Introduction

In the current paper, we study the problem of hydraulic fracturing in a naturally fractured saturated rock mass. It is clear that hydraulic fracturing is one of the most commonly used methods for improving oil recovery, so that lots of scientific papers are devoted to the problem of proper mathematic and physical description of hydraulic fracture propagation in different types of rock masses. In the current study, we mainly focus on naturally fractured reservoirs, where the hydraulic fracture propagation is considerably complicated by its interaction with natural fractures existing in the rock mass. This interaction is essential for understanding as one of the main goals of hydraulic fracturing when dealing with such reservoirs characterized by low matrix permeability is the creation of a complex network of fluid conductive fractures. So, there are several important problems to solve when dealing with hydraulic fractures in naturally fractured rock masses: we need to understand the interaction between fractures to estimate the geometrical properties of created network and find a way to evaluate fluid conductivity of natural and induced fractures in the rock mass after fracking.

Usage of discrete fracture network models is one of the most commonly used methods for solving the mentioned problems. The general workflow was formulated by Weng et al., 2014 and Zhang et al., 2017, while the overview of various modifications of such workflows was given by Lecampion et al., 2018. According to the general workflow, hydraulic fracture propagation is modeled numerically in a rock mass containing distinct natural fractures. Mechanical interaction between all the fractures is modeled using different techniques, including calculation of stresses acting near the tips of each fracture. These stresses are used to determine geometrical properties of all the analyzed fractures including their shapes at each moment of time. Fluid flow is also analyzed in each fracture. As a result, one can obtain the total flow pattern in the fracture network and adjust hydraulic fractures to optimize oil recovery. Different methods for mathematical description of fracture patterns exist: some methods are mostly based on considering each fracture in particular (Yan et al., 2016), while other methods deal with effective properties of fracture pattern — such values as fracture porosity and connectivity, averaged for the considered volume (Zhou et al., 2011). In the current study, we basically use the second approach for the description of fracture network created after hydraulic fracture: instead of using a discrete fracture network model to study hydraulic fracture propagation, we consider a rock mass as an effective medium with inclusions. We try to predict which fractures will be involved into the fracture network after hydraulic fracturing operation. We generally consider the behavior of pre-existing fractures in terms of rock deformation: their propagation is related to the accumulation of inelastic strain in the rock mass. So the main problem considered in the current paper may be formulated as follows: prediction of positions and spatial orientations of natural shear fractures involved in hydrodynamically connected fracture network during the hydraulic fracturing process.

Methods

In order to solve the stated problem, we use the critically stressed fractures concept. It was initially proposed by Barton et al., 1995 to predict whether natural shear fractures tend to be hydraulically conductive or not based on the actual stress state of the rock mass. According to this concept, any shear fracture tends to be hydraulically conductive if the following relationship takes place: \( \tau_n \geq \mu \tau_n \), where \( \tau_n \) and \( \sigma_n \) are shear and normal stresses acting on the fracture’s plane respectively, \( \mu \) is internal friction coefficient. It is clear that in order to check this condition for a particular fracture one needs to know both the stress tensor acting in vicinity of this fracture and the spatial orientation of the fracture itself, meaning that there are nine independent parameters in total (ten if internal friction coefficient is taken into account). Keeping in mind the concept of critically stressed fractures being also hydraulically conductive one may expect that knowledge of fracture spatial orientation and stress state in the fracture’s vicinity makes it possible to predict if the fracture tends to be hydraulically conductive.

Dubinya, 2019 proposed an analytical solution to the problem of critically stressed fractures’ spatial orientation prediction: it was shown that there exists an analytical solution for spatial orientations of all fractures, which will be critically stressed for a given arbitrary stress tensor. An example of such
solution is shown in Figure 1: Figure 1(a) gives the boundaries of possible angles between normal vectors to critically stressed fractures’ planes and principal axes of given stress tensor; Figure 1(b) shows a stereonet with limitations on critically stressed fractures’ spatial orientations alongside with directions of principal stresses (lower hemisphere Lambert equal area stereonet is used for representation here). The following coordinate system will be used throughout this paper: the first axis is aimed vertically; the second axis is directed towards East, and the third one is directed towards South. Blue line in Figure 1 serves as a boundary for the area of all possible spatial orientations of critically stressed fractures. In this example, the areas of critically stressed fractures are highlighted in semi-transparent blue. σ1, σ2, and σ3 are three principal stresses for the considered stress tensor σij. Their directions are obtained after finding the eigenvectors of the given tensor. It should be mentioned that the linear relationship between shear and normal stresses used in the condition for critically stressed fractures makes it possible to normalize stress tensor and obtain the same result for critically stressed-fractures’ spatial orientations. All stress tensor components will be normalized by the lowest stress in the global coordinate system (by the magnitude of σ12 = σ21 = σ23 = σ32 in the current example).

Figure 1

An example for critically stressed fractures stereonet for the given stress tensor

This solution makes it possible to obtain spatial orientations of critically stressed (and hydraulically conductive) fractures for any problem, which includes calculation of stress state of a fractured rock mass. For example, in the previous work, it was used to understand the general patterns in critically stressed fractures’ spatial orientations in the vicinity of major faults (Dubinya, 2019). In the current study, we will use it to solve the problem of critically stressed fractures in vicinity of a hydraulic fracture.

In the current study, we used a numerical model of hydraulic fracture propagation in a naturally fractured rock mass. We utilized the extended finite-element method (XFEM) to calculate a hydraulic fracture’s trajectory and aperture at each time step during its growth. Two-dimensional problem was considered, its scheme is shown in Figure 2: rock mass is subjected to two principal stresses σ1 and σ2, the well of radius r is located in the middle of the considered domain and the hydraulic fracture is initiated due to fluid injection into the well under the given pressure.

Numerical modeling of fracture growth in a plastic medium was carried out in the finite-element simulator of SIMULIA (Abaqus Student Edition 2018). The calculation area is a square with a round hole in the center. The length of the side of the square is 16 m, the radius of the hole is 0.4 m. Loads are applied to the opposite sides of the square. Along the X-axis (east direction), there is minimum stress of 10 MPa, along the Y-axis (north direction) the maximum (25 MPa). A load of 80 MPa is applied to the hole. The lower-left corner of the calculation area is fixed. The Drucker-Prager model is used as the plasticity condition. Therefore, the calculation requires the following physical parameters: Young's modulus ($E = 14.6\text{GPa}$), Poisson's ratio ($\nu = 0.4$), internal friction angle ($\phi = 46^\circ$), dilatancy angle ($\psi = 46^\circ$), flow stress rate ($r_s = 1$), the dependence of stress on plastic deformations. To simulate fracture growth, criteria for its formation and development were set. The criterion for
maximum strains \( \epsilon_f = 0.0009 \) was used as a criterion for fracture formation, and the critical displacement \( u_f = 0.0001 \) was specified as a criterion for further growth. The simulation result indicating all geometric dimensions and boundary conditions is presented in Figure 2. Here, the color indicates the probability of a fracture.

**Figure 2** General scheme of considered problem

We studied several cases with varied boundary conditions (injection pressure and principal far-field stresses), rock mass properties (elastic moduli, friction coefficient, and plastic flow law) to understand the spatial orientations of critically stressed fractures and their positions relative to hydraulic fracture in each case. The same stereonets as the one shown in Figure 1 were constructed at each point highlighted in Figure 2 at different time steps to analyze the dynamics of the fracture network. The results obtained for several cases are presented in the following section.

**Results**

Figure 3 represents the stereonets with critically stressed fractures’ spatial orientations constructed for the following case: points 1 and 2 shown in Figure 2 were considered at three different time steps, generally corresponding to different stages of fracture propagation. In Figure 3, the possible spatial orientations of critically stressed fractures are still shown using the blue lines, which serve as the boundary of these orientations. Light blue line is roughly related to the moment when fracture propagates until \( \frac{1}{4} \) of its final length; blue line is related to the moment of time when fracture has a half of its final length; dark blue line corresponds to the final stress state after hydraulic fracture finishes propagating. Principal stresses’ directions are also shown corresponding to this final step. Figure 3(a) is related to point 1 shown in Figure 2 (relatively close to hydraulic fracture), and Figure 3(b) is related to point 2 of Figure 2 (at a considerable distance from the fracture).

**Figure 3** Evolution of stereonets for critically stressed fractures’ orientations during hydraulic fracture propagation
It can be clearly seen that spatial orientations of critically stressed fractures evolve during the process of hydraulic fracture propagation; moreover, their evolution is strongly dependent on distance to the hydraulic fracture itself. Figure 3(a) represents the behavior of critically stressed fractures not far from the hydraulic fracture, so there are many possible orientations of critically stressed fractures. It is especially interesting to mention that there is a pretty little area for spatial orientations of fractures, which are critically stressed during the initial steps of hydraulic fracture propagation, but they become not critically stressed after hydraulic fracture propagates far enough. Figure 3(b) shows that the initial differential stresses are low enough for no critically stressed fractures existence before hydraulic fracture starts influencing the local stress field – there is no light blue on the stereonet meaning there are no critically stressed fractures. As long as hydraulic fracture continues propagating, the stresses acting in the vicinity of point 2 are being gradually changed, which leads to the emergence of critically stressed fractures with limited spatial orientations. As it was mentioned above, the boundary conditions provided principal stresses’ directions to be oriented along with North and East directions. Despite that fact, it should be mentioned that shear stresses induced by hydraulic fracture provide local reorientations of principal stresses’ directions and, consequently, on preferred spatial orientations of critically stressed (and hydraulically conductive) natural fractures.

Conclusions

The obtained results demonstrate the possibility to use critically stressed fractures approach to predict the general tendencies in critically stressed fractures’ spatial orientations after hydraulic fracturing a naturally fractured reservoir. Although the proposed method suffers from a number of limitations (starting from lack of usage of discrete fracture network model and consideration of mechanical interaction between natural fractures and hydraulic fracture), it allows getting some simple estimations. Moreover, there are some cases when there is no discrete fracture model in presence, so the proposed modelling may give the general understanding of preferred shear critically stressed fractures’ spatial orientations and, subsequently, preferred flow direction through the network of activated natural fractures. The proposed solution for critically stressed fractures’ orientations for a given stress tensor is analytical, so it does not make geomechanical modeling any more complicated.

References


