Computers and Geotechnics 69 (2015) 320–328

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Numerical investigation of the effect of preexisting discontinuities on hydraulic stimulation

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ARTICLE INFO

Article history:
Received 16 October 2014
Received in revised form 4 May 2015
Accepted 30 May 2015
Available online 20 June 2015

Keywords:
Discrete elements
Hydraulic stimulation
Spheropolyhedra
Discontinuities
Fracture orientation
Fracture spacing

ABSTRACT

The present work aims to investigate the effect of the orientation and spacing of preexisting planes of weakness (discontinuities) on the process of hydraulic stimulation. Structured assemblies of spheropolyhedra were created and a constant water inflow was applied at their center. The hydraulic pressure and the resulting fracture pattern were monitored during each simulation. Both showed a strong dependence on the geometry of the preexisting discontinuities and the orientation of the stress field. The dependence of the maximum hydraulic pressure in each simulation on the geometry of the preexisting discontinuities was found to be compatible with continuum considerations.

1. Introduction

The increasing demand for energy at the least possible environmental impact in the last years has led to an ever-increasing interest in geothermal energy world-wide. This kind of renewable, sustainable energy source has the advantage of continuous supply, as opposed for example to solar or wind energy. Though the energy present in the form of heat in the upper crust is abundant, geothermal power is not. This stems from the fact that the required combination of elevated temperature and relatively high permeability does not exist everywhere. Most areas with elevated temperature gradients are hot but have a relatively low permeability. In such cases hydraulic stimulation is used to increase permeability and thus reservoir productivity.

Though a lot of progress has been made in the direction of the simulation of hydraulic fracturing, the reservoir rock is usually viewed as a continuum without preferential directions as to the formation of the fractures [1–3]. The aim of the present work is to examine the problem of the hydraulic fracturing of a rock mass with pre-existing sets of discontinuities with given orientation and spacing. The schematic outline of the problem considered is exhibited in Fig. 1. In black are shown preexisting[1] discontinuities that remain closed. The fractures through which flow takes place are denoted in blue and red, for colder and hotter water respectively.

As already mentioned, the present work is concerned with the hydraulic fracturing of a rock mass with pre-existing sets of discontinuities with given orientation and spacing. Such formations are often found in rock mass joints and are a result of the preloading history of the formation. Two examples of unusually regular geometry are shown in Fig. 2. Fig. 2a shows nearly rectangular blocks with significantly larger width than their height, while in Fig. 2b rhombic blocks with a side ratio of about one are to be seen. Within the frame of this work discrete element simulations of hydraulic fracturing of relatively simple assemblies of polyhedra were performed. The aim of this rather simple procedure is to elucidate the basic mechanisms involved in the flow stimulation in fractured media. The presence of load implies that fractures and discontinuities are to remain closed in the absence of fluid pressure. In the presence of high enough fluid pressure on the other hand, it is expected that the flow will eventually settle into preferential paths offering the least resistance. The simplicity of the approach renders it easy to modify parameters of the problem one at a time, such as discontinuity orientations and polyhedra

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[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.

http://dx.doi.org/10.1016/j.compgeo.2015.05.013
0266-352X/

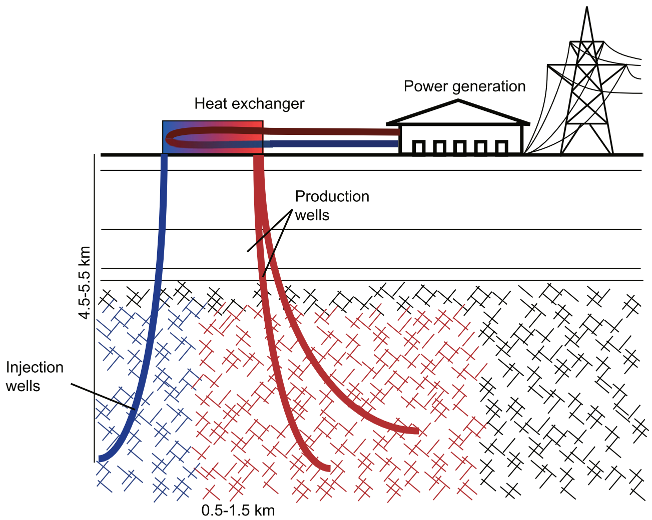

Fig. 1. Reservoir outline.

geometry, but does by no means allow for quantitative conclusions. It is however expected that the results will contribute to the insight into the governing mechanisms of the examined process and thus prove a valuable help in the effort for a physically based modeling.

The application of the Discrete Element Method to the problem of hydraulic fracturing is not new. In the majority of the available works, as for example in [6–8], disks or spheres are used in the simulations, though works with polygons are also available [9,10]. Of particular interest is the work by Hamidi and Mortazavi [11] who used a tetrahedral mesh and a highly compressible fracturing fluid to simulate the process. This work goes one step further by taking more general meshes and an fracturing fluid with a realistic compressibility. The cohesive bonds between the particles then break under the influence of the increase fluid pressure, to form fractures. Different geometries have been investigated with the above methodology. Eshiet et al. [6] considered rectangular specimens, consisting of disks, while Sousani et al. [8] considered hollow cylinder specimens consisting of spheres. Other numerical methodologies used to simulate the fracture evolution during hydraulic fracturing are extended Finite Element methods, such as Finite Elements incorporating discrete fractures and based on stress intensity factors for the fracture propagation [12], or the combined Finite-Discrete Element Method (FDEM) [13]. As the goal of the present work is to investigate the effect of the preexisting structure on the procedure of hydraulic fracturing or stimulation, polyhedra are used in our case. In many respects the present work is a continuation of the work of Galindo Torres and Muñoz-Castaño [14]. To the best knowledge of the authors, a study of structured assemblies in this context has not been performed before.

In the second section the numerical method used is described, while in the third the assumptions made are introduced. The results are presented and discussed in the fourth section, while in the fifth section conclusions are drawn.

2. Numerical method

The code used in the present work was based on MechSys [15]. Mechsys is an open source library which runs in linux systems, and therefore, unlike the popular ITASCA software is free and can run in supercomputing clusters. Furthermore, the Mechsys DEM module offers a more general collision law based on the spheropolyhedra method which works when the particles are bonded together and when they are not. It can also model non-convex shapes [16], particles obtained from Voronoi tessellations [17] and it has even been coupled, and extensively validated, with fluid dynamics simulation algorithms as shown in [18], or without as shown in [19].

A sphero-polyhedron is a polyhedron that has been eroded and then dilated by a sphere element as seen in Fig. 3. The result is a body with similar dimensions but with rounded corners. The most important advantage of the spheropolyhedra technique is that it allows a straight-forward definition of the contact laws between the particles, due to the resulting smoothing of the edges.

In the spheropolyhedra approach a particle is defined as a set of vertices, edges and faces, where each geometrical feature is dilated by a sphere. For simplicity let the set of all geometric features of a particle P_k be denoted by $\left\{\mathcal{G}_k^i\right\}$. This means that the distance between two geometric features of the particles (1) and (2) is the minimum distance of two points belonging to them:

$$\text{dist}\left(\mathcal{G}_1^i, \mathcal{G}_2^j\right) = \min\left(\text{dist}\left(\vec{X}_i^{(1)}, \vec{X}_j^{(2)}\right)\right) \quad (1)$$

where $\vec{X}_i^{(k)}$ is a vector belonging to the set $\mathcal{G}_k^i$. Assuming the minimum distance for the sets $\mathcal{G}_1$ and $\mathcal{G}_2$ to be given by the Euclidean distance between two of their points $\vec{X}_1$ and $\vec{X}_2$, the normal vector of the contact is defined as

$$\vec{n}(\mathcal{G}_1, \mathcal{G}_2) = \frac{\vec{X}_2 - \vec{X}_1}{\left\|\vec{X}_2 - \vec{X}_1\right\|} \quad (2)$$

(a) Orthogonal cross joints in a carbonate bed of the Monterey Formation, California, after Bai et. al. [4].

(b) Vertical aerial view showing joints in the flat-lying Cedar Mesa Sandstone, Utah, after Suppe [5].

Fig. 2. Jointed rock mass. (See above-mentioned references for further information.)