix, which in many simulation codes is idealised as being one-dimensional, normal to the fracture plane.

General information
State: Published
Organisations: Centre for oil and gas – DTU, Imperial College London
Authors: Salimzadeh, S. (Intern), Paluszny, A. (Ekstern), Zimmerman, R. W. (Ekstern)
Number of pages: 11
Pages: 153-163
Publication date: 2017
Main Research Area: Technical/natural sciences

Publication information
Journal: International Journal of Solids and Structures
Volume: 108
ISSN (Print): 0020-7683
Ratings:
BFI (2017): BFI-level 2
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 2.8 SJR 1.501 SNIP 1.713
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 1.502 SNIP 1.917 CiteScore 2.66
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 1.643 SNIP 2.048 CiteScore 2.72
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): SJR 1.587 SNIP 2.148 CiteScore 2.6
ISI indexed (2013): ISI indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): SJR 1.584 SNIP 2.262 CiteScore 2.33
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): SJR 1.668 SNIP 1.911 CiteScore 2.11
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 1.599 SNIP 1.845
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 1.86 SNIP 1.774
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 1.823 SNIP 1.87
A Fully Coupled XFEM Model for Flow and Deformation in Fractured Porous Media with Explicit Fracture Flow

A hydro-mechanical model with explicit fracture flow is presented for the fully coupled analysis of flow and deformation in fractured porous media. Extended finite element method (XFEM) is utilised to model the fracture discontinuity in the two-dimensional plane-strain mechanical model. Two flow models, a one-dimensional laminar flow within the fracture and a two-dimensional Darcy flow through porous media, are considered. The flow domains are coupled through a mass exchange term (leak-off) accounting for discontinuous Darcy flow velocity across the fracture. Particular attention is given to the coupling of the flow domains with the mechanical model. Spatial and temporal discretisation is achieved using the standard Galerkin method and the finite difference technique, respectively. Unlike the successive coupled models where the results of the mechanical model is used to update the fracture flow model and vice versa, the fully coupled hydro-mechanical formulation is solved simultaneously. The model is verified against several closed form solutions from the literature. The impact of formation flow and leak-off flow on the fracture opening due to injected fluid pressure is discussed.

General information
State: Published
Organisations: University of New South Wales, Imperial College London
Authors: Salimzadeh, S. (Intern), Khalili, N. (Ekstern)
Number of pages: 13
Publication date: 2015
Main Research Area: Technical/natural sciences

Publication information
Journal: International Journal of Geomechanics
ISSN (Print): 1532-3641
Ratings:
BFI (2017): BFI-level 2
Web of Science (2017): Indexed Yes
BFI (2016): BFI-level 2
Scopus rating (2016): SJR 1.413 SNIP 1.976 CiteScore 1.87
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 1.716 SNIP 1.931 CiteScore 1.7
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 1.481 SNIP 1.909 CiteScore 1.41
A Three-Dimensional Numerical Model for Double Porosity Media with Two Miscible Fluids including Geomechanical Response

The finite-element formulation of a coupled fluid flow and geomechanics for two-phase fluid flow through fractured porous media is presented. Two porosities, pores and fractures, and five phases are introduced. The two fluids are taken as wetting and non-wetting. The governing equations are derived based on the theory of poroelasticity, the effective stress principle, and the balance equations of mass and momentum, taking into account the solubility of non-wetting fluid into wetting fluid. Spatial and temporal discretisation of the governing equations have been realised through Galerkin method and the finite difference technique, respectively. A three-dimensional numerical code has been developed and validated based on the previously published data in the literature. Various applications of the model have been demonstrated through three field-scale examples.
A three-phase XFEM model for hydraulic fracturing with cohesive crack propagation

A three-phase hydro-mechanical model for hydraulic fracturing is proposed. Three phases include: porous solid, fracturing fluid and host fluid. Discontinuity is handled using extended finite element method (XFEM) while cohesive crack model is used as fracturing criterion. Flow through fracture is defined as one-dimensional laminar flow, and flow through porous medium (host reservoir) is defined as two-dimensional Darcy flow. Coupling between two fluids in each space, fracture and pore, is captured through capillary pressure–saturation relationship, while the identical fluids in fracture and pore are coupled through a so-called leak-off mass transfer term. Coupling between fluids and deformation is captured through compatibility of volumetric strain of fluids within fracture and pore, and volumetric strain of the matrix. Spatial and temporal discretisation is achieved using the standard Galerkin method and the finite difference technique, respectively. The model is verified against analytical solutions available from literature. The leaking of fracturing fluid into the medium and suction of porous fluid into the fracture around the tip, are investigated. Sensitivity analyses are carried out for cases with slow and fast injection rates. It is shown that the results by single-phase flow may underestimate the leak-off.
Consolidation of unsaturated lumpy clays
Coupled flow-deformation analysis of consolidation in unsaturated lumpy clays is presented. The governing differential equations are discretised using the Galerkin method and the finite difference technique for space and time, respectively. Particular attention is given to the cross coupling coefficients arising from the pore scale deformation compatibility between micro and macro voids. Two examples are analysed: a one-dimensional soil column, and a strip footing acting on a two-dimensional medium of lumpy clay. A range of sensitivity analyses are preformed using different values of degree of saturation and volume fraction of macro voids. All results are carefully analysed and salient features of consolation in lumpy clays are highlighted. The significance of the cross coupling coefficients in the numerical results obtained are also examined.

General information
State: Published
Organisations: University of New South Wales
Authors: Salimzadeh, S. (Intern), Khalili, N. (Ekstern)
Pages: 67-82
Publication date: 2014
Main Research Area: Technical/natural sciences

Publication information
Journal: Journal of Geo-Engineering Sciences
Volume: 2
ISSN (Print): 2213-2880
Original language: English
Unsaturated soils, Lumpy clays, Consolidation, Coupled formulation
DOIs:
Projects:

**Numerical modelling of near wellbore flow**

Department of Applied Mathematics and Computer Science  
Period: 01/07/2017 → 30/06/2020  
Number of participants: 3  
Phd Student:  
Kadeethum, Teeratorn (Intern)  
Supervisor:  
Salimzadeh, Saeed (Intern)  
Main Supervisor:  
Nick, Hamid (Intern)

**Financing sources**

Source: Internal funding (public)  
Name of research programme: Institut stipendie (DTU)  
Project: PhD

**Production performance of radial water-jet drilled wells: a modelling and laboratory study**

Department of Applied Mathematics and Computer Science  
Period: 01/10/2016 → 30/09/2019  
Number of participants: 4  
Phd Student:  
Medetbekova, Maiya (Intern)  
Supervisor:  
Christensen, Helle Torp (Intern)  
Salimzadeh, Saeed (Intern)  
Main Supervisor:  
Nick, Hamid (Intern)

**Financing sources**

Source: Internal funding (public)  
Name of research programme: Institut stipendie (DTU)  
Project: PhD