Distinct element method for solid-fluid coupled interaction in the application of hydraulic fracturing

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The interaction between hydraulically created and natural fracture is of great interest because natural fracture have the significant influence on the effectiveness of the hydraulic fracture. The viscosity of the fluid used in hydraulic fracturing also influences on the geometry of hydraulic fractures. We performed a series of simulations for hydraulic fracturing in naturally fractured rock by using the 2D flow-coupled Discrete Element Method (DEM) code to examine the influence of the fluid viscosity on the interaction between hydraulic and natural fractures. In this study, low and high viscous fluids are used respectively, and the fracture intersects with a single pre-existing fracture with three different strike angles. The results show that the pre-existing fracture influences significantly the propagation direction of hydraulic fractures and the hydraulic fracture does not always propagate in the direction of maximum principle stress. In addition, we concluded that the influence of pre-existing fracture on the propagation of hydraulic fractures could be reduced by the use of high viscous fluid.

1. INTRODUCTION

Hydraulic fracturing is a technique used in the production of unconventional oil and gas, enhanced geothermal system in hot dry rock, and the storage of green house gas. In each field, it is necessary to predict the propagation of hydraulic fracturing because the geometry of the hydraulic fractures influence strongly on the effectiveness of hydraulic fracturing. However, natural fractures around a bore-hole play an important role in the generation and propagation of hydraulic fractures (Okubo et al., 2013), and make it difficult to predict the behavior of hydraulic fractures. The field experiments in Ogachi HDR sites, whose rock is naturally fractured, showed that the hydraulic fracture did not propagate in the direction of maximum principle stress (Kondo, 1994). In addition to natural fractures, the viscosity of the fluid used in hydraulic fracturing also influences on the geometry of hydraulic fractures. In the field experiment for hydraulic fracturing at Akinomiya in Japan, the permeability of the rock around a bore-hole is improved by injecting high viscous fluid (Kaieda et al., 1988). Shimizu et al. (2011) performed a series of numerical simulations for hydraulic fracturing with two different viscous fluids to investigate the influence of fluid viscosity on hydraulic fracturing. In this way, both natural fractures and fluid viscosity have great influence on hydraulic fracturing. We, therefore, perform numerical simulations for hydraulic fracturing in naturally fractured rock by using a 2D DEM code to examine the influence of the strike of natural fractures around a bore-hole and injection fluid viscosity on the propagation direction of hydraulic fractures.

2. METHOD

We use the 2D discrete element method to simulate hydraulic fracturing. We will give a brief explanation in this paper due to limitations of space. Details can be found in a reference (Potyondy and Cundall, 2004).

The total force acting on each particle is comprised of a force arising from particle-particle overlap and a force arising from parallel bond. When two particles overlap, a contact is formed at the center of the overlap region and normal force \( f_n \), tangential force \( f_s \), and moment \( M \) arise. The increments of these forces are given as

\[
\begin{align*}
  f_n &= k_n (dn_j - dn_i) \\
  f_s &= k_s [ds_j - ds_i - (r_1 d\theta_1 - r_2 d\theta_2)] \\
  M &= r f_s
\end{align*}
\]

where, \( k_n \) and \( k_s \) are the stiffness of normal and shear springs, \( dn \), \( ds \), and \( d\theta \) are normal and shear displacement and rotation of particles, and \( r \) is radius of particles. The increments of normal force \( \Delta f_n \), tangential force \( \Delta f_s \), and moment \( \Delta M \) carried by the parallel bonds can be also calculated from the relative motion of the bonded particles, and given as
where $k_n$, $k_s$, and $k_\theta$ are the stiffness of normal, shear, and rotational spring of the parallel bonds. These stiffness are given as the following equation by the beam theory.

$$k_n = \frac{ED}{L} \quad \text{(7)}$$

$$k_s = \alpha k_n \quad \text{(8)}$$

$$k_\theta = \frac{EI}{L} \quad \text{(9)}$$

Where $L$, $D$, $E$, $\alpha$, and $I$ are the length, the diameter, the Young's modulus, the stiffness, and the inertia of the parallel bonds. The normal stress $\sigma$ and shear stress $\tau$ act at the contact point of the bonded particle and are given by

$$\sigma = \frac{\bar{f}_n}{D} \quad \text{(10)}$$

$$\tau = \frac{\bar{f}_s}{D} \quad \text{(11)}$$

When $\sigma$ exceeds the tensile strength $\sigma_c$ or $\tau$ exceeds the shear strength $\tau_c$, the bond breaks. The criterions for bond break can be written by

$$\sigma \leq -\sigma_c \quad \text{(12)}$$

$$|\tau| \geq \tau_c \quad \text{(13)}$$

When each bond breaks, a micro crack is generated at the contact point of the particles.

To suppress high-frequency vibration, viscous damping is introduced. Contact damping is calculated from the relative velocities at the contact points and are given as

$$f_{nd} = C_n (dn_j - dn_i)/dt \quad \text{(14)}$$

$$f_{sd} = C_s \left[ ds_j - ds_i - \frac{L}{2} (d\theta_i - d\theta_j) \right]/dt \quad \text{(15)}$$

where $C_n$ and $C_s$ are normal and shear coefficients of viscous contact damping, and $dt$ is duration in one time step. $C_n$ and $C_s$ are given as

$$C_n = 2 \sqrt{m_{ij}k_n} \quad \text{(16)}$$

$$C_s = C_n \sqrt{k_s/k_n} \quad \text{(17)}$$

Where $m$ is calculated by the mass of two particles and given as

$$m_{ij} = \frac{2m_i m_j}{m_i + m_j} \quad \text{(18)}$$

To simulate fluid flow, the fluid flow algorithm is introduced into the DEM program. In the fluid flow algorithm, pores are assumed to be in the center of the enclosed domain, and flow channels connecting pores are assumed to be at the contact points of particles. Since the fluid flow in the flow channels is assumed to be the laminar flow, the flow rate is calculated by the Poiseuille equation and is given as

$$Q = \frac{w^2 \Delta P}{12 \mu L_p} \quad \text{(19)}$$

where $w$ is the aperture, $L_p$ is the length of the flow channel, $\Delta P$ is the pressure difference of two neighboring pores, and $\mu$ is the viscosity of the fluid. Each pore accumulates the fluid pressure and the pressure increment at each pore is given as

$$\Delta P = \frac{K_f}{V_r} \left( \sum Q dt - dV_r \right) \quad \text{(20)}$$

where $K_f$ is the fluid bulk modulus, $V_r$ is the current pore volume, $\sum Q$ is the total flow rate from the surrounding channels, $dV_r$ is the change of the volume of the pore. Fluid pressure accumulated in the pore and the shear stress caused by fluid flow is acting on particles. Porosity pressure is acting on the particle surface and is given as

$$f_d = \int_{-\beta}^{\beta} P \cos \theta \, r dt \quad \text{(21)}$$

To consider the partially saturated condition, the saturation in each pore is introduced (Shimizu et al., 2011). The saturation is given as

$$S_t = \frac{V_f}{V_d\phi} \quad \text{(23)}$$

where $S_t$ is the saturation in each pore.

3. MODEL SETTING

Figure 1 shows the simulation model for hydraulic fracturing in our study. The simulation model is expressed as the assembly of particle bonded to each other. The size of the model is 1 m in width and 1 m in height. A bore-hole whose diameter is 0.1 m is put at the center of the model. 10MPa in the x-direction and 5MPa in the y-direction are applied to the model so that the hydraulic fracture goes in the x-direction. The microscopic parameters are calibrated by preliminary simulations of uniaxial compression test, Brazilian test, and permeability test. A pre-existing fracture is introduced in the model to examine the influence of the pre-existing fracture on hydraulic fractures. The pre-existing fracture is
introduced just by ending the particle bonds which intersect with the pre-existing fracture (Figure 2). The initial aperture of pre-existing fracture is set to $10^{-3}$ m in the present study. Fluid pressure is applied in the bore-hole by injecting fluid with the fixed injection rate and the hydraulic fracture intersects with a single fracture with a strike angle of $\theta$. We performed six simulations, A1-A3 and B1-B3. A low viscous fluid (0.1 mPa s) is used in A1-A3 and a high viscosity fluid (100 mPa s) is used in B1-B3. The strike angle is 30° in A1 and B1, 45° in A2 and B2, and 90° in A3 and B3.

4. RESULT and DISCUTION

Figure 3 - Figure 5 show close-up views of the fracture propagation and fluid flow in our simulations. The opening apertures and the pre-existing fracture are expressed as red and brown bars, and the saturated areas and the partially saturated areas ($S_t = 0.5$) are expressed as blue and light blue domains. The left pictures show the results when low viscous fluid is used and the right pictures show the results when the high viscous fluid is used.

When the strike angle is 90° as shown in Figure 5, hydraulic fracture penetrates through at the center of the pre-existing fracture. However, when the strike angle is 30° as shown in Figure 3, the microscopic fractures are generated at the tip of the pre-existing fracture after reaching the pre-existing fracture, and the macroscopic hydraulic fracture does not propagate in the direction of the maximum principle stress. These results show that the hydraulic fracture does not always propagate in the direction of the maximum principle stress. This indicates that not only in-situ stress but also the strike of natural fractures around a bore-hole influence on the behavior of the hydraulic fracture. Therefore, the strike of natural fractures should be taken into consideration when we predict the propagation direction of hydraulic fractures.

When the strike angle is 45°, the microscopic fracture generated between the center and the tip of the pre-existing fracture in low viscous fluid injection. On the other hand, two hydraulic fractures are generated after reaching the pre-existing fracture in high viscous fluid injection. One is generated between the tip and the center of the pre-existing fracture like the fracture in low viscous fluid injection. The other is generated at the center of the pre-existing fracture. This result indicates that the hydraulic fracture can penetrate straightly the pre-existing fracture by using high viscous fluid, while it cannot in low viscous fluid injection. Therefore, influence of the pre-existing fracture on the propagation of hydraulic fracture can be reduced by using high viscous fluid.

5. CONCLUSION

We performed a series of numerical simulations for hydraulic fracturing to investigate the influence of the strike of pre-existing fractures and the viscosity of injected fluid on the propagation direction. The results indicate that the propagation direction does not always correspond with the direction of the maximum principle stress. The results also show that the hydraulic fracture can penetrate linearly through the pre-existing fracture by using high viscous fluid. We conclude that the strike of natural fractures and injected fluid viscosity strongly influenced on the behavior of hydraulic fractures. The condition of natural fracture and fluid viscosity should be taken into consideration in the estimation of the behavior of hydraulic fracture and injected fluid.
Figure 3: Close-up view of the fracture propagation and fluid flow in our simulations. The left picture indicates the result of A1 and the right indicates B1. The microscopic crack and the pre-existing fracture are expressed as red and brown, and the saturated areas and the partially saturated areas ($S_e=0.5$) are expressed as blue and light blue domain. The strike angle of the pre-existing fracture is $30^\circ$.

Figure 4: Close-up view of the fracture propagation and fluid flow in our simulations. The left picture indicates the result of A2 and the right is B2. The strike angle of the pre-existing fracture is $45^\circ$.

Figure 5: Close-up view of the fracture propagation and fluid flow in our simulations. The left picture indicates the result of A3 and the right is B3. The strike angle of the pre-existing fracture is $90^\circ$. 
REFERENCES


