Simulation of artificial hydraulic fracturing of rocks in boreholes using a cell-devs approach

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Abstract

A simple model of hydraulic fracturing using the cell-devs paradigm is described and implemented. Despite the simplicity of the model it allows for the study of the 3D pattern of cracks produced by the increase of fluid pressure in boreholes. The main strength of the proposed methodology is that it is straightforward to include, test and study many subprocesses, that could have an impact on the development of cracks.

1 Introduction

Porosity and permeability are two of the primary factors that control the movement and storage of fluids in rocks layers. The exploitation of natural resources, such as groundwater, gas and petroleum or the capacity to store fluids (e.g. CO_2) in underground reservoirs, are both partly dependent on the properties of porosity and permeability.

Porosity is the ratio of the volume of openings (voids) to the total volume of material. Porosity represents the storage capacity of the geologic material. On the other hand, permeability is a measure of the ease with which fluids will flow though a porous rock. Although a rock may be highly porous, if the voids are not interconnected, then fluids within the closed, isolated pores cannot move. This situation is commonly found in nature and represents a challenge for the extraction or the injection in reservoirs.

One solution commonly used in practice to extract oil or gas from a low-permeability rock layer is to generate cracks in the rock in order to connect the pores and increase permeability. This process, called hydraulic fracturing, is initiated artificially by increasing the fluid pressure in a borehole with the purpose of generate tensile failure or splitting of the rock and, consequently, increase its permeability. This kind of fracturing process also happens in Nature forming geological structures in rocks called veins and dikes [4].

Hydraulic fracturing has been used in the petroleum industry to stimulate low-permeability reservoirs since the early fifties[1]. This often involves pumping large amounts of fluid, thus creating long fractures. A massive hydraulic fracturing job may exceed one thousand cubic meters of fluid. Then, before the applied pressure is completely released, a treatment of proppant (sand slurry, etc.) is inserted into the newly formed cracks to prevent them from completely closing . The treatment usually takes place on a time-scale of tens of minutes to a few hours, depending

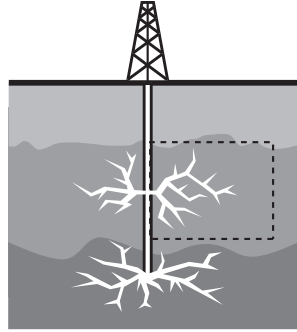This might be an interesting process to add to the model in a future work!

Figure 1: Illustration of the hydraulic fracturing process. Dotted box indicates the domain of the computational model.

upon the designed fracture size and volume of proppant to be placed. Fractures grow in a complicated manner, taking advantage of local heterogeneities, layering, and natural fracture networks in the reservoir citeadachi.

As this technique is widely used in practice, there is a large interest in understanding the hydraulic fracturing process, in order to predict where the new fractures will be located and what will be their length, width and shape.

Simulating hydraulic fracturing involves many different physics: a flow problem to model the injected fluid within the fracture to know the pressure exerted on walls of the fractures; the mechanical deformation of the solid rock walls (solid elastic problem); a fracture propagation problem to decide where and how the rock will fail and the fracture will be enlarged; usually voids remain in the fracture, (trapped air bubbles at the fracture tips) these bubbles represents a very compressible media that may alter the pressure that the fluid exerts on the fracture tip. The coupling of all these problems is an extremely challenging numerical problem, it is a active open field of research in which new techniques are required.

Many authors have studied the hydraulic fracturing process via numerical simulations; a historical background of the development of hydraulic fracturing models is provided by Adachi et. al [2]. First theoretical models were valid under plane stress [7], plane strain [6] or radial crack [5] assumptions. Variations of these models are still used today.

For example, Hunsweck and coauthors study via finite elements procedure the role of the gap between the fluid front and the crack tip in the crack propagation process [3].

coupling between the fluid pressure and the crack opening

Additional complications to the basic coupled problem described above, can be envisaged by taking into consideration, for example [2], layers of different rock types, changes of the magnitude and orientation of the confining stress, the leak-off off fluid from the fracture to the surrounding rock, the effects of shear and temperature on the fracturing fluid rheology, the transport of suspended proppant particles within the fracture, and modeling of fracture recession and closure.

In this work we propose a very simple model of hydraulic fracturing using the cell-devs paradigm. Despite its simplicity, our model has the potential to be easily extended to include the effect of any of the additional complications listed above and

many others (for example, the 3D structure of faults). In Section 2 a brief description of the modelling technique cell-devs and the framework CD++ is provided. Section 3 describes the proposed model and its implementations in CD++. Finally, in Sections 4 and 5, respectively, results are shown and conclusions are drawn.

2 Cell devs

3 Model

The hydraulic fracturing process is modelled here in a simple fashion. In order to do these simplifications, we consider the following idealized situation: a vertical borehole penetrates a stress field with isotropic horizontal stresses. The rock is assumed isotropic and homogeneous, obeying Hooke's law of linear elastic behaviour. We further assume an impermeable borehole wall, implying that the pore pressure in the formation remains constant and unaffected by the wellbore pressure.

The simulation domain, dotted rectangle shown in Figure 1, is divided using regular grid in cells. Each one of these cells represents a portion of space that can be either rock or fracture. The fluid is injected through one special cell located on the left wall and then it accommodates along the existing fractures. The fracture grow is not expected to reach the other boundaries of the domain.

The model behaviour can be divided into two parts. The first part is the flow model, it represents the distribution of fluid along the fractures. In this simplified model we only model the distribution of pressure in the fluid. All cells representing a fracture store the pressure variation of the fluid hosted on that cell on that moment (with respect to a reference pressure field). The pressure evolution of each cell is determined by averaging the pressure of its neighbours. With this simple updating rule the increase of pressure produced by the injection of water spreads along the fractures.

The second part of the model corresponds to the cells representing a solid rock. The key process at these cells is the failure forming a new fracture or extending a previous crack. Hydraulic fracturing takes place when the fluid pressure within the rock exceeds the smallest principal stress plus the tensile strength of the rock. Under the previous assumptions, the maximum supported pressure, $p_{\max}$, is

$$p_{\max} = 2\sigma - p_f + T_0$$

where σ is the smallest principal stress, p_f is the pore fluid pressure, and T_0 is the tensile strength of the rock. Every cell representing solid rock, will fail and become a crack if the pressure of some neighbour reaches its maximum supported pressure. When failure happen, the new crack is immediately filled, taking fluid from its neighbour. Each cell have its own material properties, namely its pore fluid pressure and its tensile strength. Those are computed as described in Table 3. Note that p_f and σ depend on depth, so they will different values as depth increases. In some simulations the tensile strength T_0 is varied randomly within the interval indicated at the Table.

simbol	description	units	value
ρ	rock density	kg m^{-3}	2200
T_0	rock tensile strength	Pa	$15 \pm 1 \times 10^6$
g	gravity acceleration	m s^{-2}	9.8
gP	pore fluid pressure gradient	Pa m^{-1}	10500
p_f	pore fluid pressure	Pa	depth(m)$\times gP$
σ	stress	Pa	depth(m)$\times g \times \rho$

Table 1: Properties

4 Results

5 Conclusions

References

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