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Optimal natural fracture realizations by minimizing least squared errors of distances from microseismic events

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ABSTRACT

Hydraulic fracturing plays a crucial role for economic production from unconventional resources. Especially development of shale gas resources is highly dependent on this evolving technology. Meanwhile, advanced logging tools, microseismic mapping and well testing analysis revealed the presence of abundant natural fractures and the complex induced fracture network in their presence. Natural fractures may open during fracturing treatments and change the direction of fracture growth. Despite the significance of natural fractures in formation evaluation, reservoir modeling, fracturing design and notable advances in numerical modeling of fractured reservoirs, these modeling require a description of natural fractures, which is often impossible to obtain from seismic. This paper proposes an innovative optimization technique to estimate the geometry of natural fractures based on geophysical data. A constrained mixed-integer nonlinear programming (MINLP) model is developed to compute and define possible optimal realizations of natural fractures from selected double-couple microseismic events, which will provide both geologist and reservoir engineers a robust tool for evaluating and modeling naturally fractured reservoirs. The objective of the MINLP problem was to minimize the total least squared errors of distance between microseismic events under different geodesic and technical design constraints. The performance and efficiency of the MINLP problem is tested through several instances. Computational results confirm to the expected numerical results obtained manually. An real example with field data is presented to show the model's computational capability.

1. Introduction

Hydraulic fracturing is an evolving technology that has been heavily contributing to the oil and gas production worldwide since its initial appearance in early last century (Hubbert and Willis, 1957). Massive hydraulic fracturing jobs have been conducted in the past two decades and significantly relieved the increasing energy needs worldwide (Montgomery and Smith, 2010). Meanwhile, through field observations such as core and outcrop studies and fluid flow behaviors, it has been revealed that most of the hydrocarbon resources are in naturally fractured formations, such as Marcellus Shale (Pommer et al., 2013) and Barnett Shale (Patel et al., 2013). More recently, Gale etal. (Gale et al., 2014) extensively studied the attributes of natural fractures from 18 shale formations, and reaffirmed the existence, abundance and importance of natural fractures to hydrocarbon production in low permeability reservoirs. The presence of natural fractures in hydrocarbon bearing reservoirs profoundly impacts the propagation of hydraulic fractures and the overall efficiency of fracturing treatment; thus, natural fractures are important considerations in reservoir development process such as formation evaluation, stimulation design and reservoir simulation. On one hand, open and de-bonded natural fractures may serve as highly permeable paths for oil and gas flow, which leads to additional reservoir productivity. On the other hand, however, hydraulic fractures' interaction with natural fractures form complex fracture network (Warpinski and Teufel, 1987) and complicates treatment design and stimulation results. Moreover, in low permeability formations, transmissibility between natural fractures becomes more significant, and fracture fluid flowing through natural fractures will experience extra leak-off, which results in lower fracturing efficiency. Additionally, diversion of fracturing fluid into natural fracture system impacts the bottomhole pressure (Bedayat and Dahi Taleghani, 2012), and the concurrent frac-fluid leakoff reduces the propped fracture width, which can result in early screenouts (Cipolla et al., 2010) and reduced stimulated reservoir volume (SRV). Overall, due to fracture interactions, induced fracture networks in fractured reservoirs are prone to develop in complicated patterns due to the diversion of the progressing hydraulic fracture into natural fractures and the reactivation of cemented natural fractures

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during treatment (Dahi Taleghani et al., 2018). Therefore, to realistically consider and model the natural fracture system in exploration and production of hydrocarbons, it is important to estimate the geometry and properties of natural fractures without any direct observation and knowledge of subsurface characteristics.

Geophysical data from microseismic mapping is useful in visualizing the propagation of hydraulic fractures and the growth of stimulated reservoir volume (SRV) during fracture treatment. Propagating hydraulic fractures crack the formation rock and generate mini–earthquakes with magnitudes below 3.0, also termed as microseismic events, which can be detected by sensitive seismic receivers (Vermylen and Zoback, 2011). In addition, interactions between hydraulic fractures and natural fractures also generate shear type microseismic events (ordouble couple microseismic events), which can be distinguished from those induced by propagating hydraulic fractures, or CLVD(compensated linear vector dipole) events. In other words, it would be assumed that large magnitude of shear events will occur at the intersection of hydraulic fractures with natural fractures. The optimization procedures in this research could define an equivalent natural fracture network that results in smaller overall distance squared between microseismic events and their adjacent fracture grids. Moreover, this technique could be enriched further by integrating data from other exploration and production processes, such as treatment history, production history and well testing results, to further define the best possible natural fracture configurations. By knowing the geometry of equivalent natural fracture system, processes such as formation evaluation, re-fracturing, reservoir simulation and production forecasting can all benefit from this optimization algorithm.

2. Background

Reservoir stimulation artificially generates fractures that connects the wellbore with the reservoir and facilitates the flow of hydrocarbons. One of the primary objectives of hydraulic fracturing is to maximize the stimulated reservoir volume (SRV) by connecting the wellbore with the existing natural fracture system. Typical size of natural fractures ranges from few millimeters (tiny fissures) to several thousand meters (faults), and they follow a continuous distribution pattern - their intensity (frequency of appearance) is inversely proportional to their apertures, which means "tiny fractures" are abundant and major fractures are rare. Although most of the natural fractures are cemented by precipitations due to diagenesis, propagating hydraulic fractures exert tensile stress on such natural fractures and reactivate them by de-bonding the cement. When a hydraulic fracture intersects a segment of natural fracture, the growing fracture may stop its propagation, continue propagation in its original direction, or divert into the natural fracture system (Dahi Taleghani et al., 2013).

The presence of abundant natural fractures in hydrocarbon formations has been well documented by core and outcrop analysis, wellbore imaging tools, and seismic mapping (Fig. 1). Fisher etal. (Fisher et al., 2004) studied the microseismic results from fracturing treatments in Fort Worth Basin, and observed clusters of microseismic events along the fracture path. Their analysis showed that propagating hydraulic fractures clearly interacted with natural fractures during their extension. Moreover, they observed that induced fracture network grew in a complicated pattern with major fracture growth in at least two orientations. Warpinski etal. (Warpinski et al., 2005) also analyzed the

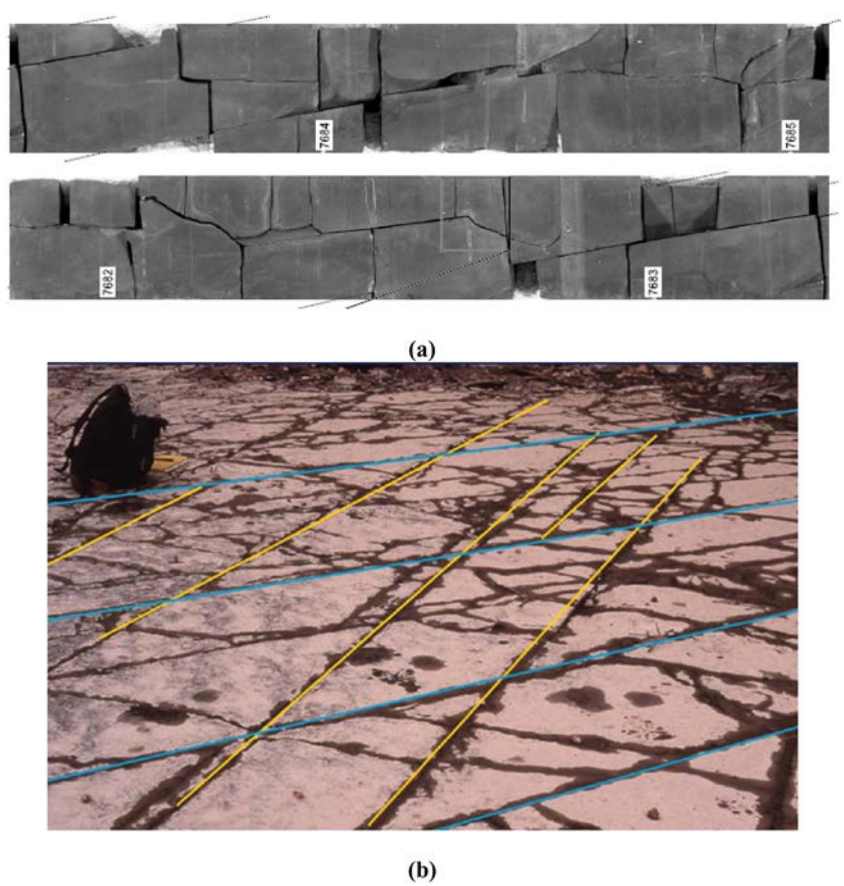

Fig. 1. (a) Core samples from Barnett Shale show sets of natural fractures. (Gale et al., 2007) (b) Outcrop of a shale formation showed natural fracture network intersecting at about 35 degree. (King, 2014).