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A new three dimensional approach to numerically model hydraulic fracturing process

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ABSTRACT

In this paper, a Three-dimensional Distinct Element Code (3DEC) was used and developed for simulating the initiation and propagation of hydraulically induced fractures in a typical reservoir hosted by a rock mass. Due to the fact that the modeling of the initiation of fracturing through intact rock within the Discrete Element Method (DEM) is not possible, a fictitious joint technique was introduced in order to simulate the process. The analysis results substantiate the previous understanding that the success of the hydraulic fracturing process not only depends on controllable parameters such as fracture fluid properties and injection rate, but also relies on the uncontrollable parameters such as ground in-situ stress regime, orientation of principal stresses, and in-situ rock mass properties. Moreover, a sensitivity study of input variables was carried out to examine the effect of different field conditions which involved the orientation and magnitude of principal stress components, fracture fluid properties, injection rate and rock parameters. Comparing the results with analytical solution indicated that the model provides a reasonable approximation for computing fluid injection pressure. Thus, the proposed modeling procedure can be employed in more complicated cases for further studies, such as interaction between induced hydraulic fractures and natural fractures.
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1. Introduction

Hydraulic Fracturing (HF) is a widely used method for enhancing oil exploitation in petroleum industry. In this method, some artificial cracks are induced within the reservoir by hydraulic pressure and the permeability of the reservoir is increased sequentially. The geometry of the induced fracture is dominated by the rock's mechanical properties, in-situ stresses, the rheological properties of the fracturing fluid, and local heterogeneities such as natural fractures and weak bedding planes (Dahi Taleghani, 2009). Although HF has been used for several decades, a thorough understanding of the interaction between induced hydraulic fractures and natural fractures is still lacking. Selection of an appropriate fracture propagation model is a crucial task in HF design.

In this study, the fracture growth process in a typical extended Leak-Off Test (XLOT) was investigated. An extended leak-off test is essentially a standard leak-off test where pumping continues long enough to ensure that a fracture is created (Fjaer et al., 2008). A validated DEM model for induced hydraulic fracture growth through intact rock was constructed in this paper. The effect of pre-existing fractures in hydraulic fracture growth is work in progress and will be the subject of further publications.

Therefore, initially, a compatible geometry was created and imported into the three-dimensional Distinct Element Code. The geometry consists of multi-dimensional polyhedral which are connected to one another to build the wellbore and the surrounding rocks. Each polyhedral is introduced as a block and the interfaces between the blocks are imported as to fictitious joints. The question arises as which deformation and strength parameter values should be assigned to fictitious joints so that they behave as intact rock. Based on the work by Kulatilake et al. (1993), in order to tackle the problem, an innovative method was proposed and was used in this study.

In the second stage, a representative 3D model of reservoir was constructed. By injecting the fluid into the wellbore, the hydraulically induced fractures were propagated throughout the host rock which was simulated by the fictive joints technique. In this technique, it is assumed that a rock fracture is created when the aperture of the fictitious joints exceeds the defined hydraulic aperture at zero normal stress.

Finally, the model results were validated and a sensitive analysis of critical input parameters was carried out. A preliminary set of results was published by Hamidi and Mortazavi (2012). The final results obtained from the analysis are presented in the following sections in a more comprehensive fashion.

2. Background

Different modeling approaches have been recently developed to simulate complex fracture networks in naturally fractured formations. These methods are briefly introduced below.

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Sousa et al. (1993) combined a FRacture ANalysis SYStem (FRANSYS), for three-dimensional structural modeling of arbitrary fractured solids, and a Boundary Element System (BES) with a HYdraulic Fracturing SYStem (HYFSYS) to solve the coupled fluid flow structural response. Zhang et al. (2007) incorporated fluid flow into this problem and solved the resultant coupled equations. Sesetty and Ghassemi (2012) presented a boundary element-based method for modeling the interaction of both single and double pre-existing natural fractures in different directions on hydraulic fractures.

The fracture network geometry depends on the shape of the elements. Very fine elements are needed to reduce the sensitivity of the results to the size and shape of the elements (Dahi Taleghani, 2009). Lecampion (2009) used the Extended Finite Element Methods (XFEM) to solve this problem. In this method, modeling was limited to fractures located along the element edges. Fracture propagation and coupling process were not addressed in this model. Dahi Taleghani (2009) tried to develop a model using the XFEM for analyzing the interaction between induced and natural fractures.

Kresse et al. (2011, 2013) used Finite Difference Method (FDM) based code, FLAC3D, to simulate simultaneous propagation of multiple fractures from a wellbore in a formation with pre-existing natural fractures.

All the models described above are based on continuous methods in which only limited joint elements can be considered for modeling the interaction between hydraulically induced fractures and natural ones. However, the rock masses contain several joints and natural fractures which influence the hydraulic fracture treatments. A numerical model must represent two types of mechanical behavior in a discontinuous system such as naturally fractured reservoirs: (1) the behavior of the discontinuities and (2) the behavior of solid materials (Nagel et al., 2011). First, the model must recognize the existence of contacts or interfaces between discrete bodies that comprise the rock system. Second, the mechanical behavior of the model must represent the behavior of solid material that constitutes the particles or blocks in the discontinuous system.

Recently, many studies have been conducted based on discontinuous approaches which are briefly discussed. De Pater and Beugelsdijk (2005) used DEM to handle multiple fracture propagation, but the fracture network geometry depends on the shape of the elements. Meyer and Bazan (2011) presented a Discrete Fracture Network (DFN) numerical simulator which is formulated for a pseudo-three-dimensional (P3D) hydraulically induced fracture system. Damjanac et al. (2010, 2013) superimposed a field-derived DFN on an intact rock particle model to create a Synthetic Rock Mass (SRM). They proved the concept of using DEM in a new three-dimensional numerical code (HF Simulator) for modeling HF in naturally fractured rock. Riahi and Damjanac (2013) carried out a series of two dimensional numerical analyses by a DEM based code, UDEC, to model fluid injection into the fractured rock mass. They found the interaction between HF and DFN. The shortcoming point of their study was that the trajectory of the fracture, which may affect the model results, should be defined explicitly in the model prior to simulations. Nasehi and Mortazavi (2013) employed a 2D DEM approach (UDEC) for simulating the fully coupled hydro-mechanical interaction between fluid flow and rock in a typical HF process.

3. Methodology

The Discrete Element Method (DEM) introduced by Cundall (1971) has become an effective numerical technique for general geomechanical problems. In this method, the rock mass assembly of rigid or deformable blocks is interfaced by a joint network. Joint behavior is prescribed for the interaction between distinct blocks. The deformation of each block is modeled by internal discretization of a finite number of elements. Considering the interaction of intact blocks and joints, DEM can effectively calculate the

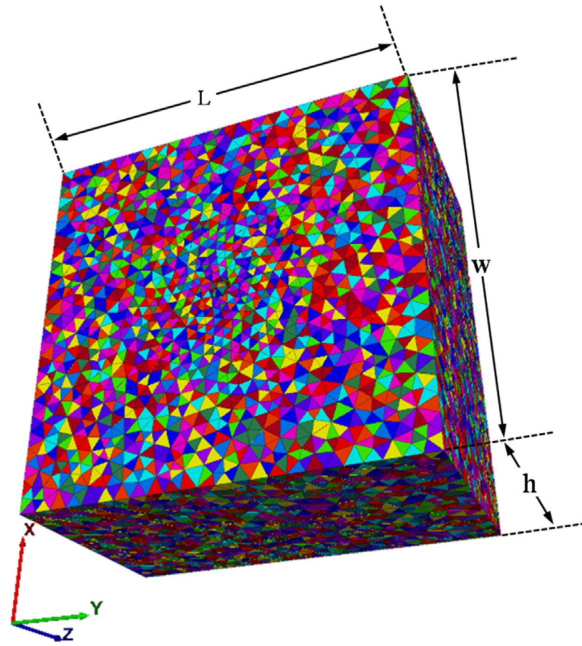

Fig. 1. A three dimensional view of the constructed 3DEC model.

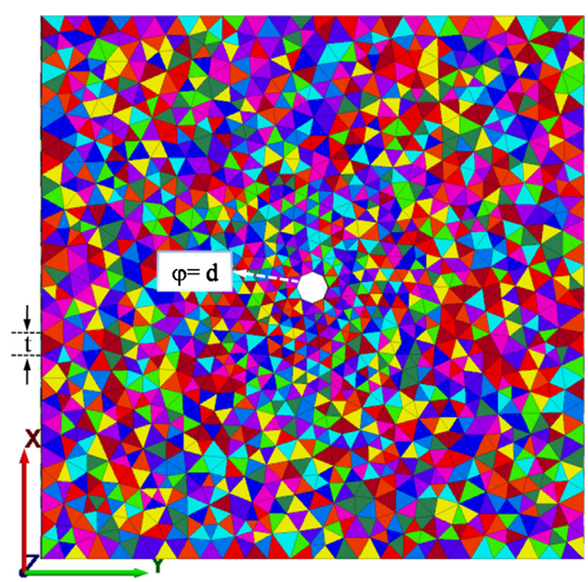

Fig. 2. A plan view of the constructed model.

Table 1
The geometrical specifications of the 3D model.

Geometry parameter	Value
Model length (L) and width (W)	5 m
Model height (h)	3 m
Largest dimension of polyhedral (t)	20 cm
Borehole diameter (d)	30 cm
Number of constitutive polyhedral	79,411

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