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Numerical investigation of hydraulic fracture propagation in a layered reservoir using the cohesive zone method

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ABSTRACT

Complex hydraulic fractures are often reported in layered formations as the existence of a geological discontinuity. A seepage-stress-damage coupled finite element model was built to study the hydraulic fracture propagation behavior of the X5 sandstone and shale layered reservoir in the western Sichuan basin. The cohesive zone method (CZM) based on damage mechanics was used to simulate hydraulic fracture initiation and propagation. The influence of geologic parameters and fracturing execution parameters on hydraulic fracture morphology were studied. The results show that hydraulic fractures are mainly penetrating the interface and extending along the interface to generate a branched fracture, while others are forming normal bi-wing fractures.

1. Introduction

Hydraulic fracturing is a widely used technology in the stimulation of an unconventional reservoir [1]. One of the important features required in hydraulic fracturing design is the ability to predict the geometry and characteristics of hydraulically induced fractures. In most homogeneous and isotropic formations, the constant height, ideal fracture (planar bi-wing) models of Perkins and Kern [2], Geertsma and De Klerk [3], and Nordgren [4] may adequately represent the hydraulic fracturing process. However, the widely maintained assumptions (constant height and ideal fracture) are probably untenable in many layered reservoirs. In layered reservoirs, hydraulic fractures develop in sandwiched layers with different mechanical properties, situ stresses, interface properties and field executing parameters [5–8]. Therefore, understanding how hydraulic fractures evolve in layered formations might contribute to efficient hydraulic fracturing design.

1.1. Experimental research on fracture extension in layered formations

A considerable number of field and laboratory studies have demonstrated that branched and non-planar fracture growth is not only possible but fairly common in layered reservoirs.

From year 1980 to 2000, researchers focused on the fracture geometry in geologic discontinuities through mineback and coal seam hydraulic fracturing experiments. In the colored propped sand experiment, Warpinski [9] found that a small amount of first stage sand (black sand) crossed the joint, meanwhile red and black sand filled the joint. That is to say, there was an offset when hydraulic fractures propagated in geologic discontinuities. Additionally, in the colored-sand proppant mineback experiment, Anderson [10] discovered that hydraulic fractures terminated at a parting plane with 2.5–5 cm across

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the parting plane because of the bedding plane and stress contrast. Hydraulic fractures from mineback and coring [11] showed that fractures were offset when they crossed the joints, and often two or more fractures initiated from the joints. A hydraulic fracturing experiment [12] in coal showed that the fracture was vertical in the coal seam and grew horizontally along the interface between the coal and the overlying rock to form a T-shaped fracture.

From 1960 to 2010, researchers carried out a large number of laboratory experiments to identify the parameters that influence hydraulic fracture propagation in layered formations. In hydraulic fracturing triaxial experiments, Lamont and Jessen [13] noted that hydraulic fractures can directly cross the unbounded interface when the approaching angle was less than 30°. It was also found in Hanson's studies [14] that the poor interface property reduced the hydraulic fractures' ability to penetrate the interface. Similar hydraulic fracturing triaxial tests [6,15–19] have indicated that not only the interface property but also the approaching angle, situ stress, fracturing fluid viscosity and elastic modulus have a significant influence on the hydraulic fracture propagation path in layered formations (Fig. 1).

The aforementioned experiments show that there are two types of hydraulic fracture shapes when propagating in layered reservoirs [20]. The first type is a hydraulic fracture directly penetrating the interface, which includes three patterns: crossing (hydraulic fractures directly cross the interface without any deflection), opening (hydraulic fractures cross the interface with horizontal extension along the interface) and offsetting (hydraulic fractures cross the interface with a re-initiation after a short extension distance along the interface). The second type is a hydraulic fracture that cannot cross the interface, which also includes three patterns: arresting (a hydraulic fracture is arrested before interface), diversion (a hydraulic fracture propagates on both sides when entering the interface) and re-initiation (a hydraulic fracture re-initiates on the other side of interface after a horizontal extension distance along the interface) (Fig. 2).

1.2. Numerical techniques to simulate hydraulic fracture behavior

In recent decades, different numerical techniques have been developed to simulate the propagation of hydraulic fractures. The most widely used numerical methods include the finite element method (FEM) [21,22], finite difference method (FDM) [23], boundary element method (BEM) [24,25], displacement discontinuity method (DDM) [26], discrete element method (DEM) [27] and the extended finite element method (XFEM) [28]. Commonly used numerical simulation software includes FLAC3D [23], FRANC3D [25], HYFRANC3D [24], RFPA [29], ABAQUS [30,31], UDEC/3DEC [32] and so on. Currently, a solid-fluid coupling model is proposed with the software ABAQUS [33,34] for hydraulic fracture propagation. The stress-seepage-solid finite elements are used to discretize and describe formation mechanics and seepage behavior. The cohesive elements are used to describe fluid flow, hydraulic fracture initiation and propagation [20,35,36].

In this paper, a fluid-solid coupling finite element model was established to study hydraulic propagation behavior in the X5 layered reservoir. A cohesive pore pressure element was employed to simulate fluid flow and hydraulic fracture propagation. The influence of geologic and fracturing operation parameters on fracture geometry are analyzed in this paper.

2. Governing equations

2.1. Damage initiation and propagation criterion of cohesive elements

The damage pattern of cohesive elements follows traction-separation rules (Fig. 3).

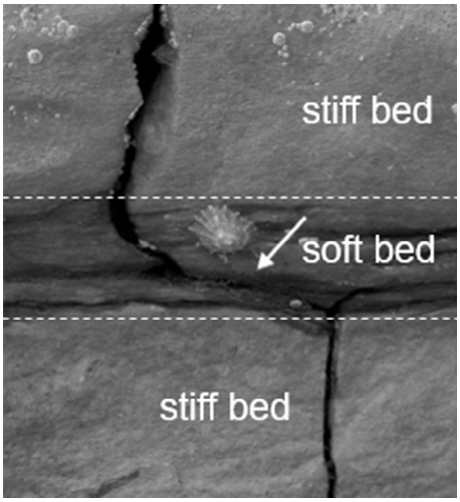

Fig. 1. Hydraulic fracture re-initiation in the alternations of stiff bed and soft interbed [16]