Numerical model of microseismicity in hydrofracturing: our prediction for seismic moment tensors

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Summary

Recently, hydrofracturing is being monitored by detecting and analyzing microseismic activity (microseismic monitoring). However microseismic monitoring is limited by the cost, location errors and poor understanding of the physical processes occurring at depth. Numerical modeling is a cost-effective tool that has a high potential to improve our understanding of the relationship between the microseismic events and the induced hydraulic fracture and possible shear failure of the rock mass around the crack. We are developing a technique to simulate the occurrence of microseismic events during hydrofracturing via numerical modeling of fracture self-localization and deformation-modes. Our numerical simulations successfully predict the orientation of the hydrofracture parallel to the maximum stress orientation in agreement with the general observations. For relatively homogeneous rocks (e.g. massive shale), the observed microseismicity forms a narrow belt whereas for heterogeneous rocks (e.g. turbidite fan) the belt is wide.

Microseismic monitoring is focused mainly on the microseismic locations as a sign of the fracture extent, however, lately also on the determination of the mode of fracture opening which may have consequences for the production assessment. Fracture opening is thought to be recognized by the detection of tensional events based on the assumption that tensional forces open the fracture. So far, however, no tensional events have been detected. According to our simulations, the events that occur under the tensional stress conditions (at least for one stress axis) are possible only where the regional stress field is close to hydrostatic conditions. These events will be seismically recorded as a failure that has a low shear component (~40% double-couple), and significant non-shear components (60%). For tectonically active regions where the regional differential stress is high, the failure, even though activated by fluids, is mostly in the shear regime (90% double-couple). Both end-members of deformation mode have been recorded in gas fields in Texas, USA, as well in Europe. We conclude that the mode of deformation is heavily dependent on the regional stress field and its proximity to shear failure and is not necessarily sign of the presence or absence of fluid in the fracture.

Introduction

Hydraulic fracturing is a field technology widely used in the petroleum industry in order to increase the effective permeability of rock and thus the production of gas. Having control over hydrofracturing is crucial for the success of the treatment. It is important to estimate the final extent of the fracture as well as the permeability of the fracture system (e. g., Settari et al., 2009), to determine the most important factors that influence the fracturing and to learn how to control them. Microseismic monitoring can be a very useful tool for calibrating numerical models of hydrofracturing. However, it is necessary to improve our understanding of the relationship of the microseismic events to the induced hydraulic fracture. The field of numerical modeling of microseismic events in a rock subjected to a stress field is practically nonexistent due to the complexity of the problem (Zhao and Young, 2009). Here, we present a numerical model that predicts microseismicity patterns that are similar to the observed patterns.

Method

The numerical simulation of hydrofracturing involves the coupled (or interactive) solution of the mechanical equations and the equations for the fluid motion in the porous medium. The interaction may be very strong because the hydrofracture is initated by the (very high) fluid pressure and the fluid flow is influenced by the fracture opening and orientation.

We use the finite-difference scheme in order to solve the mechanical equilibrium and constitutive equations. The heterogeneity of the material can be introduced through random distribution of the material properties (Young's modulus and compressive and tensional strengths) throughout the domain of analysis.

The fracture initiates when the Mohr-Coulomb or tensile failure criterion is satisfied in any point of the grid. The behavior of the fracture is numerically simulated using the isotropic elastic damage theory, where the elastic modulus of an element degrades gradually as the damage (fracture) progresses (Tang et Kaiser, 1998, Wang et al., 2009). The damage variable D ranges between 0 and 1, with the end-members corresponding either to the limiting or residual strains in the element. This geomechanical system is interactively linked to the reservoir model (Geosim) that solves the fluid mass conservation equations in a porous media enabling to consider multiphase fluid (oil, water, gas) and various degrees of saturation. The ultimate goal is the simultaneous modeling of the fracturing process (including reservoir flow and fracture mechanics) together with predictions of microseismic events in the rock mass being fractured.

Results

We present a test where we simulate hydrofracturing in a 2-D box loaded with regional stresses. In the box, fluid pressure is simulated by a radial log function that increases with time and simulates the injected pressure. Increasing the fluid pressure perturbs the regional stress field and results in series of cracks that together form a single fracture or a system of fractures, depending on the heterogeneity of the rock. When an individual crack is formed, energy is released from the system. We associate this energy with a seismic event. Figure 1 shows crack formations, i. e., microseismic events, for the heterogeneous and homogeneous cases. In both cases, the cracks form a fracture aligned with the maximum stress direction. In the heterogeneous case the cracks are spread out in broader zone than cracks in the homogeneous case. All cracks form under the shear failure criterion. Based on the stress state and the angle of friction considered in the model, the cracks most likely form "en echelon" fracture, e.g. all cracks are inclined 30 degrees from the maximum stress axis.

The type of the microseismic event is determined by the decomposition of the seismic moment tensor, i. e., the forces acting in the source. The seismic moment tensor is usually assumed to be the sum of the volumetric component, the double-couple (shear component) and compensated linear vector dipole (clvd, basically uniaxial force where volumetric component was subtracted) (for a review see Julian at al., 1998). This procedure is typically applied to the resolved seismic tensors detected during hydrofracturing. We applied the same procedure to the effective stress field immediately preceding the cracking.

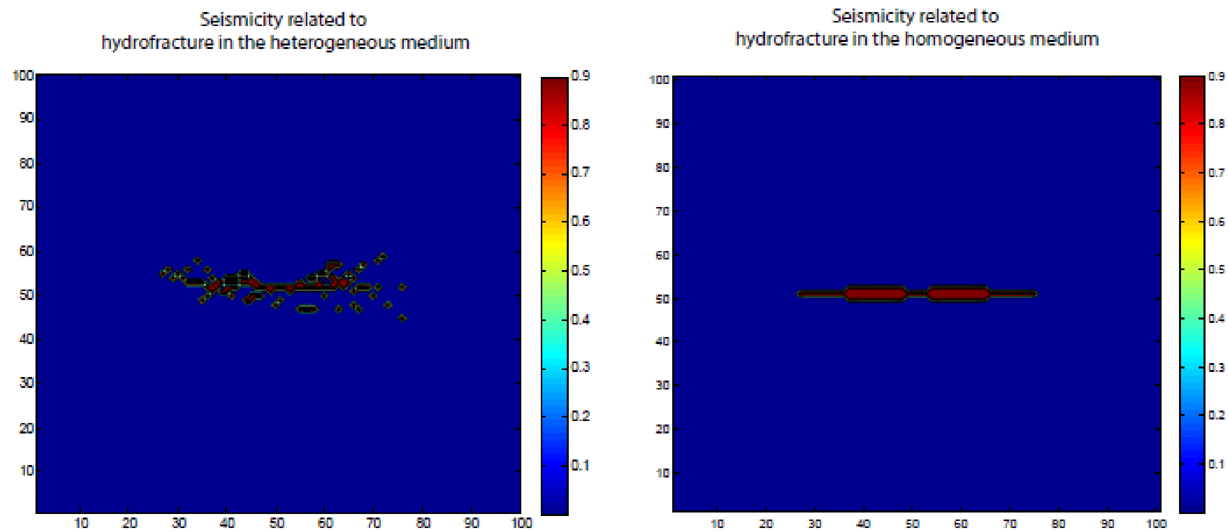

Figure 1: Microseismic events released during the simulation of the hydrofracturing.

Microseismic monitoring is focused currently mostly on the microseismic location, as a sign of the fracture extent, but is should be ultimately used also for the determination of the fracture geometry (length, height and opening) which are required for production assessment. The hydraulic fracture results from coalescence of small cracks but it is large-scale and pressurized and must be therefore computed using fracture mechanics. However, its growth at the tip is thought to be recognized by the detection of the tensional events based on the assumption of the tensional force opening the fracture. So far, however, the tensional events have not been detected, because the pressure field used was not recognizing the effect of the fracture on the flow. We intend to couple fracture mechanics model with the model described here in future work.

Based on our numerical results for a simple homogeneous medium, the mode of deformation is largely dependent on the regional stress field. When the difference in the regional stress magnitudes is high, the individual cracks develop under the shear mode. If the rock is close to failure, the predicted seismic moment tensors show more than 90% of the double-couple component, whereas if a high fluid pressure is needed to fracture the rock, the resulting seismic moment tensor shows both double-couple and volumetric components. When the difference in the regional stress magnitudes is small, events below the tensional failure criterion occur. The modeled seismic moment tensor is 40% double-couple, 30% volumetric and 30% clvd. The occurrence of tensional events is dependent on the injection rate.

Conclusions

The numerical simulations successfully predict the orientation of the hydrofracture parallel to the maximum stress orientation. For homogeneous rocks, the observed microseismicity will form a narrow belt whereas the belt will be wider for heterogeneous rocks. For the homogeneous rock, the mode of deformation is heavily dependent on the regional stress field and its proximity to the failure. For the active regions where the regional differential stress is high, or at larger depths, the failure, even though activated by fluids, will be mostly in the shear regime. The events that occur under the tensional stress conditions (at least for one stress axis) are possible only under the regional stress field close to the hydrostatic conditions. These events will be seismically recorded as a failure that has significantly low of shear component (~40%), and significant volumetric and clvd components (30%). Both end-members of deformation mode have been recorded. The high double-couple mechanisms were determined for geothermal stimulation in

Soulz, France, (Horalek et al., 2010), the low double-couple mechanisms were found in geothermal field in Java (Foulger and DeLuca, 2009), and both types were detected simultaneously during hydrofracturing in Texas, USA (Sileny at al., 2009).

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