CHAPTER 3

Numerical analysis of the interaction between two zipper fracture wells using the continuum damage method

This chapter introduces the 3D numerical modeling of zipper fractures/modified zipper fractures. The purpose of this numerical modeling is to determine the most effective operational means to perform a hydraulic injection of the zipper fracture. With reference to the numerical damage distribution solution for a given injection plan, simultaneous injection was found to obtain a significantly larger area of damage distribution than that obtained by sequential hydraulic injection.

The plastic damage model is presented in Chapter 1; its parameter values, presented in Chapter 2, are adopted in this calculation.

3.1 INTRODUCTION

Zipper fracturing/modified zipper fracturing (Rafiee et al., 2012) is a popular reservoir stimulation method used to develop unconventional resources, particularly for tight-sand oil and shale oil and gas. An adequate understanding of the influence of neighboring stimulation stages on the generation of the stimulated reservoir volume (SRV) significantly affects the fracturing design. To investigate the interaction mechanism between neighboring stimulation stages, numerical simulations were performed on the stimulation process. These simulations progress through each step of the stimulation process using a hydro-mechanical finite element method (FEM). A continuum damage model is used to simulate the fracture phenomena created by the fluid injection used for reservoir stimulation.

In rock mechanics, the mechanical damage variable is interpreted as an index of material continuity, which varies from 0 for intact rock to 1 for completely separated, broken rock. The volumetric density of cracks created by the injection fluid can be represented by a scalar damage variable.

Submodeling techniques are used to accommodate the field-to-borehole-section scale discrepancy. The submodeling technique uses a large-scale global model to produce boundary conditions for a smaller scale submodel. In this way, the hierarchical levels of the submodel are not limited. Using this approach, a highly inclusive field-scale analysis can be linked to a very detailed local-stress analysis at a much smaller scale. The benefits are bidirectional, with both the larger and smaller scale simulations benefiting from the linkage.

This chapter introduces a plasticity-based damage model and presents a set of connected hydro-mechanical problems calculated using a 3D model of the FEM. The numerical results for the distribution of the mechanical variables, including continuum damage, pore pressure, and horizontal stress components, are analyzed and shown.

The plastic damage model, presented in Chapter 1, and its values of parameters, presented in Chapter 2, are adopted in this calculation. The field model presented in Chapter 2 is used as the global model in this chapter. Section 3.2 presents the numerical results of the hydraulic fracturing simulation obtained with the submodel.
3.2 SUBMODEL FOR STIMULATION PROCESS SIMULATION

For the submodel under stimulation injection loadings, the submodel geometry is established with a width and length of 200 m and a thickness of 20 m. The calculation focuses on the lateral scope of the fractured volume generated by the fluid injection. Therefore, the vertical direction of the model has been simplified by taking only a thin slice in 3D space.

The discretization of the model uses 7560 3D eight-noded continuum elements (C3D8RPH). Figure 3.1 shows the mesh of the submodel.

The load is the injection flow at the injection points of the submodel. Figure 3.2 shows the horizontal well sections designed for the zipper fracture. The red points shown in Figure 3.1 represent the locations of the injection points. Because of the symmetry of the model, only a quarter of the model was meshed. All four side-surfaces are symmetrical planes.

The task of this calculation is to estimate the injection effects with the previously described parameter values for the modified zipper fracture of two horizontal wells. The perforation length section is set at 20 m. Because of the symmetry of the geometric model, only 10 m of the perforation section are modeled with the injection points. The flow rate is the controlled loading variable and is provided as a known value; the pressure at the injection points is variable, solved as an unknown value, and changes with the injection process.

The numerical simulation of each injection step at the five locations (shown in Fig. 3.1) of the injection loading case are performed sequentially to simulate the stimulation process as practice for reservoir stimulation.

This calculation simulates fracture generation under a bottomhole pressure ($BHP$) of 39.5 MPa (5730 psi), along with the following conditions:

- The initial reservoir pore pressure is 20.7 MPa (3000 psi), corresponding to $TVD = 1700$ m.
- Boundary conditions are taken from the numerical results of the global model described previously.
• The initial geostress values are taken from the numerical results of the global model described previously, also corresponding to $TVD = 1700$ m.

For the numerical results of the submodel under the stimulation injection loadings, the stimulation processes are numerically simulated.

To investigate the interaction of the fracture zones created by stimulation injection, the loading sequence used for the injection includes the following:

• Stage 1: injection loading at Location A
• Stage 2: injection loading at Location B
• Stage 3: injection loading at Location C
• Stage 4: injection loading at Location D
• Stage 5: injection loading at Location E

Figures 3.3 through 3.6 show the resulting contours of the major mechanical variables at the end of Stage 1 of the stimulation injection. Figure 3.3 shows the pore pressure distribution within the submodel corresponding to the end of the Stage 1 injection at Location A. Figure 3.4 shows the fractured reservoir volume, which is a rather narrow band in 3D space. Figure 3.5 shows the distribution of the horizontal stress component $S_x$ in the $X$-direction. The stress components shown are all effective stresses, whose values are the result of the total stress minus the pore pressure. Figure 3.6 shows another horizontal stress component $S_y$ in the $Y$-direction. The variation of the
vertical stress component $S_z$ is the result of the amount of total vertical stress minus pore pressure, and is therefore omitted for brevity.

Figures 3.7 through 3.10 show the resulting contours of the major mechanical variables at the end of Stage 2 of the stimulation injection. Figure 3.7 shows the pore pressure distribution within the submodel that corresponds to the end of the Stage 2 injection at Location B. Figure 3.8 shows the fractured reservoir volume, which is also narrow. Although the pore
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**Figure 3.8** Fractured volume at the Stage 2 distribution of the continuum damage.

**Figure 3.9** Contour of stress component $S_x$, which is the effective stress in the $X$-direction.

**Figure 3.10** Contour of stress component $S_y$, which is the effective stress in the $Y$-direction.

Pressure at Point A becomes increasingly less, its fractured volume and damage variable value continue to increase as a result of the residual injection energy at this region (which degrades with time). Figure 3.9 shows the distribution of the horizontal stress component $S_x$ in the $X$-direction. Figure 3.10 shows another horizontal stress component $S_y$ in the $Y$-direction.

Figures 3.11 through 3.14 show the resulting contours of the major mechanical variables at the end of Stage 3 of the stimulation injection. Figure 3.11 shows the pore pressure distribution in the submodel corresponding to the end of the Stage 3 injection at Location C. Figure 3.12 shows the fractured reservoir volume. Although it is still narrow, it connects the fracture volume created by injections at Location A and B, respectively, which means that the fractured volumes
Figure 3.11 Pore pressure distribution of the submodel at Stage 3 of the injection stimulation.

Figure 3.12 Fractured volume at the Stage 3 distribution of the continuum damage.

Figure 3.13 Contour of the stress component \( S_x \), which is the effective stress in the \( X \)-direction (which is shown as \( S_{11} \) in legend).

...are “zippered.” Figure 3.13 shows distribution of the horizontal stress component \( S_x \) in the \( X \)-direction. Figure 3.14 shows another horizontal stress component \( S_y \) in the \( Y \)-direction. To clearly show the internal distribution of the mechanical variables, multi-cut views are used to visualize these figures.
Figure 3.14  Contour of the stress component $S_y$, which is the effective stress in the $Y$-direction direction (which is shown as $S_{22}$ in legend).

Figure 3.15  Pore pressure distribution of the submodel at Stage 4 of the injection stimulation.

Figure 3.16  Fractured volume at the Stage 4 distribution of the continuum damage.

Figures 3.15 through 3.18 show the resulting contours of the major mechanical variables at the end of Stage 4 of the stimulation injection. Figure 3.15 shows the pore pressure distribution within the submodel corresponding to the end of the Stage 4 injection at Location D. Figure 3.16 shows the fractured reservoir volume. All four fractured volumes are now connected or “zippered.”
Figure 3.17 Contour of stress component $S_x$, which is the effective stress in the $X$-direction.

Figure 3.18 Contour of stress component $S_y$, which is the effective stress in the $Y$-direction.

Figure 3.19 Pore pressure distribution of the submodel at Stage 5 of the injection stimulation.

Figure 3.17 shows the distribution of the horizontal stress component $S_x$ in the $X$-direction. Figure 3.18 shows another horizontal stress component $S_y$ in the $Y$-direction.

Figures 3.19 through 3.22 show the resulting contours of the major mechanical variables at the end of Stage 5 of the stimulation injection. Figure 3.19 shows the pore pressure distribution within the submodel corresponding to the end of the Stage 5 injection at Location E. Figure 3.20 shows the fractured reservoir volume. The fractured reservoir volume created by this injection stimulation is significantly larger than that created by previous stimulation steps with approximately the same
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Figure 3.20 Fractured volume at the Stage 5 distribution of the continuum damage.

Figure 3.21 Contour of the stress component $S_x$, which is the effective stress in the $X$-direction.

Figure 3.22 Contour of the stress component $S_y$, which is the effective stress in the $Y$-direction.

injection pressure. Figure 3.21 shows the distribution of the horizontal stress component $S_x$ in the $X$-direction. Figure 3.22 shows another horizontal stress component $S_y$ in the $Y$-direction.

Figures 3.23 through 3.26 show the resulting contours of the major mechanical variables with a different stimulation injection method: two stimulation injections begin simultaneously at Locations A and B, rather than performed consecutively. Figure 3.23 shows the pore pressure distribution within the submodel corresponding to the simultaneous injection method. Figure 3.24 shows the fractured reservoir volume created in this case. The fractured volume is significantly wider than that shown in Figure 3.4 and Figure 3.10 with approximately the same injection pressure. This indicates that, for the zipper fracture under the given initial geostress, the same injection rate will produce more fractured reservoir volume using the simultaneous injection method than by using the sequential injection method. Figure 3.25 shows the distribution of the horizontal
3.3 CONCLUSIONS

The numerical results presented in this chapter include the following:

- Distribution of the fractures, which are represented by the contour of the continuum damage variable resulting from the injection flow.
A comparison of the numerical results of $SRV$ shown in Figure 3.4 and Figure 3.10 indicates that for a zipper fracture under the given initial geostress, the $SRV$ generated by the sequential injection method is narrow and significantly less than that generated by the simultaneous injection method.

The numerical results of $SRV$ shown in Figure 3.20 indicate that because the changes of the geostress field caused by neighboring injections, the $SRV$ created by stimulation at the central area of this submodel model is much larger than those created at the corner locations.

As a special form of the zipper fracture, the so-called modified zipper fracture can increase efficiency of hydraulic fracturing operations.

The anisotropic distribution of permeability and distribution of the natural fractures are necessary data for obtaining a solution that is near the measured data of the fracture distribution obtained with microseismic monitoring. The calibration of the damage model with microseismic data will be a major part of the next step of this study. The calibration and modeling of the initial damage field is also important for accurately modeling this multi-physics phenomenon.