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An enhanced stochastic optimization in fracture network modelling conditional on seismic events

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ABSTRACT

This paper presents an approach to modelling fracture networks in hot dry rock geothermal reservoirs. A detailed understanding of the fracture network within a geothermal reservoir is critically important for assessments of reservoir potential and optimal production design. One important step in fracture network modelling is to estimate the fracture density and the fracture geometries, particularly the size and orientation of fractures. As fracture networks in these reservoirs can never be directly observed there is significant uncertainty about their true nature and the only feasible approach to modelling is a stochastic one. We propose a global optimization approach using simulated annealing which is an extension of our previous work. The fracture model consists of a number of individual fractures represented by ellipses passing through the micro-seismic points detected during the fracture stimulation process, i.e. the fracture model is conditioned on the seismic points. The distances of the seismic points from fitted fracture planes (ellipses) are, therefore, important in assessing the goodness-of-fit of the model. Our aims in the proposed approach are to formulate an appropriate objective function for the optimal fitting of a set of fracture planes to the micro-seismic data and to derive an efficient modification scheme to update the model parameters. The proposed objective function consists of three components: orthogonal projection distances of the seismic points from the nearest fitted fractures, the amount of fracturing (fitted fracture areas) and the volumes of the convex hull of the associated points of fitted fractures. The functions used in the model update scheme allow the model to achieve an acceptable fit to the points and to converge to acceptable fitted fracture sizes. These functions include two groups of proposals: one for updating fracture parameters and the other for determining the size of the fracture network. To increase the efficiency of the optimization, a spatial clustering approach, the Distance-Directional Transform, was developed to generate parameters for newly proposed fractures. A simulated dataset was used as an example to evaluate our approach and we compared the results to those derived using our previously published algorithm on a real dataset from the Habanero geothermal field in the Cooper Basin, South Australia. In a real application, such as the Habanero dataset, it is difficult to determine definitively which algorithm performs better due to the many uncertainties but the number of association points, the number of final fractures and the error are three important factors that quantify the effectiveness of our algorithm.

1. Introduction

Hot dry rock (HDR) geothermal energy has the potential to make a significant contribution to achieving a sustainable energy future. Potential HDR geothermal systems occur in deep underground crystalline rock, where the rock matrix (granite) is almost impermeable and the only viable pathway for geothermal flow is through an engineered fracture network. Understanding the fractures and the fracture network within the geothermal reservoir is therefore critically important for the design and operation of the system [4,20,28,33].

Earlier mathematical models for fracture networks and flow through them include continuum models that assume a fractured rock mass can be represented as an equivalent porous medium [14,17,21,29] and discrete fracture networks (DFN) that rely on a detailed description of discontinuity geometry [7,9,10,18,19,26,28,30,31,32]. In DFN, which provides an approximate representation of the reservoir fracture network, it is very difficult to obtain a reliable description of the fracture geometry as, in most cases, it is impossible to observe or measure fractures directly on any scale relevant to the problem. Studies are generally limited to sparse,

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small-scale observations (e.g., on drill cores) or indirect measures such as those provided by geophysical surveys or, in the case of engineered geothermal systems (EGS), micro-seismic events generated during the fracture stimulation process. The seismic point cloud can be used not only to determine the geographical extent of the HDR reservoir but also to detect fracture geometry in a fractured reservoir [33,24]. Establishing the discrete fracture network model (DFN) conditioned to this seismic point cloud is a way of creating a more realistic model of a HDR EGS.

The significant uncertainties associated with DFN necessitate a stochastic approach. Stochastic modelling of fracture networks originated in percolation studies [22,23] and was promoted in the 1980s for its wider application to rock engineering (e.g., [16,2,1,6]). It is a general approach in which the fracture characteristics, such as size and orientation, are treated as random variables with inferred probability distributions. In the simplest case, once the parameters of the distributions are inferred, the rock fracture model is constructed by Monte Carlo simulation [30]. More realistic models include the spatial variability of the variables in the simulation.

Recently, DFN conditional on two- and three-dimensional data have been proposed; see for example: Fadakar et al. [11], Mardia et al. [18,19], Seifollahi et al. [24], Seifollahi et al. [25], Tran [27], Xu et al. [33]. A Markov Chain Monte Carlo (MCMC) approach was applied to the conditioning of a fracture model to borehole data in a 2D application [18] and the model was later extended to 3D applications [19]. An extension of MCMC to the conditioning of a fracture model to the seismic events was used in Xu et al. [33] for a data set from the Habanero geothermal field. In this model the number of fractures is fixed in advance and the unknown fracture variables (e.g., size and orientation), are optimized during the MCMC process. In the present work, the number of fractures is also a variable to be optimized during the optimization process. We also extend the work of Seifollahi et al. [24,25] by including more components in the objective function and introducing more update proposals to improve the conditioning process.

This paper presents a general stochastic model for fracture networks in a fractured HDR reservoir. Two challenging factors in a global optimization problem are the construction of an appropriate objective function and the formulation of an efficient model modification scheme. In our approach, the objective function consists of three components to minimize, respectively, the distances of the points to the fitted fracture model, the amount of fracturing and the volumes of the convex hull of the points associated with fractures. The model modification functions include two categories of proposals. The first category is for updating fracture geometry variables and the second is for adjusting the size of the fracture network (number of fractures). Simulated annealing (SA) is the core of our model in which it is used to minimize the objective function by accepting or rejecting any update proposed by the model modification functions [25]. To enhance the optimization process, a spatial clustering approach, developed by Seifollahi et al. [24], and termed the DD-Transform, is used to help determine the fracture geometry. It should be noted that the accuracy of the seismicity detection and the inversion process in deriving the locations of seismic points are not concerns of this paper; readers interested in these topics should consult Baisch et al. [3].

The paper is organized as follows: In Section 2, we give a description of the model and the problem formulation, with a focus on fracture bandwidth. The fracture bandwidth is an interval around fractures used to weight the objective function to reflect the importance of the locations of the points to the fracture model as well as controlling the number of fractures in the network. In Section 3, we describe the DD-Transform, which determines a solution for the parameters of newly proposed fractures during the optimization process. In Section 4 we present the proposals for updating fracture parameters and for permitting the network to grow or diminish (by pruning), which is followed by details of the proposed model. The performance of the proposed model is illustrated in Section 5 using two validation datasets, first using a simulated dataset and then a real dataset from the Habanero reservoir [3,33].

2. Problem formulation

In discrete fracture network modelling, the most common approach is to use simple representations of fractures although it is possible to represent fractures by tortuous surfaces. Common approaches include circular discs, elliptical discs, planar polygons or planes with infinite extents [19,24,25,33]. In the work reported here, we represent a fracture by an ellipse. We consider this to be a simple, but reasonable, approximation to actual fracture surfaces as fractures with curved features can be subdivided into planar regions connected to each other. With this simplification, each fracture can be described by eight parameters, (x, y z, α, β, γ, a, b) where x, y and z are the coordinates of the fracture centre, α and β are the dip direction and dip angle of the plane, γ is the rotation angle of the major axis against the dip direction of the ellipse and a and b are the major and minor axes of the ellipse. Xu and Dowd [30] provide more detailed descriptions of these parameters.

The fracture model consists of a number of fractures each with its associated cluster of seismic points so that each point is associated with one, and only one, fracture in the model. Note that even the ‘best’ fitted model will not intersect all seismic points but the distances of the points to fracture planes (the orthogonal projection measure) can be used to assess the goodness-of-fit of the fracture model. The final objective function can be written as [25]:

$$f(w) = \sum_{i=1}^{n_o} \lambda_i f_i(w), \tag{1}$$

where w is a set of unknown fracture variables to be optimized, n_o is the number of objectives and f_i and λ_i are, respectively, the ith objective and its weight. Constructing a proper objective function (i.e., the number of components and their structures) is critical in ensuring the optimization process converges to a solution. The proposed objective function consists of three components as follows.

1. Distances of the points to fracture planes: the summation of the shortest distances of the points to fracture planes is a major component of the objective function [25,33]:

$$f_1(w) \equiv \sum_{j=1}^{m} d^2_{jk^*}, \quad k^* = \underset{k}{\operatorname{argmin}}(d^2_{jk}) \tag{2}$$

   where m is the number of points, j and k are the indices of the jth point and kth fracture and d^2_{jk} is the squared projection distance of the jth point to the kth fracture. When the orthogonal projection of a point does not intersect any fracture ellipse, the point is not associated with any fracture and a penalty value is applied to the point in the calculation of the objective function.
2. The amount of fracturing: the following objective is used [25] to achieve a network with an appropriate amount (area) of fracturing:

$$f_2(w) = \sum_{i=1}^{n} \frac{\delta + a_i \times b_i}{1 + m_i} \tag{3}$$

   where n is the number of fractures, a_i and b_i are the major and minor axes of the ith fracture, m_i is the number of points associated with the ith fracture and δ is a positive number proportional to the penalty for an outlier (isolated point); $m = \sum_{i=1}^{n} m_i$ and is used later. The function ensures that in any updating of the DFN