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DEM simulation of confining pressure effects on crack opening displacement in hydraulic fracturing

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ABSTRACT

Hydraulic fracture is one of the key methods in well stimulation to increase production of oil and gas. Crack Opening Displacement (COD) is of great importance in this method since it is in direct relation with permeability and production rate. In this paper COD is measured by a distinct element model which has been validated by an exact solution. A comprehensive study has been performed on confining pressure effect on COD which is neglected in the analytical solution. Numerical results showed that confining pressure considerably affects COD. A multi-parameter regression (considering effect of confining pressure, rock mass properties and fluid pressure) was performed on numerical results which resulted in an equation. The proposed equation considers the effect of confining pressure and its results are in good agreement with numerical results.

1. Introduction

Hydraulic fracturing is a widely used technique in the oil industry, in-situ stress measurement, geothermal reservoirs, coal mines, etc. [1–12]. It has played a key role in unlocking production of shale gas and light tight oil in the world. Hydraulic fracturing was first introduced in the 1940s as an oil well stimulation technique designed to increase productivity by fracturing an isolated section of well which is under pressure (see Fig. 1).

Fractures initially formed in the rock are extended by continuous pressurized pumping and are held open by injection of solid particles such as sand or glass [13]. The method significantly increases the productivity of the well by increasing the permeability of rock. Development of the first simple theoretical models for estimation of hydraulic fracture geometry began in 1950 [14–16]. Sneddon and Lowengrub [17] considered crack propagation based on material properties, such as fracture toughness, the critical stress intensity factor and the specific energy. The effect of high viscosity fluids on the vertical fractures and fracture width has also been investigated [18]. Poroelastic parameters including pore pressure, fluid viscosity, and permeability can significantly affect the behavior of a fracture. Abdollahipour et al. developed a Boundary Element Method (BEM) formulation for analysis of Poroelastic media [19]. In recent decades, the hydraulic fracture has been studied analytically and numerically by many researchers [20–28]. The boundary element method has been frequently used in past decades to analyze fracture problems and hydraulic fracturing processes [29–33]. Failure process and crack formation in rock and materials with similar characteristics have been modeled numerically by several researchers using Particle Flow Code (PFC) (discrete element method) model [34–37]. In this code cracks are formed simply by breaking the bonds between the circular particles rather than solving complex mathematical equations pertaining to fracture mechanics.

The COD (Crack Opening Displacement) measurement is of paramount importance in hydraulic fracturing process. It has a direct relation to obtainable oil or gas flow rate in wells. Many methods have been developed for estimation and evaluation of COD [38–43]. In this paper, the hydraulic fracturing process and COD measurement for a crack under uniform fluid pressure is simulated using UDEC (based on distinct element method). Various conditions of confining pressure are investigated. The main objective of the present study is to derive a relation which reflects the effect of confining pressure in the COD measurement.

2. Crack opening displacement

COD is one of the most important parameters used in fracture mechanics in the effort to characterize fracture properties. Many analytical and numerical approaches have been reported for different conditions to predict COD [44–46]. The analytical solution for fracture opening of the desired problem is given by Eq. (1) [47],

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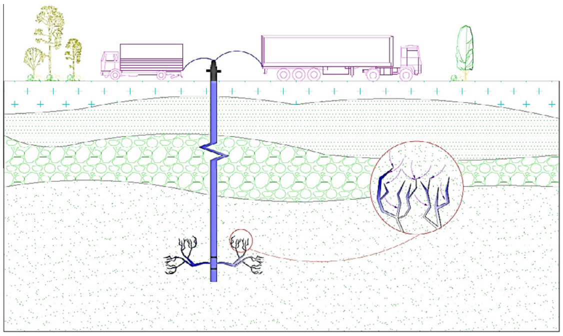

Fig. 1. Hydraulic fracturing process.

$$w = \frac{|\sigma_y + p|4(1-\upsilon^2)}{E}\sqrt{a^2 - x^2} \quad (1)$$

where ω is fracture opening, σ_y vertical stress, v Poisson's ratio, E Young's modulus, a crack half-length and x distance from crack center.

The analytical solution neglects the effect of confining pressure i.e. σ_x. A numerical model based on DEM will be established and the effect of confining pressure on reported COD will be examined.

3. Numerical simulation

3.1. Assumptions

It is assumed that the fluid pressure is applied uniformly into a crack. There are no other cracks or discontinuities in the computing environment. The modeled problem is shown schematically in Fig. 2.

The medium is assumed to be elastic since the elastic block model is generally applicable for cases in which slip along discontinuities is the predominant mechanism for failure. The crack is straight with a length of 21.6 m. COD will be measured in all crack lengths.

3.2. Numerical model

The DEM model domain is 46.08 m by 46.08 m, with a zone size of 1.44 m for the mentioned crack length (21.6 m) and will change properly for other crack lengths. The particular size of the zoning is used to facilitate the simulation and control of hydraulic fluid pressure. The embedded crack is modeled by preventing the ends of a through-going joint (located at mid-height in the model) from opening or sliding. This is achieved by using two fictitious vertical cracks to separate middle of crack from its ends and then assigning high strength properties and a value of joint stiffness equal to about 10 times the apparent stiffness of neighboring zones to these

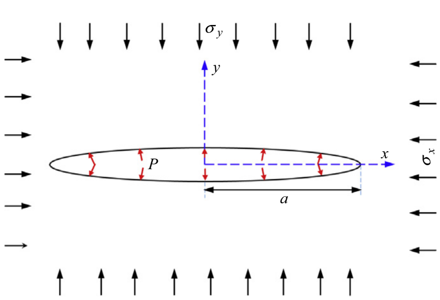

Fig. 2. Schematic view of modeled problem in numerical model.

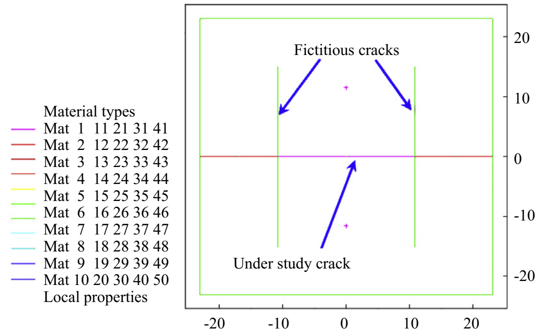

Fig. 3. Modelling the desired crack in UDEC.

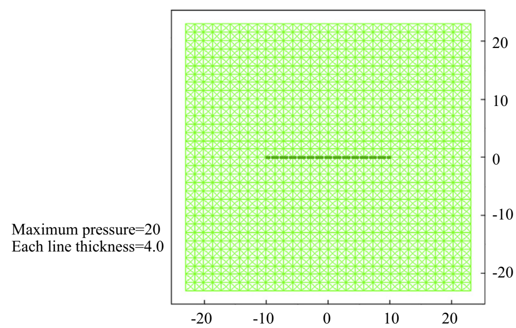

Fig. 4. Uniform fluid pressure inside the crack.

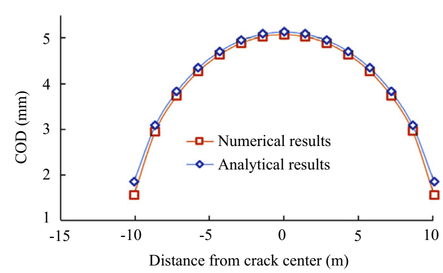

Fig. 5. COD results of numerical and analytical method.

fictitious cracks and ends of considered crack (see Fig. 3). The in-situ stresses are specified in the model, and a boundary element representation is utilized for the far field to increase accuracy in far field condition estimation. A uniform domain fluid pressure is assigned inside the crack. Fig. 4 shows the prepared model applying a uniform pressure of 20 MPa inside the crack. A FISH (FISH is a programming language embedded within UDEC that enables the user to define new variables and functions) function is used to read and report displacement from crack surface. The FISH function is provided in the appendix.

The following FISH function was used to extract the results of COD in all the crack length in a single text file. "DefineCOD" is the function used for extracting data from DEM model. It searches all grid points and finds those falling in crack geometry. Then it extracts y displacement for upper and lower faces of crack. The displacements are used to calculate crack opening displacement which will be logged in a table. Finally, the table, which is a UDEC