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# Hydrodynamic modeling of mud loss controlled by the coupling of discrete fracture and matrix

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ABSTRACT

In drilling engineering, the knowledge and control of mud loss are significant. Previous models of mud-loss exhibit two deficiencies: (1) fracture networks were not considered and (2) the fluid flow between the fracture and the matrix was not considered. In these regards, this study adopted a Monte Carlo stochastic simulation method to construct a geological model of discrete fracture networks of naturally fractured reservoirs and then found leakage tunnels. The coupling of discrete fractures and matrix was considered to establish the mathematical model. Consideration of the mud compressibility and the yield-power-law of fluid rheology have produced a more general model compared with previous ones. The finite element method and finite difference method were selected to deduce the numerical format of the matrix and fracture. The laws of mud loss in naturally discrete fractured reservoirs can be mastered through numerical calculation based on MATLAB. A sensitivity analysis is conclusively performed to identify the most influential factors on mud loss. The current model, which is more realistic compared with previous models, was validated by application to practical projects.


## 1. Introduction

Drilling through naturally fractured formations can cause severe mud loss. Numerous studies have been conducted to understand the fluid flow and transport processes in fractured rock since the 1960s and hydrodynamic modeling of mud loss began in the 1990s. Dyke et al. (1992) initiated a quantitative analysis of mud loss. They proposed a mud-loss equation for a Newtonian fluid and constructed dimensionless type curves in terms of a dimensionless radius and a dimensionless time. The fracture width can be inversely obtained by fitting type curves and actual data (Lietard et al., 1996). Type curve analysis took the center stage in mud loss studies for a long period of time, and it became the main tool for fracture aperture inversion despite of its low accuracy (Lietard et al., 1996; Verga et al., 2000; Majidi et al., 2008a, 2008b, 2008c; Hoffman and Narr, 2012). Lietard et al. (1999, 2004) considered non-Newtonian incompressible mud with Bingham rheology to develop a model for the radial mud flow into a non-deformable fracture with constant aperture and infinite length based on Darcy's law. Neither fracture plugging by mud particles nor permeability of the fracture wall were considered in their work. Lavrov and Tronvoll (2004) addressed the particular mechanism of mud loss in a single isolated fracture. They numerically integrated the mud-loss equation using an explicit finite difference scheme. They further refined their model to include the Herschel–Bulkley rheology and the azimuthal circular fracture (Lavrov and Tronvoll, 2005; Lavrov, 2006). Ozdemirtas et al. (2007a, 2007b) took into account of fracture roughness by adopting fractal geometry to simulate a fracture surface. Tempone and Lavrov (2008) performed a study of the mud loss in the case of fracture networks. They solved their model equations numerically by the discrete-element method (DEM), and concluded that the total length of the network and the fracture stiffness control the cumulative loss during drilling. However, the facture distribution they used failed to correspond to any practical formation, and the fluid flow between the fracture and the matrix was not considered in their model. Majidi et al. (2008a, 2008b, 2008c) proposed a model for simulating the mud loss of non-Newtonian drilling fluids in naturally fractured formations. The flow of yield-power-law (YPL) fluids was coupled with Newtonian reservoir fluid in a single fracture. They presented an analytical formula to describe the mud loss in drilling-induced fractures based on the notion that the volume and rate of loss in an induced fracture are quantified in terms of fluid properties, fracture parameters and operational conditions (Majidi et al., 2011). Some authors have also examined the influence of fracture fractal dimension (Ozdemirtas et al., 2009) and various deformation laws (Pordel Shahri and Mehrabi, 2012) on mud loss.

While improvements in the existing models for mud-loss are constantly made, two deficiencies still remain, limiting the

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**Nomenclature**

| | |
|---|---|
| $\tau_y$ | drilling mud yield stress, Pa |
| $K$ | consistency index, Pa $s^n$ |
| $m, n$ | flow behavior index |
| $h$ | thickness of leakage layer, m |
| $p_w$ | wellbore pressure, MPa |
| $p_i$ | initial formation pressure, MPa |
| $K_n$ | normal fracture stiffness, Pa/m |
| $C_f$ | rock compressibility factor, $MPa^{-1}$ |
| $C_L$ | drilling mud compressibility factor, $MPa^{-1}$ |
| $k_m$ | matrix permeability, mD |
| $r_w$ | wellbore radius, m |
| $w_0$ | initial fracture width, mm |
| $w$ | fracture width after deformation, mm |
| $v$ | flow velocity, m/s |
| $Q_f$ | volume rate of flow, $m^3/s$ |
| $Q_i$ | storage mass, $m^3/s$ |
| $\phi$ | formation porosity, |
| $q^*_{wvnf}$ | fluid mass exchange between matrix and fractures, kg/$m^2$ s |
| $p_{fi}$ | pressure in fracture, MPa |

applicability of these models. First, the distribution law of fractures in naturally fractured formations is not considered, which is responsible for the large discrepancy between prediction and practice. Because fractures always distribute in clusters, it is necessary to construct a realistic fractured rock mass geological model prior to simulation. Secondly, fluid flow between the fracture and the matrix is not modeled, which will result in an overly fast decrease in the mud-loss rate. To address these two deficiencies, this study adopts a Monte Carlo stochastic simulation method to create a geological model of discrete fracture networks (DFNs) and leakage tunnels, and considers the coupling of the discrete fractures and the matrix to form an appropriate model. The new model equations are then solved numerically by a numerical technique that combines the finite element method and the finite difference method, and the laws of mud loss in naturally discrete fractured reservoirs are obtained. The new model provides a more realistic approximation than the previous models, and it is validated by field projects.

## 2. Monte Carlo random geological model of fractured formation

If a pre-existing natural fracture is hit during drilling in a formation, mud loss occurs until action is taken at the rig and the fracture is effectively bridged by lost circulation materials (LCM). A single isolated fracture was simulated in previous studies (Lietard et al., 1996; Verga et al., 2000; Lavrov and Tronvoll, 2005; Windarto et al., 2012; Lu et al., 2012a,b). Only DEM was performed to simulate mud loss in fracture networks (Tempone and Lavrov, 2008), in which the distribution law was not considered. In practical naturally fractured rock mass, fractures always distribute in clusters (Fig. 1(a) and (b)). Thus, a realistic geological model of naturally fractured rock mass based on the regularities of fracture distribution in a specific formation is critical.

From Fig. 1(a) and (b), it is seen that more than one fracture must exist on the face of a borehole. Fracture distribution is more complex when both naturally and induced fractures are present during drilling. A multi-scale naturally fractured formation consists not only of highly-permeable reservoir-scale fractures but also core-scale micro-fractures. Based on limited geological surveys, this approach is a practicable method for adopting a stochastic simulation technique to obtain simulated discrete fractured rock mass, which exhibits the same statistical regularity as a practical formation.

An accurate geologic model is required for accurate results. Five parameters are required to characterize fractures in planar rock mass (length, width, midpoint, strike, and density). The statistical law of each fracture parameter can be obtained by imaging logging and core analysis. In the discrete-fracture model, all variables inside the fractures are assumed to remain constant in the lateral direction; the aperture of fracture can be disregarded in a geometric model (Yao et al., 2010). The Monte Carlo method is adopted to simulate fractured rock mass with a specific statistical regularity obtained from the oil field. The steps for constructing the geometric model are listed as follows:

– *Step* 1: Compile data from the oil field.
– *Step* 2: Perform a clustering analysis of the fracture parameter. Fractures of different types and scales satisfy different statistical law. The dominant orientation can be established by clustering analysis.
– *Step* 3: Select a probabilistic model. Provided that fracture parameters satisfy specific statistical laws, such as normal distribution, logarithmic distribution and exponential distribution, the best probabilistic model of each parameter can be fitted according to field data.
– *Step* 4: Perform a Monte Carlo stochastic simulation. Random numbers obtained according to the selected probabilistic model can be considered to be the magnitude of the fracture parameters for generating fractured rock mass.

Fractures are considered to be lines and disks in two dimensions and three dimensions, respectively. The geological models that are generated from the probabilistic model are shown in Fig. 2(a) and (b) (Fig. 2(a) presents a single group of fracture whereas Fig. 2(b) displays random-directional fractures).

In our simulation, micro-fractures are disregarded when simulating the macro-flow of mud loss. The geological model is rectangular with dimensions of 100 m × 100 m, which consists of the internal (wellbore) and outer boundaries. The radius of the wellbore is 0.1 m (Fig. 3).

Three types of fractures exist in which fluid cannot flow according to the knowledge of DFNs (Zhang, 2005; Yao et al., 2010; Biryukov and Kuchuk, 2012):

1) Isolated fractures which have not connected with other interconnected fractures.
2) Fractures clusters which have not connected with other tunnels or boundaries.
3) Fracture clusters which connect with neighboring clusters on one end where no fluid flows.

Leakage tunnels exist if the fractures connect with the wellbore. The three types of fractures can be removed from the geological model (Fig. 4):

## 3. Hydrodynamic coupling model of mud loss

Mud loss primarily exists in fractured formation due to the high conductivity of the fractures. Although the permeation from the fracture wall to the matrix is a significantly slower process, the