Hydraulic Fracturing in Layered Media

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Introduction

Hydraulic fracturing has been proven as an efficient method to improve recovery from unconventional reservoirs as well as a potential method for improving the sweep in the North Sea chalk reservoirs. While the majority of the published research focus on a single (or multiple) fracture(s) in a homogenous, single layer rock, it is evident that the real reservoirs are consisted of multiple, soft and stiff layers, which makes the hydraulic fracturing process more complex. When a hydraulic fracture hits a layer interface, it can be arrested at the interface, or the new layer can act as a favourable medium for the fracture to grow. If the layers have different mechanical properties, a stress jump is developed across the interfaces that can affect the growth direction and the size of hydraulic fractures. Furthermore, as the hydraulic fractures are commonly induced under toughness regime, the fracture toughness of each layer plays an important role, and soft, more ductile layers are expected to have higher resistance against fracturing. In this study, hydraulic fracturing process in a three-layer system is investigated using a robust finite element code. Both penny-shaped and plane-strain (KGD) fractures are considered, and the results are compared. A sensitivity analysis on the parameters of the middle layer (Young’s modulus, fracture toughness and layer thickness) is performed to see whether a soft layer can prevent hydraulic fractures from growing upward. The effect of gravity is also included and the results are presented. The outcomes of this research can be utilised in designing the hydraulic fractures in the chalk reservoirs in the Danish North Sea.

Method

The model developed by Salimzadeh et al (2017a,b) on Complex Systems Modelling Platform (CSMP++) has been utilized in this study. The fractures are represented as discontinuous surfaces in a three-dimensional domain. Using Galerkin finite element method, quadratic triangles and tetrahedra are used to discretise the surfaces and volumes in space, respectively. The fluid flow inside the fracture is modelled based on the lubrication theory. The aperture is given by the differential displacement between two sides of the fracture. The stress intensity factors are computed by computing the energy-based interaction integral (Yau et al., 1980) over a set of virtual disk domains distributed along the fracture tip (Nejati *et al.*, 2015).

Results

A three-layer system is considered in which the middle layer is assumed to be softer than the other two layers. Plane-strain condition is assumed such that a KGD hydraulic fracture is induced from the well as shown in Fig. 1a. The injection well is located 10 meters below the middle layer, and injection is performed with a constant rate of 0.001 m^2/s. The middle layer has a thickness of 5, 10 or 20 meters and a Young's modulus of 5, 10 and 15 GPa, while the other two layers have a constant Young's modulus of a 20 GPa. The critical stress intensity factor, or fracture toughness, was set to 2 $MPa.m^{0.5}$ for the middle layer and 1 $MPa.m^{0.5}$ for the surrounding layers.

As shown in Fig. 1b, for single-layer system, the gravity stops the fracture from growing downward, but when there is a softer layer above the pay layer, the stress concentration at the interface competes against the gravity and manages to prevent the upward growth. The magnitude of the stress concentration depends on the Young’s modulus and the thickness of the soft layer. Lower thickness or lower Young’s modulus contrast reduces the stress jump so the hydraulic fracture may grow upward as in the case for E = 15 GPa as shown in Fig. 1b. In a KGD fracture, if the fracture is arrested at the top, the fracture has to continue downwards. But this may not be the case in real reservoirs. Therefore, a radial fracture is being modelled in the same system to study the shape of the fracture.

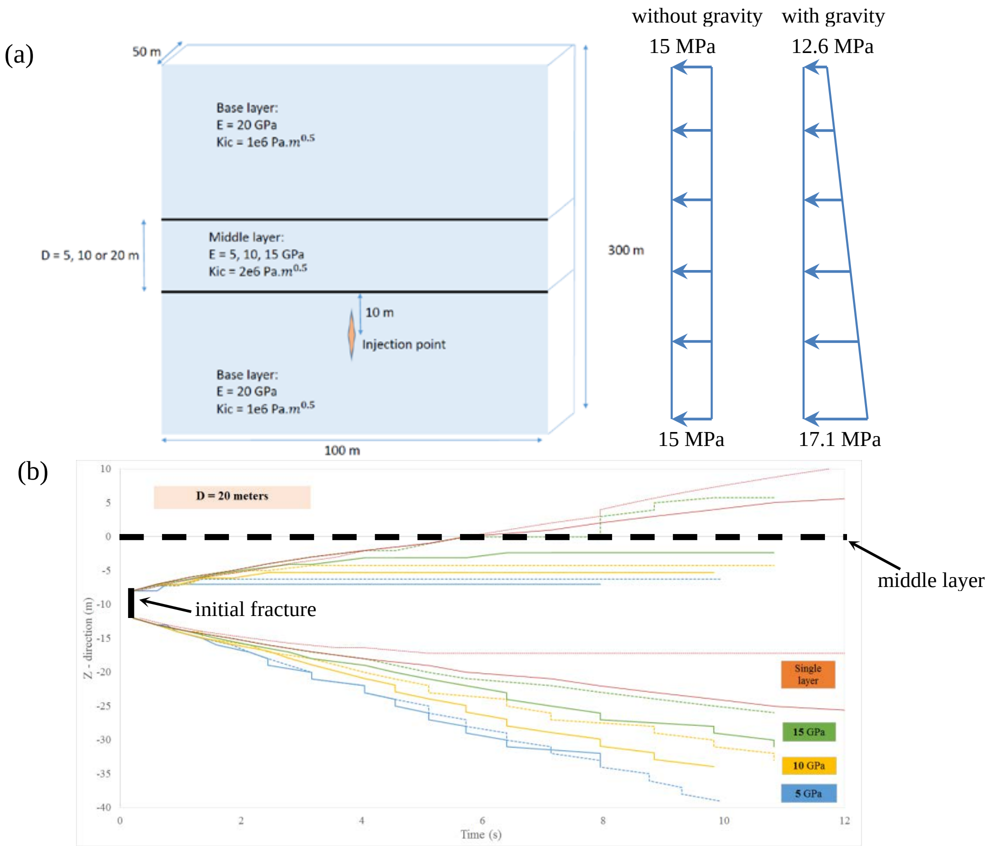

Fig. 1: (a) The three-layer model used in simulations, (b) The fracture front (top and bottom) for different stiffness of the middle layer. Dashed lines show the cases with gravity effects.

Conclusions

A finite-element model is utilised to study the upward growth of a hydraulic fracture towards a softer layer above the pay layer. The soft layer has different properties (lower Young's modulus and higher fracture toughness) than the two surrounding layers. The gravity was also included to see the effect. Results suggest that the existence of a soft layer above the reservoir layer may prevent propagation of hydraulic fracture under specific conditions. The fracture's upward growth is seemed to be controlled by the value of the mechanical properties and the thickness of the layer. However, the gravity tends to push the fracture to grow upward.

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