FDEM modelling of hydraulic fracturing in jointed rocks

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ABSTRACT: Hydraulic fracturing has been widely used in tight reservoirs to generate fractures to improve conductivity and productivity. However, presence of discontinuities such as joints, faults, bedding, and cementations, the complex interaction between the HFs and theses geological features influences the efficiency of an injection treatment. Considering the mechanical differences between natural fractures (NFs) and rock matrix, the type of interaction varies and demands a detailed study to explore such behaviour, specifically for the filled joints. In this study, the combined finite-discrete element method (FDEM) is used to investigate the influence of the pre-existing joints and their filling material on hydraulic fracture (HF) propagation. The coupled hydromechanical model is used to allow for the fluid flow through the rock mass. Models with some filled joints are built and HF propagation is modelled to investigate the interaction type. The results reveal strong influence of the fillings on the HF interaction and propagation.

Keywords: FDEM, Hydraulic fracture, Filled joints, Interaction.

1 INTRODUCTION

Many factors affect the performance and efficiency of hydraulic fracturing, including but not limited to the magnitude of in-situ stresses, discontinuities, fluid properties, and rock mass properties. For example, Warpinski and Teufel (1987) conducted laboratory-scale experiments to investigate the effects of natural discontinuities on HF propagation and developed some equations to assess the influence of ancillary parameters. Their results showed that the in-situ stresses, frictional characteristics, joint orientation, fluid pressure, and viscosity were the main controlling factors of the discontinuities behavior. Among these controlling factors, discontinuities such as joint, flaw, fault, bedding, and shear zones play a crucial role in controlling the pattern and efficiency of hydraulic fracturing. Over the last decades, many efforts have been devoted to studying the influence of such sources of inhomogeneity in HF development. Discontinuities impose some problems while the fluid injection is carried out such as lost circulation during drilling, which is believed to be directly related to the induced fracture and their interaction with the natural discontinuities (Savari et al. 2016). Furthermore, it has been widely studied and demonstrated that the resulting complexity of the stimulated network of HFs is because of the complicated interaction between the induced and natural fracture (Liu et al. 2022, Sun et al. 2022, Zhang et al. 2022, Yao et al. 2020, Zheng et al. 2020, Rueda et al. 2020). Moreover, the interaction between the natural and stimulated HFs increases the contact area with the reservoir, resulting in increased drainage paths for fluid flow and cause improved productivity. On the other side, the activated natural fractures (NF) can divert fluid from the primary HFs or decrease their width, which in turn causes proppant bridging (Rueda et al. 2020). As a result, premature proppant transport blockage can occur, failing a hydraulic fracturing treatment and forming a screen out (Potluri et al. 2005). On the other side, the interaction between the natural and induced fractures can improve and enhance the reservoir permeability and generate favorable channels for oil, gas, and fluid seepage paths.

Although the experimental studies can help to understand the mechanism of the interaction between the natural and induced HFs (Zhuang et al. 2022), they cannot consider all the controlling factors and complex situations at once. The scale, real geometry, complex geometry, various fluid pressure, fluid properties, discontinuities characteristics, and in situ stresses are among critical parameters that are difficult to mimic in an experiment. Numerical simulations have become popular and extensively used to model HF and their interaction with real NFs to overcome these difficulties. The continuum and discontinuum methods have been used, each with different capabilities and weaknesses. The common grouping used for numerical methods classification is the discrete element method (DEM), displacement discontinuity method (DDM) and finite element method (FEM). DEM is used to model the conditions in which discontinuities present in a rock mass and fracture can interact with such geological features. This method has been widely used to simulate the interaction of NFs with HFs (Zhang et al. 2022, Sun et al. 2021, Huang et al. 2019, Chong et al. 2017, Chen et al. 2018). The extended finite element method (XFEM) was also proposed to deal with fracture propagation in the content of the FEM. This method has also been used to study the interaction of natural and induced HFs (Luo et al. 2022, Zheng et al. 2020, Cheng et al. 2019, Ghaderi et al. 2018). There are some limitations associated with the conventional numerical methods, such as increasing computing costs for search, diagnosis, and updating among particles, representation of both the continuity and discontinuity characteristics of heterogeneous rocks, considering the intersection and bifurcation behavior of fractures, well representation of realistic fracture paths, and calibration of microscopic parameters (Wu et al. 2022, Lin et al. 2022). To overcome these limitations, the combined finite-discrete element method (FDEM) was proposed by Munjiza et al. (1995), which inherits and combines the advantages of both FEM and DEM. The FDEM can track fracture initiation and propagation by considering nonlinear elastic fracture mechanics. The FDEM has been extensively used in rock engineering in various applications and employed to model HF development in complex ground conditions. Wu et al. (2022a) studied the influence of slip and permeability of beddings on hydraulic fracturing using FDEM. Lin et al. (2022) employed the FDEM to simulate HF propagation in rocks with irregular inclusions. Wu et al. (2022b) studied the effect of rock heterogeneity on hydraulic fracturing by using the FDEM. Zheng et al. (2020) investigated the HF propagation under the influence of in-situ stress, and operating parameters on the stratum interface based on the FDEM method. Also, Liu et al. (2020) used hybrid phase-field modeling to study HF development in layered rocks. This study aims to investigate the influence of the filling material on the HF propagation in deep reservoirs by using coupled hydromechanical FDEM. Models with the filled joints are simulated and the interaction between the HFs and the filled joints under the various influencing factors are studied.

2 SIMULATION MEHDOLOGY

In this study, Irazu2D V5.1.0 (Geomechanica Inc. 2022) is used which is an FDEM software capable of fully modeling hydromechanical simulations. Fluid flow is assumed to occur through a network formed from triangle meshes used for mechanical calculations. The models have dimensions of 5m×5m, and two meshing regions are used. A mesh refinement zone is introduced within the large default model around the filled fracture with a mesh size of 0.015 m and the outer surface is meshed gradually to 1m with a transition speed of 1. This mesh arrangement introduces a fine mesh size inside the mesh refinement around the pre-existing fracture, increasing analysis precision. This study considers an isotropic in-situ stress state with the maximum and minimum principal stresses fixed at 5 MPa for the basic models. To simplify the analysis, the fluid injection borehole is modelled by an injection point in a grid which decreases the calculation time and has little influence on the propagation of HFs. This is because a small borehole in a large modeling area produces minimal stress distribution, and no significant effect is imposed on the surrounding media. The simulations begin with a mechanical analysis, enabling in-situ stress distribution inside the models under the defined stress regime. Once the in-situ stresses are fully distributed and in equilibrium, fluid is injected into the injection grid. After this time, the HM analysis is enabled and fluid can flow into the media with a constant flow rate condition of 0.001 m^3/s. The mechanical properties of the rock mass, fluid and filling are: density 2400 kg/m^3, Young's modulus 50 GPa, Poisson's ratio 0.24, Cohesion 15 MPa, tensile strength 8 MPa; Fluid density 1000 kg/m^3, Kinetic viscosity 1e-6 m2/s, Fluid bulk modulus 0.05 GPa; filling density 1800 kg/m^3, Young's modulus 2 GPa, Poisson's ratio 0.21, Cohesion 3.42 MPa, tensile strength 1.85 MPa. The rock mass and fillings are permeable with a permeability of 1e-16 m^2 and 2e-15 m^2, respectively, and fluid can flow through fractures. The joint with a thickness of 5 cm is filled with a soft material. Also, the fillings are set permeable with a permeability of 3e-15 m^2.

3 RESULTS AND DISCUSSIONS

Figure 1 illustrates the HF interaction with the 30° filled joint. Under the low flow rate in Figure 1a, a few fractures develop inside the filling, and an offset crossing occurs. Increasing the flow rate to 0.002 and 0.003 m3/s leads to excessive HF propagation inside the filling material and causes more offset fracturing and interface breakage between the filling and the host rock. Similar behavior is observed under various fluid kinematic viscosities in Figure 1b. Once the magnitude of difference in in-situ stresses increases (Figure 1c), under 5 MPa stress difference, a few filling branching occurs, and an offset HF crosses the filling. However, the high difference in in-situ stress (10 MPa) causes more filling branching, activation, and dilation of the upper segment of the filling and interface breakage due to the help of stresses directing the fluid to flow into the filling.

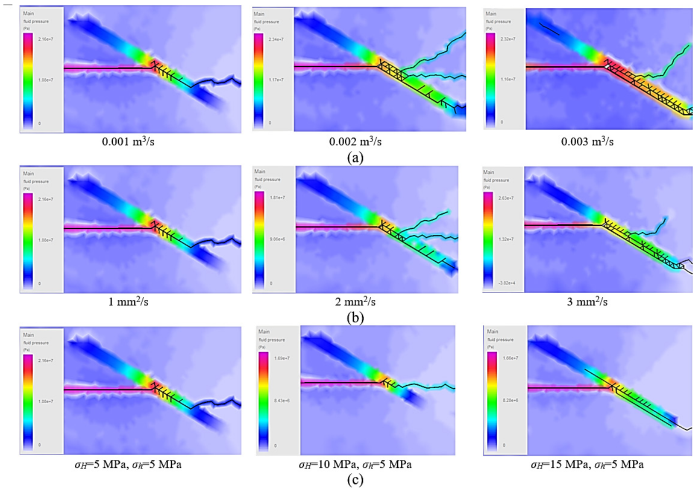


Figure 1. HF propagation pattern (represented by contours of fluid pressure) for a 30° filled joint under different (a) flow rates, (b) fluid kinematic viscosities, and (c) in-situ stresses.

The interaction of the HF with a 60° filled joint is shown in Figure 2. Under the low flow rate of 0.001 m3/s shown in Figure 2a, the lower segment experiences moderate filling branching and development of multiple offset crossing HF from the right side of the filling in addition to some interface breakage. Under the higher flow rates, the filling shows excessive branching close to the fluid penetration point, interface breakage, and frequent offset crossing. It is observed that the interaction is different when the stresses are under anisotropic conditions, as shown in Figure 2c. It can be seen that the higher the difference between the magnitude of the in-situ stresses is, the higher the number of offset crossing HF is, and the lower interface breakage occurs. Because the high-stress anisotropy makes it consistent for the fluid flow and creates a better fluid path in the horizontal direction.

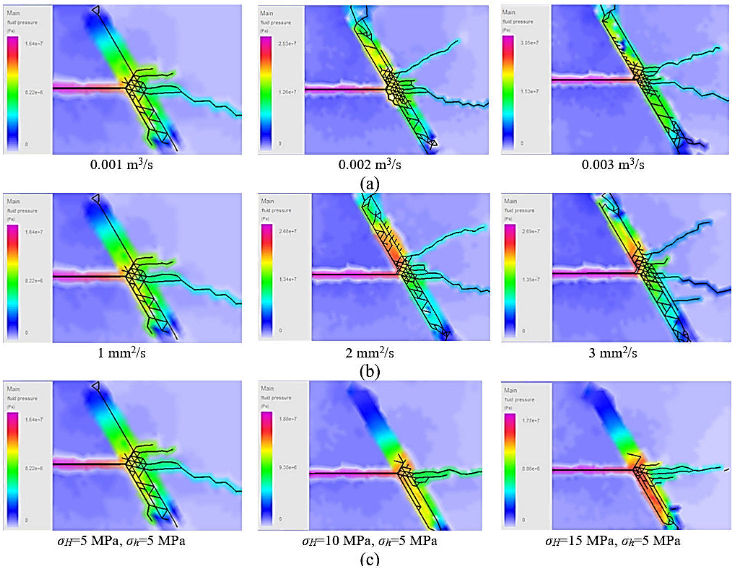
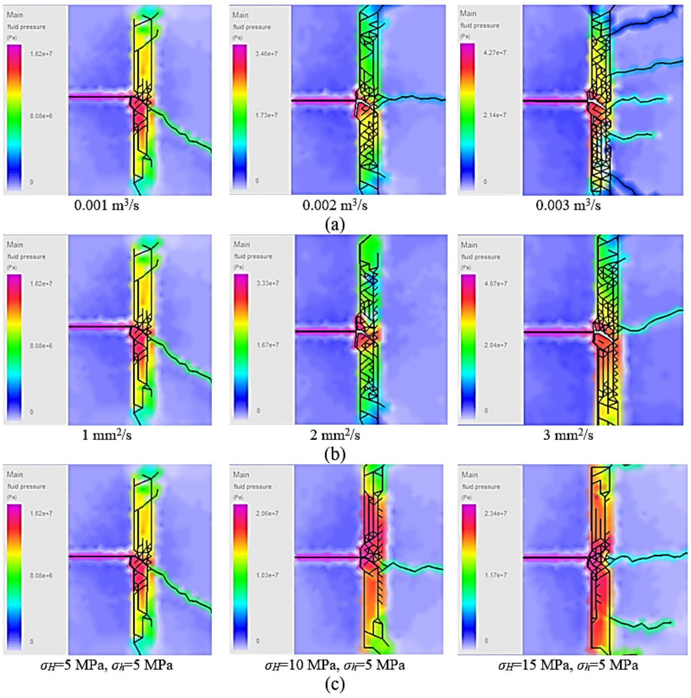


Figure 2. HF propagation pattern (represented by contours of fluid pressure) for a 60° filled joint under different (a) flow rates, (b) fluid kinematic viscosities, and (c) in-situ stresses.

The 90° filled flaw in Figure 3 exhibits similar interaction behavior under different situations. Three fracturing stages occur when the flow rate, fluid kinematic viscosity, and difference in the in-situ stresses increase. First, the filling undergoes excessive branching by the fluid penetration; second, the entire interface of the filling and the host rock are penetrated by the fluid, and HF develops; and third, the number of offset crossing HF increases. Based on the observation of the interactions between the HF and the fillings, the 90° filling is observed to be more fractured because the high orientation angle of the filling is against the favourable direction of HF in the horizontal direction, and thus, the fluid tends to suppress inside the filling, resulting more fluid pressure rise, and thus further fracturing occurs. Figure 4 shows the failure type (tensile or shear) of all models discussed earlier for Figures 1, 2, and 3. For the 30° orientated filled joint shown in Figure 4a, tensile fracturing is the dominant failure type (either inside the filling material or in the interface), and a few shear fractures develop when the flow rate or fluid kinematic viscosity increases. For the models with the 60° filled joint in Figure 4b, it is observed that tensile failure governs the failure type at the left side of the joint while shear failure dominates the right side. It is also observed that shear failure contributes more to failure when the flow rate or fluid viscosity increases. In contrast, tensile failure remains the governing type under high anisotropic in-situ stress. The observations also confirm that all the offset crossing HF are in tensile mode. The 90° filled joint shown in Figure 4c also shows a similar trend in the failure type to the 60° joint. The difference between the failure types of these joints is that shear cracks develop in the entire right side interfaces for the 90° joint under high anisotropic in-situ stresses and contribute more to HF development than tensile failure.

4 CONCLUSION

The combined finite-discrete element method (FDEM) is used to study HF propagation in deep reservoirs containing joints filled with a soft material. °. It was found that the approach angle had a significant influence on the interaction mechanism, and the interaction type converted from activation (dilation) to crossing. In the case of a single filled joint inclined at 30°,60°, and 90°, it was observed that the injecting fluid diffused and broke the filling in the bottom segment when the approach angle was low. In contrast, the entire length of the filling experienced breakage and fluid penetration under higher approach angles. Moreover, the higher the approach angle was, the more shear failure was observed. The results suggest that a thorough investigation will be required for a successful HF treatment in deep reservoirs containing filled joints.



0.001 m^3/s 0.002 m^3/s 0.003 m^3/s

(a)

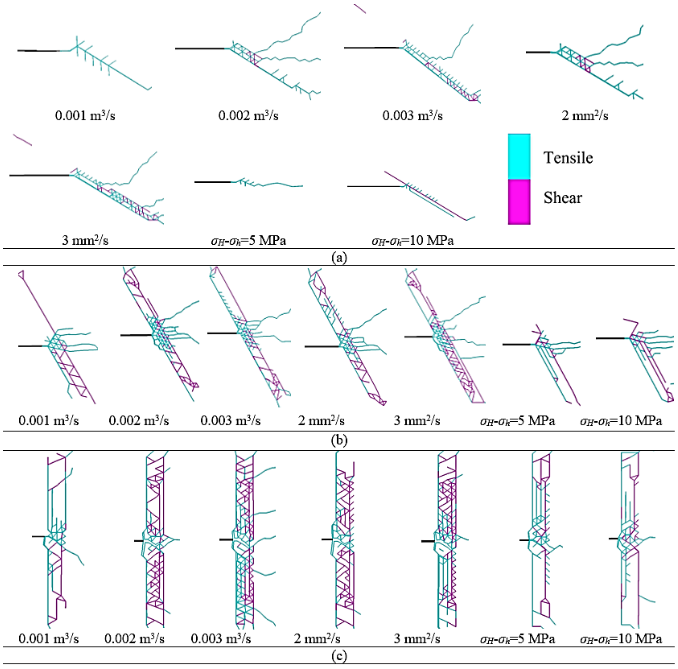
1 mm^2/s 2 mm^2/s 3 mm^2/s

(b)

σ_H=5 MPa, σ_h=5 MPa σ_H=10 MPa, σ_h=5 MPa σ_H=15 MPa, σ_h=5 MPa

(c)

Figure 3. HF propagation pattern (represented by contours of fluid pressure) for a 90° filled joint under different (a) flow rates, (b) fluid kinematic viscosities, and (c) in-situ stresses.



0.001 m^3/s 0.002 m^3/s 0.003 m^3/s 2 mm^2/s

3 mm^2/s σ_H-σ_h=5 MPa σ_H-σ_h=10 MPa

(a)

0.001 m^3/s 0.002 m^3/s 0.003 m^3/s 2 mm^2/s 3 mm^2/s σ_H-σ_h=5 MPa σ_H-σ_h=10 MPa

(b)

0.001 m^3/s 0.002 m^3/s 0.003 m^3/s 2 mm^2/s 3 mm^2/s σ_H-σ_h=5 MPa σ_H-σ_h=10 MPa

(c)

Figure 4. Failure type of the models under different controlling factors with a filled joint inclined at (a) 30°, (b) 60°, and (c) 90°.

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