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A simple 3-D thermoelastic model for assessment of the long-term performance of the Hijiori deep geothermal reservoir

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ABSTRACT

In order to assess the thermoelastic influence on the long-term performance of hot dry rock (HDR) reservoirs, a simple three-dimensional (3-D) thermoelastic model has been developed based on an assumption of a spherically symmetric volume of cooled rock within reservoir. This model has been incorporated into a 3-D stochastic network model, FRACSIM-3D, which incorporates a fracture network designed to mimic natural fracture distributions as well as stimulation and circulation. The model has been used to evaluate the possible long-term performance of the deep HDR reservoir at Hijiori, Japan. Simulation results showed that thermoelasticity could exert a significant influence on production temperature, injection pressure and water loss. For a multi-well geothermal system, thermoelasticity seemed to have a potential to cause the development of high flow rate/rapidly cooling flow paths (thermal short circuits).

1. Introduction

Renewable energy, especially after the great east Japan earthquake on March 11, 2011, becomes more and more important in ensuring self-sufficiency of energy supply and mitigating climate change. Among renewable energy options, geothermal power generation has the advantage of providing baseload energy supply, i.e. a stable energy supply and unaffected by weather conditions, in contrast to solar and wind power generation.

HDR geothermal field experiments have been carried out at several sites worldwide to explore the potential for exploiting geothermal energy (Laughlin et al., 1983; Nakatsuka, 1999; McDermott et al., 2006; Hebert et al., 2010; Zaigham and Nayyar, 2010; Watanabe et al., 2011; Feng et al., 2012; Zeng et al., 2013). The concept of HDR typically involves: (a) stimulation, i.e. pumping highly pressured fluid through an injection well to open up predominantly pre-existing natural fractures in the 'hot' rock, thereby creating a man-made or "engineered" geothermal reservoir of fractured rock; (b) circulation, i.e. circulating fluid through the stimulated fracture networks in hot rock where the fluid is heated, and recovering the heated fluid via production well(s) to move heat from the reservoir to the surface. Commercial design considerations typically require the operation of these systems for more than 20 years before abandonment due to drops in production rates or temperature. Therefore the potential effect of prolonged thermoelasticity induced by temperature drawdown of the rock mass around fluid paths needs to be considered. A priori, thermoelastic deformation is considered likely to cause both widening and narrowing of the fracture apertures in different parts of the rock mass, which will inevitably affect the permeability distribution of the fracture network and reservoir performance.

To model HDR engineered systems, a three-dimensional (3-D) stochastic network model, FRACSIM-3D, has been presented (Jing et al., 2000), which incorporates a fracture network whose statistical parameters are derived from borehole observations and is designed to be similar to that in the HDR reservoir under study, and addresses both the changes that occur within the rock mass during hydraulic stimulation (chiefly slip along fractures, fracture opening and resulting stress changes) and the circulation under steady-state of the heat exchange system to move heat from the reservoir to the surface. The model, however, failed to incorporate the effects of thermoelasticity and water/rock chemical interaction (WRCI), thought to be very important in the evolving performance of HDR reservoirs.

As an extension, a water/rock chemical interaction (WRCI) module has been incorporated into FRACSIM-3D (Jing et al., 2002), and applied to estimate the effect of WRCI on the performance of the Hijiori deep reservoir. The objective of this work is to incorporate thermoelasticity into the 3-D stochastic network model, so as to complete another extension of FRACSIM-3D.

Thermoelastic effects on the flow path (Elsworth, 1990), on deformation along a single fracture (Evans et al., 1992), on thermal short circuits (Duteau et al., 1994) and on the performance of HDR reservoirs (Hicks et al., 1996) have been modeled. However these existing one- or, two-dimensional (1- or 2-D) models, which used a parallel plate or

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other regular fracture grid, were unable to show how thermoelasticity might exert an influence in the context of a near realistic 3-D fracture network system. A finite-element model, coupled mechanical deformation and alteration of fracture parameters with pressure-, temperature- and salinity-dependent fluid parameter functions, indicated that preferential fluid flow paths and shortcuts may develop, depending on the mechanical and thermal stress releases (McDermott et al., 2006).

To the best of our knowledge, there seems to be no published work estimating the influence of thermoelasticity in geometrically complex 3-D fracture network systems. Before attempting a mathematically rigorous simulation of thermoelastic influence, it may be useful to obtain some rough estimates of this effect in a fracture network under some 'audacious' simplifying assumptions. This paper tries to do so, and is a first step in developing a truly 3-D natural fracture-dominated system able to more exactly evaluate the thermoelastic influence on natural fractured systems.

In this article, we have sought rough estimates of the thermoelastic influence on natural fractured systems. For small HDR systems (in terms of open borehole length and well separation) with high fracture density, earlier simulations (Jing et al., 2000) showed that the temperature distribution in reservoir could be crudely approximated by a sphere in moderately mature flow systems. Thus, as a first approximation, we have assumed a spherically symmetric temperature field for thermoelastic stress calculation purposes in this article. From the assumption, a simple analytical model for thermoelastic calculation is possible. The style of this approximation is similar to that employed in FRACSIM-3D in order to calculate rock stress effects during stimulation; taken together they permit the approximate resolution on a personal computer of what would be a supercomputer problem were the mathematical formulation more rigorous.

2. Brief description of the stochastic fracture network model

The main features of the 3-D stochastic model mentioned above are that: (a) it integrates many field observations such as the orientation, size and density of natural fractures etc., into the fracture network distribution, and thus has the capability of generating a fracture network very similar to the natural fracture distribution in the reservoir, and (b) it addresses problems associated with stimulation, circulation and heat extraction on such a stochastic natural fracture network. The model was described in detail by Willis-Richards et al. (1996) and Jing et al. (2000).

2.1. Stochastic fracture network

The fracture network in this model is held as a file of idealized circular fractures each defined by its position, orientation, radius, frictional, surface geometric and other mechanical properties of rocks. Fractures are assumed to be rough undulating frictional contacts without any cohesive infilling minerals causing resistance to sliding, opening or fluid flow. The model accepts files of fractures generated by a simple stochastic fracture generator; it could also, in principle, accept files of fractures from any source of data available or stochastic data sets conditioned by borehole observations.

Fractures are generated randomly within a cubic fracture generation volume being larger than the model volume. The fracture centers are uniformly random, while the radii are fractally distributed within lower and upper bounds. For each generated fracture, the initial fracture aperture, at zero effective stress, is assumed to be proportional to the fracture radius. The proportionality constant is chosen such that the macroscopic permeability of the undisturbed fracture network approximately matches the in-situ measured permeability, which might be derived from low pressure open hole tests. Fracture orientation distributions are based on re-sampling of field data sets, typically gathered from borehole imaging, so as to mimic the fracture orientation distribution inferred from field observations. Fractures are generated until the fracture density (m^2 of fracture per m^3 of rock) reaches the observed level. Fig. 1 shows the appearance of a subset of the larger fractures from a natural fracture distribution generated by the 3-D stochastic fracture network model. A typical FRACSIM-3D model might incorporate over 100,000 fractures in total.

2.2. Stimulation, circulation and heat extraction

The dominant mode of fracture stimulation considered in the model is shear dilation. Hydraulic stimulation allows shearing to take place on pre-existing fractures under the influence of natural rock stresses, and this sliding causes dilation in the direction normal to the fracture surface due to the roughness of fracture walls (Fig. 2). Sheared fracture apertures, a_s, are a function of effective normal stress across the surface, the rate of normal opening with lateral displacement and the amount of the shear displacement. The resultant change in fracture aperture may be expressed as follows (Goodman, 1976; Hicks et al., 1996; Willis-Richards et al., 1996):

$$a_s = U \tan\left(\phi_{dil}^{eff}\right) \tag{1}$$

where U is fracture displacement and ϕ_{dil}^{eff} an effective shear dilation angle at a given effective normal stress. The concept of ϕ_{dil}^{eff} is not mechanically of geometrically rigorous and incorporates implicitly the notion of fracture closure with increasing normal stress; calculations using this would need to relate ϕ_{dil}^{eff} to the effective normal stress at any moment.

Using φ_{dil} to represent the shear dilation angle at zero effective normal stress and using an approximate hyperbolic aperture closure curve defined by the fracture and rock specific parameter σ_{nref}, we can write a simple expression for the aperture (a) of a fracture after a shear displacement U, with un-abrading asperities in contact and small shear dilation angle indirectly after Goodman (1976), Hicks et al. (1996) and Willis-Richards et al. (1996):

$$a = \frac{a_0 + U \tan(\phi_{dil})}{1 + {}^{9(\sigma_n - p)}\Big/_{\sigma_{nref}}} \tag{2}$$

where a_0 represents the initial (i.e. unstimulated) aperture of the fracture at zero effective normal stress; σ_{nref} is the effective normal stress applied to cause a 90% reduction in the compliant aperture, σ_n is the

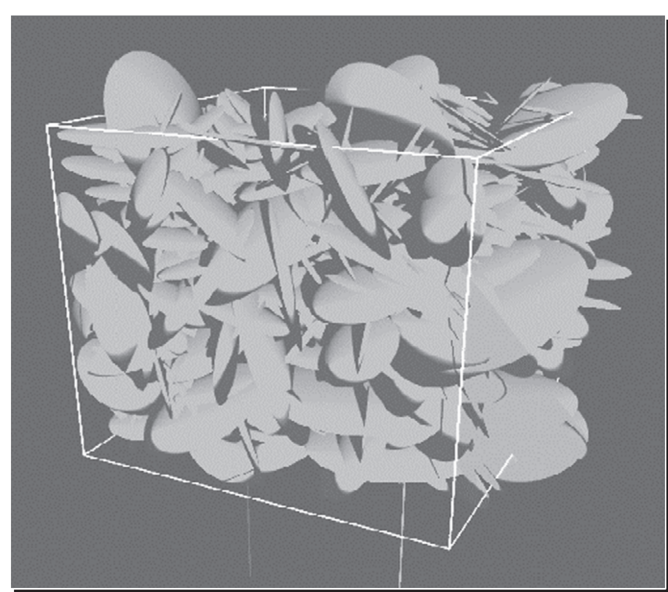

Fig. 1. Image of fracture distribution generated by the 3-D stochastic network model.