Stress concentration in fractured medium due to formation pressure changes

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It is well known that the hydraulic fracturing is a tool commonly used for stimulating hydrocarbon reservoirs and that the orientation and the propagation length of fractures created by hydraulic pressure influenced by in-situ stress field. It is, however, difficult to predict the behavior of fracture propagation from boreholes in a medium under regional stress due to a lack of numerical schemes to simulate rock failures. In order to solve this problem of hydraulic fracturing, we have developed a program to simulate fracture propagation from a borehole due to increasing fluid pressure using an extended finite difference method (X-FEM), which deals with any fractures independent from grid or mesh for the numerical simulation. Numerical simulations are conducted for a 2D elastic medium having a borehole and a fracture. We first confirmed that our program could simulate the stress distribution whose local stress field near the borehole showed some deviated orientation from the regional stress field. We then confirmed that the tendency of fracture propagations to be a function of fluid pressure to induce the extension of fracture. The orientation of the fracture propagation converges to that of the principal stress. However, the higher the fluid pressure is, the smaller the curvature of fracture trace becomes. We would like to conclude that the orientation of maximum in-situ principal stress and the fluid pressure for fracturing is a major parameter to control the propagation of fractures due to increasing fluid pressure.

1. INTRODUCTION

Hydraulic fracturing is an indispensable scheme to stimulate fluid production in hydrocarbon reservoir development in conjunction with various well testing methods such as drillstem, buildup tests, etc. In recent years, it is also well known that hydraulic fracturing also plays the major part in the development of shale oil. It is also known that the extension length and the orientation of fractures induced by hydraulic fracturing are strongly influenced by the crustal stress field under which any reservoir is located. Therefore, it is, in general, necessary to have some understanding of regional stress field before the application of hydraulic fractures as well as acquiring the rock physical properties of reservoir formations.

The propagation of fractures is controlled by the regional stress field that could be estimated by the locations of acoustic emissions (AE) during the well testing, borehole breakouts or induced fractures at the time of drilling, etc. The results of these tests would be used to estimate the regional stress field and the behavior of fractures hydraulically induced. On the other hand, it is known that hydraulically induced fractures may not be created as planned and could cause some environmental issues such as pollution, induced seismicity, etc. It is, we think, very important to estimate how fractures are induced under various crustal state conditions to cope with unexpected behavior of fracture propagation. Although numerical simulation is a powerful tool to understand the behavior of propagating fractures, we need to develop numerical simulation tools to deal with failure of rocks.

To simulate failures in crustal materials in a simple manner, we utilize an extended finite element method (X-FEM) in this study. For an example of complex stress environment, we first simulate the stress distribution around borehole under the existence of a fracture. Then, we try to see how the fracture could propagate due to changes of fluid pressure inside the fracture. Finally, we would conclude what the differences in the orientation and propagation length of fractures would be due to those in the fluid pressure and the stress field surrounding the borehole.
2. METHODS

X-FEM

We adopt X-FEM to consider the influence of fractures on the stress fields and simulate fracture propagation. This method makes us to calculate without remeshing associated with fracture propagation by adding secondary function into conventional FEM, which is called enrichment and the function is defined as the enrichment function.

In the X-FEM, a displacement approximation for six-node triangle elements is defined as follows:

$$u'(x) = \sum_{i=1}^{\phi} \phi_i(x)u_i + \sum_{i=1}^{\gamma} \gamma_i(x)u_i' + \sum_{i=1}^{\beta} \beta_i(x)H(x)b_i$$ (1)

$\phi$ is shape function used by classical FEM. $C$ is the set of top nodes of finite elements which includes crack tip, while $J$ is that which includes the intermediate part of the fracture (Figure 1). $\gamma$ is defined as

$$\gamma_1 = \sqrt{r} \cos \frac{\theta}{2}, \quad \gamma_2 = \sqrt{r} \sin \frac{\theta}{2},$$
$$\gamma_3 = \sqrt{r} \sin \frac{\theta}{2} \cos \theta, \quad \gamma_4 = \sqrt{r} \cos \frac{\theta}{2} \sin \theta$$ (2)

where $(r, \theta)$ are the local polar coordinates at the crack tip, and this expresses the stress concentration around the crack tip based on linear fracture mechanics. $H$ is also defined as

$$H(x) = \begin{cases} 1 & x \in \Omega_i \\ -1 & x \in \Omega_j \end{cases}$$ (3)

This is a jump function so that we can take account of the discontinuity of stress distribution caused by the fracture cutting into two disjoint region.

3. SIMULATION MODEL

Figure 2 shows a two-dimensional simulation model. The number of finite elements is 2010 and the model scale is 4m × 4m. The borehole diameter is 0.2m. The Young modulus of the background rock mass is 15.0GPa and the Poisson ratio is 0.3. The maximum principal stress is 20MPa along y-axis and the minimum principal stress is 10MPa along x-axis as in-situ stress. These principal stresses do not change during fracture propagation.

4. DISCUSSION OF RESULTS

Influence of pre-existing fracture on the stress distribution

We investigated the stress distribution around the borehole. Figure 3 shows each distribution of the Mises stresses in the cases of no fractures, one fracture tilting with 30 degrees, and with 45 degrees, respectively. These results demonstrated an influence of the pre-existing fracture on the stress distribution around the borehole. In the left of Figure 3, we can only find the stress concentrations that cause the borehole breakout or drilling induced fracture. On the other hand, if a pre-existing fracture is included (the middle and right figure in Figure 3), we can observe that the pre-existing fracture disturbs the stress field around the borehole. The pre-existing fracture shifts the position of stress concentration away from borehole wall. Therefore, the pre-existing fracture can have a significant effect on hydraulic fracturing test using the borehole breakout.

Fracture propagation simulation

We simulated fracture propagation under various formation pressures. Figures 4 and 5 show the results of fracture propagation in which the
formation pressure is 8 MPa and 20 MPa, respectively. These results show that the higher formation pressure is added, the stronger tendency to y-direction fracture propagation is indicated. The orientation of the fracture propagation finally converges to direction of the maximum principal stress at any formation pressure even if angles of single pre-existing fracture are varied. The convergence speed depends on formation pressure. When the formation pressure is 8MPa (Figure 4), the fracture propagation turns to the orientation of the maximum principal stress relatively quickly. However, as formation pressure is increased to 20MPa (Figure 5), the fracture propagates to the y-direction with curving moderately.

From these results, we conclude that the direction of the maximum principal stress, rather than the strike of pre-existing fracture, is dominant on fracture propagations. We also conclude that we can hold off on turning to the direction of the maximum principal stress by increasing injection pressure. Thus, our simulation contributes to predicting quantitatively how the fracture propagates.

5. CONCLUSIONS

We confirmed how the pre-existing fracture and the in-situ stress field around the borehole influence the stress concentration and the propagation of hydraulic fracture using an X-FEM code developed in this study. From the results of our numerical simulations, we would like to conclude as follows:

(1) A pre-existing fracture near the borehole strongly influences the stress concentration around the borehole. The estimation of stress field from the orientations of borehole breakouts or drilling-induced fractures may lead to a wrong estimation of principal stress orientation and of the minimum stress magnitude. We should therefore take the effect of a pre-existing fracture around borehole into account to get better implications in hydraulic fracturing.

(2) The propagation of fractures is also strongly influenced by the fluid pressure in the fracture. No matter how the fluid pressure is, we could confirm that the orientation of fracture propagation converges to that of principal stress and that the difference in the fracture propagation could be seen in the curvature of the fracture trace. The higher the fluid pressure is, the smaller the curvature of the fracture propagation trace becomes.

When we develop a hydrocarbon reservoir using hydraulic fracturing, we would like to conclude that the orientation of the maximum in-situ principal stress and the fluid pressure for fracturing should be quantitatively taken into account for the environmental safety and for the stimulation efficiency.

REFERENCES

Figure 3: Stress distribution of Mises stress around borehole

Figure 4: Fracture simulation: Formation pressure is 8MPa

Figure 5: Fracture simulation: Formation pressure is 20MPa