Mechanics Research Communications 80 (2017) 16–23

Contents lists available at ScienceDirect

Mechanics Research Communications

journal homepage: www.elsevier.com/locate/mechrescom

Initialization of phase-field fracture propagation in porous media using probability maps of fracture networks.

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ARTICLE INFO

Article history:
Received 30 October 2015
Received in revised form 3 April 2016
Accepted 5 April 2016
Available online 24 May 2016

Keywords:
Hydraulic fracturing
Probability map
Phase-field fracture formulation

ABSTRACT

It is well known in the geophysical community that surface deflection information/micro-seismic data are considered to be one of the best diagnostics for revealing the volume of rock fracture. However, the in-exactness of the data representing the deformation induced to calibrate and represent complex fracture networks created and connected during hydraulic fracturing presents a challenge. In this paper, we propose a technique that implements a phase-field approach to propagate fractures and their interaction with existing fracture networks using surface deflection data. The latter one provides a probability map of fractures in a heterogeneous reservoir. These data are used to initialize both the location of the fractures and the phase-field function. In addition, this approach has the potential for optimizing well placement/spacing for fluid-filled fracture propagation for oil and gas production and or carbon sequestration and utilization. Using prototype models based on realistic field data, we demonstrate the effects of interactions between existing and propagating fractures in terms of several numerical simulations with different probability thresholds, locations, and numbers of fractures. Our results indicate that propagating fractures interact in a complex manner with the existing fracture network. The modeled propagation of hydraulic fractures is sensitive to the threshold employed within the phase-field approach for delineating fractures.

1. Introduction

The injection of large volumes of fluids in to the subsurface such as during geologic sequestration of CO_2 or during hydraulic fracturing operations can cause geomechanical deformation of the rock mass in the vicinity of the well. This in turn can trigger shear-slip events along existing faults and fractures or can manifest in the form of surface deflection that can be recorded by satellite-based remote sensing equipment. Because the network of natural fractures has an important effect on these types of responses either as locations along which micro-seismic slip events [3] or by acting as conduits for fluid flow that in turn determine the direction and extent of surface deflection, it is conjectured that inverse modeling of these responses can yield better characterization of the natural fracture network in the vicinity of wells. This notion is explored in the following study.

Fig. 1 shows a map of surface deflection recorded using remote sensing sensors on board an InSAR (Interferometric Synthetic Aperture Radar) satellite. This data was collected for the In Salah Gas Joint Venture in Algeria which is an ongoing CO_2 storage project operational since August 2004. The Krechba field is part of the In Salah gas field development, and is currently the largest onshore CO_2 storage site in the world [11]. At Krechba, CO_2 from several gas fields is removed from the production stream and injected into the deep saline carboniferous formation away from the producers. The large volume of injected CO_2 causes ground upheaval that is shown in Fig. 1.

Various methods deriving fracture networks from micro-seismic data as a framework for modeling reservoir performance have been suggested in order to connect a given natural fracture network with propagating hydraulic fractures [30]; here we employ a phase-field approach. Presently, this technique for fracture propagation is subject of intensive research in both

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[1] This work by S. Lee, M.F. Wheeler, and S. Srinivasan was supported as part of the CFSES, an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Basic Energy Sciences under Award #DE-SC0001114.
[2] T. Wick would like to thank the JT Oden Program of the *Institute for Computational Engineering and Science (ICES)* and the Center for Subsurface Modeling (CSM), UT Austin for hospitality during his visit in August 2015.

http://dx.doi.org/10.1016/j.mechrescom.2016.04.002
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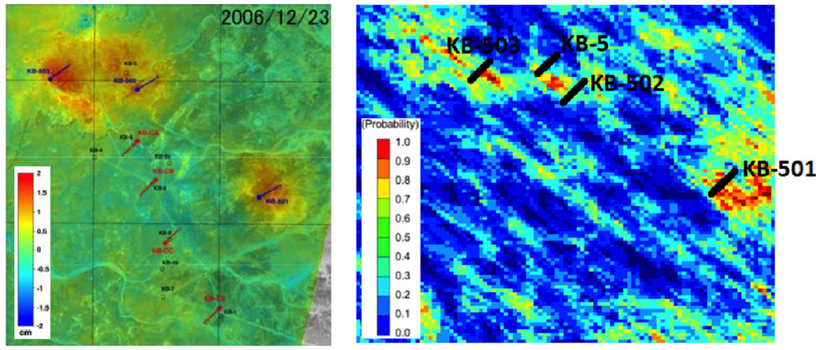

Fig. 1. Left: Surface deformation map at the site in December 2006 [23]. Right: Posterior probability of fractures based on the ensemble mean of the models in the selected cluster. The location of the wells is also indicated in the figure.

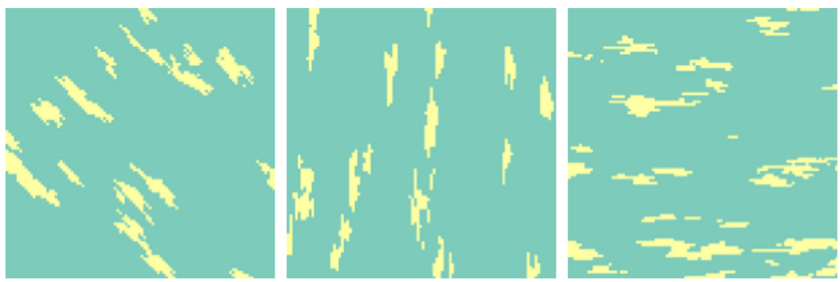

Fig. 2. Initial set of fracture models generated using geostatistical schemes.

mathematical theory and applications. Based on variational principles, they provide an elegant way to approximate lower-dimensional surfaces and discontinuities. Rewriting Griffith's model [8] for brittle fracture in terms of a variational formulation was first accomplished by [6,7]. In [16,15], the authors refined modeling and material law assumptions to formulate an incremental thermodynamically consistent phase-field model for fracture propagation. Numerous examples and benchmarks have been studied in [16,15,4,5,10,25,1]. Recent modeling and numerical studies of hydraulic fracturing in porous media and other multi-physics applications including thermo-elastic-plastic solids have been considered in [20,19,28,18,17]. Important computations of fluid-filled fractures in porous media with related findings using extended finite elements have been reported, for example, in [26,27].

The goal of this paper is to detect given (natural) fractures with a probability map that can be obtained from microseismic or InSAR data. Then, these initial data are used to build the initial phase-field solution for our fluid-filled fracture models [14,13,19,21]. More precisely, a probability map reflects the regions in which the stress conditions are such that there is a high probability of propagating fractures and so, this becomes the basis for our treating the probability map as the phase-field function for the fracture propagation modeling.

2. Construction of probability map and phase-field initialization

The procedure to constrain a set of models for the natural fracture network to the surface deflection information starts with an initial suite of models that reflects the prior uncertainty in describing the network. Models in this initial set reflect fractures of arbitrary orientation and possibly extent as shown in Fig. 2.

Flow and geomechanics responses of the prior models were obtained using a coupled proxy developed in [22]. The proxy utilizes a particle tracking simulation to model the flow of CO_2 in the prior models and couples that response to a simplified geomechanical scheme for computing the surface deflection corresponding to the injection of large volumes of CO_2 into the model. The simplified proxy allows evaluating the response of a large suite of models efficiently. The dissimilarity between pairs of models in the prior set are computed. These dissimilarities are subsequently transformed to a metric space using multidimensional scaling (MDS) [12]. Fig. 3 depicts the cluster of responses when projected in the metric space obtained by MDS. In this figure, models (depicted by points) that are close to each other exhibit similar dynamic responses. Cluster analysis can be performed and the grouping of models is also shown in Fig. 3 in the form of clusters of different colors. The optimal number of clusters is selected on the basis of a silhouette measure [24] that is a ratio of the inter-cluster to the intra-cluster distances.

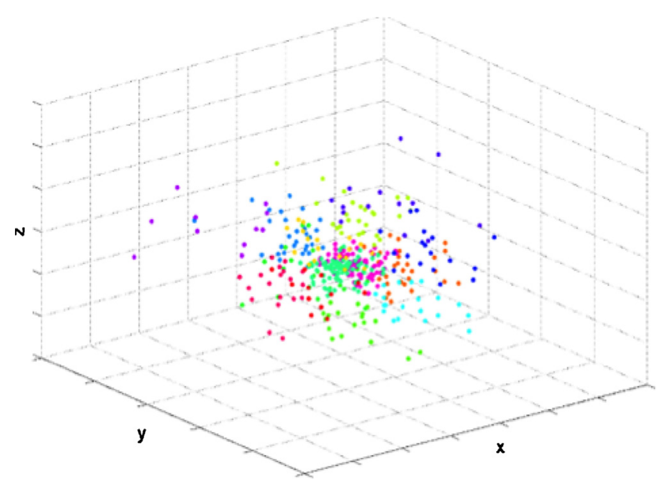

Fig. 3. Results of MDS and clustering of 400 model observations in three-dimensional space.

Coupled geomechanical-flow simulation was performed for one representative member of each cluster. These simulations solve the