geoconvention
Calgary • Canada • May 15-19 2017

New Stress Inversion Method for Microseismic Data

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Summary

A majority of measurements in the World Stress Map (WSM) project are derived from earthquake focal mechanisms, as this approach provides the most cost-effective way to estimate stress states in the earth crust. However, current methods simplify the problem into pure shear faulting, which is not optimal for hydraulic fracturing where a large amount of fluid injected into the reservoir to induce tensile opening. This contribution introduces a new algorithm to invert the stress states from microseismic data. We introduce a generalized Bott hypothesis to accommodate hybrid (tensile-shear) failure mechanisms, and allow for out-of-plane slip vector. For accuracy assessment, a suite of synthetic data is constructed to conduct forward modelling. Results show that principal stress orientations are successfully recovered under different loading condition and failure modes from the new program. Finally, we apply our new method to a mircoseismic dataset from the Barrnet shale in the Fort Worth Basin, Texas. A disturbed effective stress state is obtained with a sub-horizontal maximum principal stress oriented in the NE-SW direction.

Introduction

A cost-effective way of estimating the stress state is to conduct the formal stress inversion for the best fitting stress orientation when a set of focal mechanisms is available within the studied area. Current stress inversion methods are limited to double-couple (shear) source mechanisms. This limitation is less significant for tectonic earthquakes, where double-could mechanisms predominate. One big contribution to the non-double-couple (non-DC) components of moment tensor is a tensile source. Earthquakes associated with tensile opening or closing are called tensile earthquakes (Vavrycuk, 2001; Vavrycuk, 2011). The occurrence of tensile earthquakes is particularly linked to fluid rich areas, such as geothermal and volcanical environments. Furthermore, in oil and gas reservoirs, hydraulic fracture treatments induce large amount of microseismic events typically with magnitude lower than 0. Among all these microearthquakes, 'wet' mircoseismic events are directly related to volume changes due to fluid injection, which in turns leads to non-double-couple components (Sileny, 2009). That means these events are unlikely to satisfy the traditional Bott hypothesis (requiring pure double-couple sources) assumed in the current stress inversion algorithm as their slip directions deviate from the fracture surface causing tensile opening or closing.

The goal of this paper is to present a stress inversion algorithm for tensile earthquake focal mechanisms to provide better insights on hydraulic fracturing design, optimizing completion process and maximizing production. The tensile earthquake model considers the inclination angle α (the angle between the slip vector and the projected slip vector on the fault plane) adding flexibility to the slip vector along the normal direction with respect to the fault plane. As the tensile earthquake model associates with crack opening and closing, here we call it hybrid events instead of tensile events. Additionally, a MATLAB package is present, which is modified after the original Vavrycuk's stress inversion code: a linear stress inversion method based on the Michael's method (Vavrycuk, 2014). In order to test the reliability of the code under various conditions, a suite of synthetic data is generated and divided into separate schemes based on failure modes and stress regimes. In the last section, the stress inversion package is applied to the microseismic dataset collected from the Barrnet shale formation located in the Fort Worth Basin, Texas.

Theory

Traditional Stress Inversion Method for Shear Earthquake Model

The original linear stress inversion method proposed by Michael (1984) follows the assumption of Bott hypothesis:

$$\hat{\tau} = \frac{\vec{\tau}}{|\vec{\tau}|} = \hat{s}$$

where $\hat{\tau}$ is the shear stress on the fault plane, $\hat{s}$ is the unit slip vector. The resolved shear stress on the fault plane can be expressed as:

$$\tau_i = \sigma_{kj} n_j (\delta_{ik} - n_i n_k)$$

where **n** is the fault normal vector, σ is the stress tensor and δ is the Kronecker delta. Assuming the magnitudes of resolved shear stress for all events are 1, one can get a linear relationship between $\hat{\tau}$ and $\hat{s}$. After stacking all the observations, we can get:

$$\mathbf{A}^i \sigma_r = \hat{s}^i$$

where the superscript i implies the i^{th} measurement of the whole fault group. This can be solved using the linear least square method. Once the reduced stress tensor is obtained, the principal stress directions and shape ratio R = $(\sigma_1 - \sigma_2)/(\sigma_1 - \sigma_3)$ can be calculated as well. Vavrycuk's code basically follows the theory described above but make changes to the fault plane picking process and the accuracy test.

New Stress Inversion Method for Tensile Earthquake Model

To accommodate the tensile components of fluid-driven earthquakes, Vavrycuk (2001) proposed a tensile earthquake model, in which the slip vector does not lie within the fault plane. Unlike the shear source model, the tensile earthquake model is described by four angles: strike θ, dip δ, rake λ and inclination angle α, defined as the deviation angle of the slip vector from the fault plane. The α value is directly related to fault failure modes, which ranges from 90° for pure tensile events (Mode I) to -90° for pure compressive events, and when it is 0°, the source is pure shear (Mode II and III). Other than those three end members, earthquakes caused by mixed source mechanisms is defined as 'hybrid events' to distinguish them from events consisting of a single failure mode. We introduce generalized Bott hypothesis to add more flexibility to the fault movement in three dimensions. In generalized Bott hypothesis, the direction of slip vector is assumed to be parallel with the integrated traction vector of the fault surface.

A major challenge for all stress inversion methods is clearing the fault plane ambiguity due to the interchangeable nature of two nodal planes. Correct selections on the fault plane can significantly improve the inversion accuracy as the fault geometry is a key input (Michael, 1987). For shear-tensile failure, composite Griffith-Coulomb failure criteria enables us to quantify the susceptibility of faults by comparing the maximum shear stress on the fault plane with a corresponding critical value. Once the shear stress τ exceeds a critical value, the fault fails.

A MATLAB package is developed and modified from Vavrycuk (2014) code aiming to solve the stress inversion problem for tensile earthquake model. This tensile earthquake stress inversion package, abbreviated as TESI, is composed of four main parts:

1. Pre-inversion obtaining input data and parameters.

2. Stress inversion in iterations based on noise-free data.
3. Stress inversion from noisy data for accuracy analysis.
4. Post-inversion, plotting all the results.

This program is then applied to a synthetic catalog and a microseismic dataset recorded from the Barrnet shale in the Fort Worth Basin, Texas. Results are compared with those obtained from the original shear earthquake model.

Examples

Synthetic Tests

We created a 2D fault geometry grid by uniformly distributing the strike angle and the dip angle in the range of (0°, 360°) and (0°, 90°), respectively, to cover the whole range of fault geometry without any bias. Under the pre-define stress condition, faults that are activated are selected based on the composite Griffith-Coulomb failure criteria and the corresponding moment tensors are generated. In this case, we assume normal faulting stress regime with $\sigma_v = 50MPa, \sigma_H = 30MPa, \sigma_h = 10MPa, and\ Pp = 15MPa$. The dataset is split into two parts based on their failure modes: shear dominated faults (|α|≤30°) and hybrid faults (|α|>30°). Those two parts are input into both the Vavrycuk's original source code and the TESI code. Results are indicated in Figure 1. As expected, for shear events, both inversion algorithms recover the stress states and the fault geometries properly. On the other hand, for hybrid events, stresses inverted from the shear earthquake model show significant deviations comparing to the tensile earthquake model. For the shear model, the deviations of the principal axes are up to 15° from the true value.

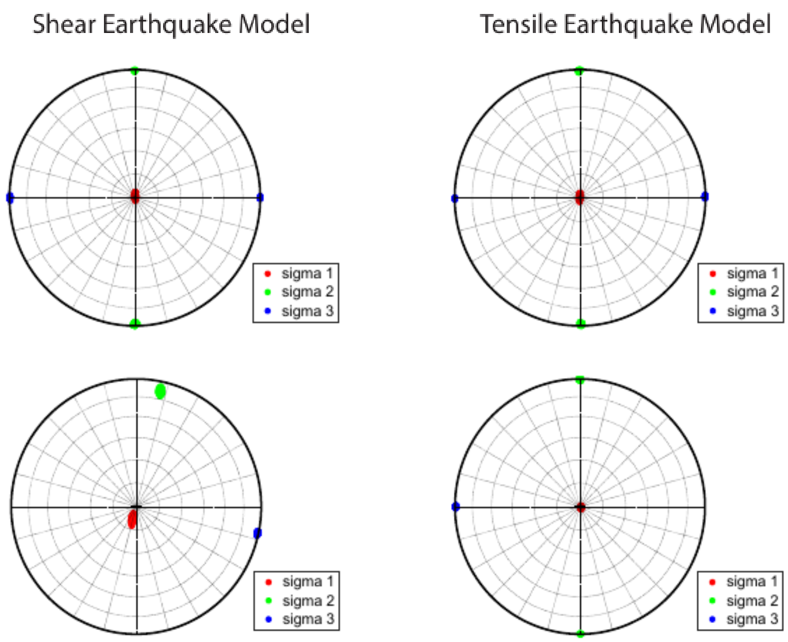

Figure 1. Stereonets shows stress inversion results in the normal faulting stress regime based on both shear earthquake model and tensile model. Upper panel: shear source mechanisms. Lower panel: Hybrid events.

Application to the Microseismic Dataset

The stress inversion approach was used on the Stocker microseismic dataset acquired by ConocoPhillips in 2010. The detailed description of the dataset and the geology of the studied area can be found in Busetti (2014a), and Busetti (2014b). Previous data from wellbore breakouts and WSM map indicate an overall maximum 'sub-horizontal' stress in the NE-SW direction. The complete catalog consists of 7444 microseismic events. This analysis aims to invert all the events for stresses using both shear and tensile model. Figure 3 plots the overall results in stereonets. Smaller clusters of noisy stress axes indicate both models provide stable and robust inversion results. The σ_1 is subhorizontal striking 0° for shear model and 15° for tensile model. Although both strike angle of σ_1 is small, the stress obtained from the TESI program is more consistent with the stress state estimated from previous interpretations. This new method introduces a small but significant angular rotation of the principal stress axis, which could be important for the design processes.

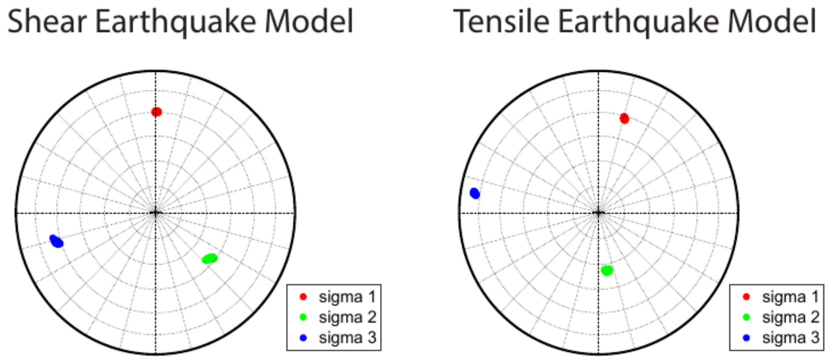

Figure 3. Stress inversion results of the microseismic dataset are shown in steronets.

Conclusions

A new iterative stress inversion algorithm is developed based on the tensile earthquake model. The tensile/compressive components are included in the inversion by assuming a generalized Bott hypothesis allowing movements of the slip vector in three dimensions. A MATLAB package called TESI is developed based upon the original Vavrycuk's code and the new inversion technique to facilitate the stress inversion on microseismic data. Synthetic tests are carried out to test the reliability of TESI code, and results show the new stress inversion method can successfully recover the principal stress orientations and stress regime. The TESI code is also applied to the microseismic data obtained from the Barrnett Shale in the Fort Worth Basin, Texas. This requires further investigation to link the results to the geomechanical processes through numerical simulations or acoustic emissions for a better insight.

Acknowledgements

The author would like to thank the sponsors of the Microseismic Industry Consortium for financial support. ConocoPhillips is thanked for providing the Stocker dataset. I also want to thank Qiang and Megan for their generous help.

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