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Proceedings of the 2012 Australian Geothermal Energy Conference, 2012 / C. Huddlestone-Holmes, E. Gerner (eds.): pp. 62-66

Application of Connectivity Measures in Enhanced Geothermal Systems

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Abstract

The three major determinant factors for the productivity of hot dry rock geothermal reservoirs are fractures, fluid and heat. Fractures create an interconnected network that provides the pathways for fluid flow, which in turn facilitates heat exchange from the rock masses. The connection between fractures is therefore a critical characteristic of a successful heat producing geothermal system. Connectivity analysis is also an important component in the design, assessment and development of fracture-based reservoirs particularly enhanced geothermal systems. In this paper, we evaluate the application of two connectivity measures: the connectivity field and the connectivity index, of a fracture network. Both measures are well suited to stochastic modelling, which provides a means of incorporating the uncertainty due to lack of data. We demonstrate the effectiveness of both measures in the determination of preferential pathways through the fracture network. We also demonstrate the use of the connectivity field in determining the optimal location of an injection or production well so as to maximise the reservoir performance. The two measures show good correlation with other established connectivity measures such as X_f and P21 (P32). They are also shown to be useful in the evaluation of percolation state of a fractured rock mass.

Keywords Connectivity Index, Connectivity Field, Ranked Flow Pathways, Optimal Drilling Locations

Introduction

The productivity of hot dry rock geothermal reservoirs is mainly dependent on three factors: heat, fluid and fractures. In an enhanced geothermal system (EGS) reservoir, the heat transfer is facilitated by fluid passing through the channels established by interconnected fractures, termed the heat exchange chamber of the geothermal reservoir. The injection and production wells are connected directly through the chamber, completing the geothermal energy extraction circle.

Connections between fractures in fracture networks create basic pathways for the geothermal flow. The characterisation of the geothermal reservoir connectivity as a fundamental step of fracture network modelling is therefore vitally important in all stages of the reservoir's life cycle, including the design, the assessment and the development. The methods introduced in this paper are helpful to increasing our understanding of connectivity of fracture-based reservoirs.

We demonstrate applications of two important connectivity measures i.e., Connectivity Index (CI, Xu et al. 2006) and Connectivity Field (CF, Fadakar-A et al. 2012) for the effective connectivity characterisation of fracture networks. The methods are well-suited to stochastic modelling where the uncertainty associated with the evaluations is addressed in a probabilistic form. We demonstrate some particular applications of the two measures including the determination of main directions of geothermal flow using CI, preferential flow pathways using CF and optimal locations of injection and production wells using CF.

Connectivity in Fracture Networks

The Connectivity Measures

The connection between two fractures in a fracture network can be defined based on the connectivity measure between two points in space introduced in Allard (1993) and later developed in Pardo-

Iguzquiza and Dowd (2003), which is basically an indicator variable of 1 if the two points are connected and 0 otherwise. Accordingly, if two fractures are directly connected to each other (i.e., they intersect) or are indirectly connected (i.e., there is a pathway via other connected fractures) then they have a connectivity indicator of 1 (see Fadakar-A et al. 2011 for intersection types). The measure can be extended for different scenarios as follows:

C_p	$\mathbf{1}(x \leftrightarrow y)$		between two points
C_v	$\mathbf{1}(x_v \leftrightarrow y_v)$	$v \in S = R^n$	between two supports
C_f	$\mathbf{1}(f_i \leftrightarrow f_j)$	$f = \{v\}$	between two fractures : set of supports
C_c	$\mathbf{1}(c_m \leftrightarrow c_n)$	$c = \{f\}$	between two fracture clusters
C_w	$\mathbf{1}(w_p \leftrightarrow w_q)$	$w = \{c\}$	between two wells

where supports are representative subspaces in the region of study and fracture clusters are generated by explicitly interconnected fractures.

The Connectivity Index (CI)

The Connectivity Index is a probabilistic measure which results in the likelihood of connectivity between two support cells in a fracture network. A successful application of CI in determining the main direction of flow in a fracture network is reported in Xu et al. (2006). Although the CI does not deal with flow through fractures, the resulting preferential flow direction is noticeably consistent with the output from finite element method. The CI is defined as follows (Xu et al. 2006):

$$\mathbf{CI} = \tau(v) = \mathbf{Pr}(x_v \leftrightarrow y_v), \qquad \forall x_v, y_v \in R^n$$

The Connectivity Field (CF)

The Connectivity Field as proposed in Fadakar-A et al. (2012) is a new measure which quantifies the connectivity relationship between fractures in a fracture network. The CF is defined as follows:

$$\mathbf{CF} = \int_v^{\xi} C_\xi dv, \qquad C_\xi = \mathbf{1}(x_{v\xi} \leftrightarrow y_v)$$

where for a two-dimensional grid of size $m \times n$, the connection measure $C_\xi\left(\xi = \{(i, j) | i = 1..m, j = 1..n\}\right)$ is computed as the indicator value between the ξ^{th} cell and all other cells. This generates a total number of $m \times n$ sets of connectivity matrices. The CF is then evaluated by summing up indicators in these matrices (Fadakar-A et al. 2012).

Relationships between CI and CF

One extension of CF is the Probabilistic Connectivity Field (PCF, Fadakar-A et al. 2012) that provides a means of CF assessment in a stochastic fracture modelling framework. PCF basically uses fracture network realizations generated by Monte Carlo simulations from the fracture network model. PCF shows close relationships with CI and the extension of CI termed Connectivity Index Field (CIF, Fadakar-A et al. 2013) as follows:

$$\mathbf{PCF} = \frac{1}{k}\sum(\mathbf{CF})_{r=1}^{k} = \frac{1}{k}\sum\left(\frac{1}{\eta}\sum\left(\mathbf{1}(v_{i,j} \leftrightarrow v_{p,q})_{\begin{cases}p=1\\q=1\end{cases}}^{\begin{cases}p=m\\q=n\end{cases}}\right)_{\begin{cases}i=1\\j=1\end{cases}}^{\begin{cases}i=m\\j=n\end{cases}}\right)_{r=1}^{k} = \frac{1}{k}\sum\left(\frac{1}{\eta}\sum\left(\mathbf{1}(v_{i,j} \leftrightarrow v_{p,q})^{p,q\in A}\right)^{i,j\in A}\right)_{r=1}^{k} = \frac{1}{k}\sum\left(\frac{1}{\eta}\sum((\mathbf{C}_A)^{i,j\in A})\right)_{r=1}^{k}$$

$$\mathbf{CI} = \frac{1}{k}\sum\left(\mathbf{1}(v_{i,j} \leftrightarrow v_{p,q})_{\begin{cases}p=1\\q=1\end{cases}}^{\begin{cases}p=m\\q=n\end{cases}}\right)_{r=1}^{k} = \frac{1}{k}\sum\left(\mathbf{1}(v_{i,j} \leftrightarrow v_{p,q})^{p,q\in A}\right)_{r=1}^{k} = \frac{1}{k}\sum(\mathbf{C}_A)_{r=1}^{k}$$

$$\mathbf{CIF} = \frac{1}{\eta}\sum\left(\frac{1}{k}\sum(\mathbf{C}_A)_{r=1}^{k}\right)^{i,j\in A}$$

where k is the number of realizations per simulation, η is the standardization factor, A is the region of study, v is support cell, and m, n are dimensions of the grid covering A.

Applications of CI and CF in characterising fracture networks

The stationary CI (SCI, Xu et al. 2006) is an extension of CI for stationary cases which considers distances between supports rather than their actual coordinates. SCI can effectively be used to determine preferential flow directions in a connected fracture network by comparing the SCI computed for different directions. The preferential flow directions can be visualised clearly as demonstrated in a 2D example shown in Figure 1. Note that the choice of distance h here can be guided by the available information of the region of study otherwise a series of simulations for varying h sizes can be conducted (see Fadakar-A et al. 2012 and 2013 for details). Preferential flow direction of the fracture network is closely related to the overall major direction of flow passing through the fracture network. As shown in Figure 1, the resulting preferential flow direction (solid lines) is noticeably consistent with the one computed using finite element method (dashed lines).

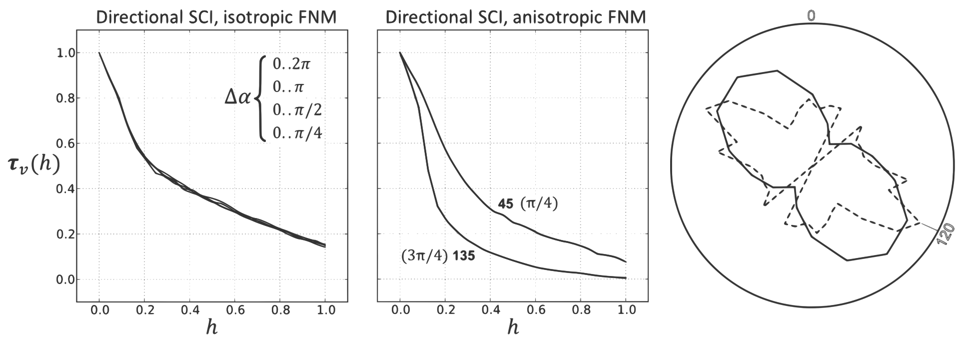

Figure 1: *SCI is able to distinguish effectively between isotropic and anisotropic fracture networks. As a result, SCI determines the major flow direction that is comparably accurate with regard to the one derived from conventional finite element methods.*

The procedure of the application of CF for the assessment of potential flow pathways in a fracture network is shown in Figure 2(A). The CF is also useful to help determine ranked pathways. Ranked pathways are those that can be of interest in fracture stimulation process for the expansion of the reservoir. An example of a ranked pathway is marked in Figure 2(A, "Pathways") where pathways with higher rank are shown as bold dashed line. In the example given two lower rank pathways are shown as dotted line. PCF, on the other hand, is also helpful to the characterisation of flow pathways in a fracture network model as demonstrated in Figure 2(B). The figure clearly demonstrates that there is a preferred orientation towards NE-SW (i.e., ~45 degree) in the connectivity through fracture network model which is consistent with the model parameters given in Figure 2(B).

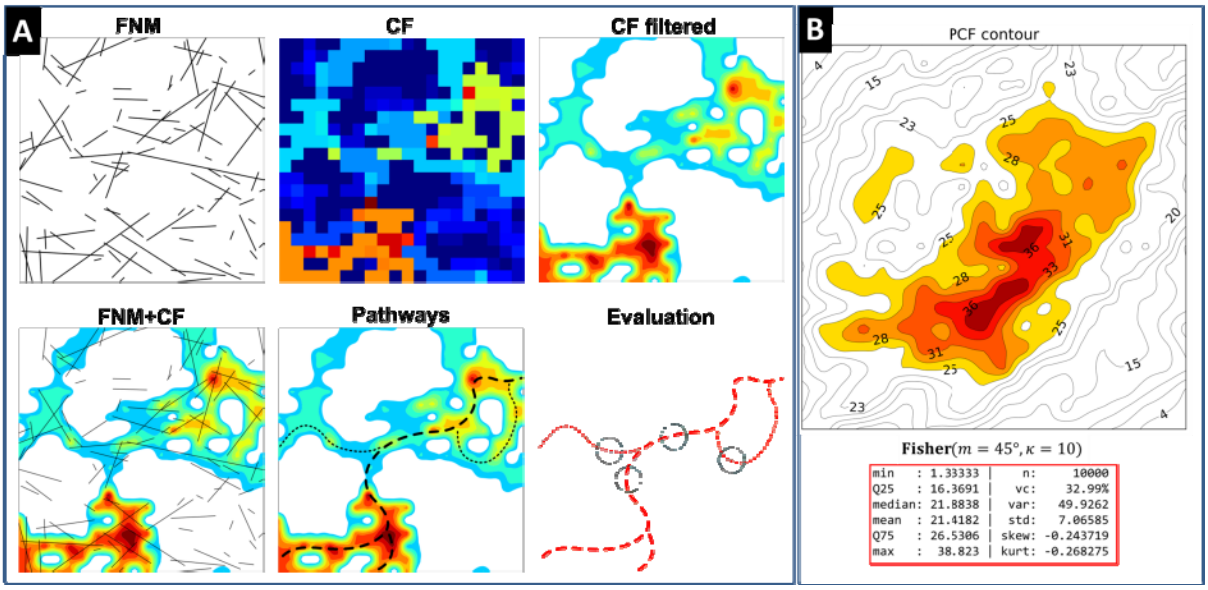

Figure 2: *(A) The procedure of determining ranked flow pathways using the CF measure. (B) PCF is used to characterise the connectivity of a fracture network model.*

The map of CF (filtered) shown in Figure 2(A) suggests potential further interesting applications. One is to locate the optimal drilling locations considering that the higher the value of CF the larger the fracture cluster connected to that location. In the example shown in Figure 2(A), the red region in the "Pathways" map is the most suitable area in terms of high connectivity within the region. In addition, in the case of using the fracture network model to evaluate the uncertainty associated with the CF map, PCF can be used to determine the optimum locations for drilling to maximise connectivity between the well and the reservoir (Figure 2(B)). PCF is also useful in the determination of the reservoir extent (connected area) as shown in Figure 2(B) with filled contours.

Our studies also show that both CI and CF are highly correlated with the traditional connectivity measures such as Xf, P21 (P32) and the percolation state. The detailed comparisons and discussion are reported in Xu et al. (2006), Fadakar-A et al. (2012) and Fadakar-A et al. (2013) and therefore are not to be repeated here.

Concluding Remarks

Connectivity Index (CI) and Connectivity Field (CF) are two new connectivity measures which can help characterise connectivity of fracture networks and provide practical applications especially for fracture-based geothermal reservoirs such as EGS. While CI is shown to be able to provide comparable results in the determination of the main flow direction in the fracture system with conventional deterministic methods (such as FEM), CF gives new insights into the evaluation of flow pathways in the network. CF is also helpful in locating optimal drilling locations. Full coverage of applications of the two measures can be found in Fadakar-A et al. (2012) and Fadakar-A et al. (2013).

Acknowledgements

The work was funded by Australian Research Council Discovery Project grant DP110104766.

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