PS Development of an Analytical Method Based on Two Failure Criteria to Study Slip Risk Related to Fluid Injection: Case Study North-Central Oklahoma, U.S.A.*

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Abstract

The increment in induced seismicity in North-Central Oklahoma has been related to saltwater disposal wells. Despite the many studies that have been completed to understand the main cause of the induced earthquakes related to disposal wells in the Arbuckle Formation, more studies are required to predict the areas and operational conditions where fluid injection could trigger fault slip. This study aims to identify the parameters with higher and lower impact in fault slip, and it is divided into three steps. First, we created an analytical model based on the Mohr-Coulomb criteria and the modified slip tendency, parameters that indicate the risk of slip on a fault. This model considers the stress field, the azimuth of the maximum horizontal stress, pore pressure, friction coefficient, Biot coefficient, and the geometry (orientation and dip) of the fault planes in three-dimensions. Then, we use data from previous studies in the area (Walsh and Zoback, 2016) to verify our model. Finally, with a sensibility analysis, we determine the fault reactivation potential when varying each of the parameters in our model.

We conclude that the fault geometry with respect to the azimuth of maximum horizontal stress is the most important parameter that triggers fault slip. Variations in pore pressure are also important in fault slip. While in normal and strike regimens, like North-Central Oklahoma, an increase in pore pressure leads to fault slip; in reverse regimens, a decrease in pore pressure may lead to fault slip. With this study, we propose a practical analytical model to identify the relationship between the fault geometry and pore pressure needed to avoid fault reactivation in North-Central Oklahoma.

DEVELOPMENT OF AN ANALYTICAL METHOD BASED ON TWO FAILURE CRITERIA TO STUDY SLIP RISK RELATED TO FLUID INJECTION: CASE STUDY NORTH-CENTRAL OKLAHOMA, U.S.A.

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Abstract

The increment in induced seismicity in North-Central Oklahoma has been related to saltwater disposal wells. In spite many studies have been completed to understand the main cause of the induced earthquakes linked to saltwater injection in the Arbuckle Formation, more studies are required to predict the areas and operational conditions where fluid injection could trigger fault slip. This study aims to identify the parameters with higher and lower impact in fault slip, and it is divided into three steps. First, we created an analytical model based on the Mohr-Coulomb criteria and the Modified Slip Tendency (Tsm), parameters that indicate the risk of slip on a fault. This model considers the stress field, the azimuth of the maximum horizontal stress, pore pressure, friction coefficient, Biot coefficient, and the geometry (orientation and dip) of the fault planes in three-dimensions. Then, we use data from previous studies in the area (Walsh and Zoback, 2016) to verify our model. Finally, with a sensibility analysis, we determine the fault reactivation potential when varying each of the parameters in our model. The coefficient of friction (u), the dip of the fault and the pore pressure (Pp) were the parameters that influenced the most in fault reactivation. With this study, we propose a practical analytical model to identify the relationship between the fault geometry and pore pressure needed to avoid fault reactivation in North-Central Oklahoma.

Introduction

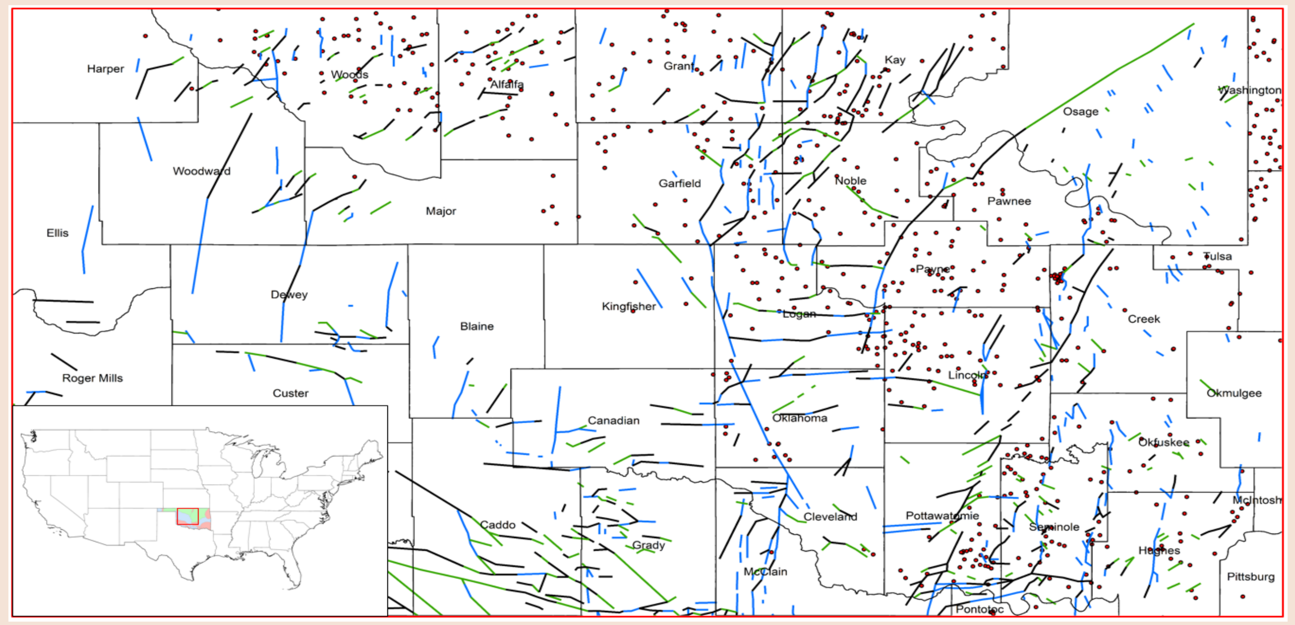


Fig. 1: Location of the study area (Central Oklahoma, US) with the mapped faults (OGS) and the disposal wells in the Arbuckle formation (DrillingInfo). Faults with more probability (optimal) to have an earthquake within the contemporary stress field are represented in green; moderately optimal faults (black) and sub-optimal faults (blue) are also depicted.

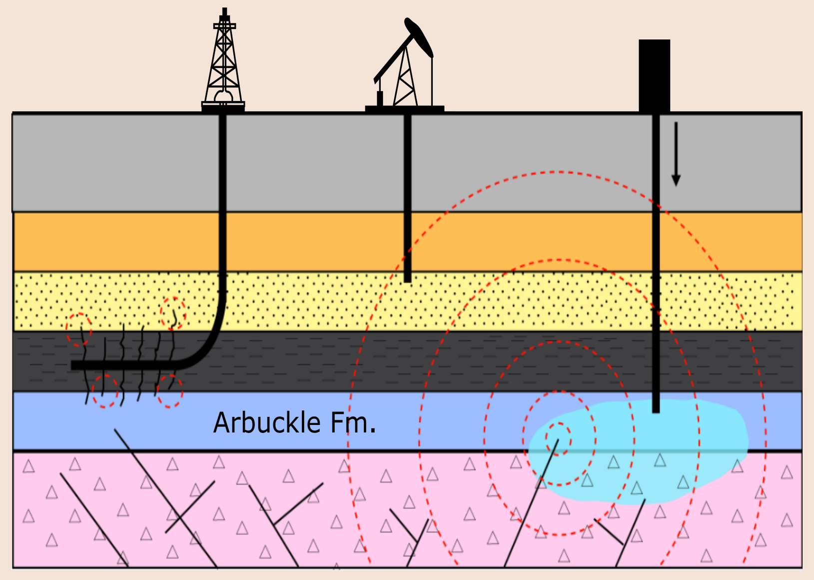
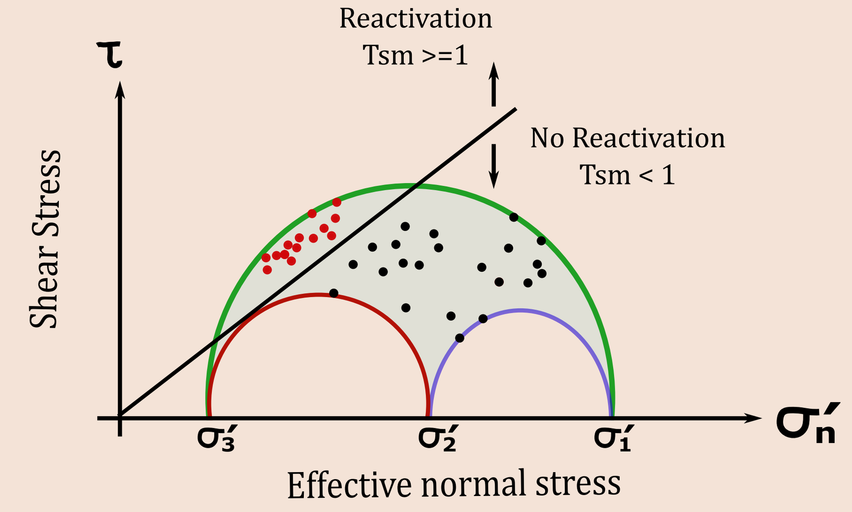


Fig. 2: Previous studies have concluded that the induced earthquakes are related to disposal wells rather than hydraulic fracturing. Both, the injection of saltwater in the Arbuckle Formation and faults in the basement are linked to the increase in seismicity in Central Oklahoma since 2009, approximately. More studies are required to predict the areas and operational conditions where fluid injection could trigger fault slip. This study aims to identify the parameters with higher and lower impact in fault slip.

Methodology

- Methods
  - Formulate research problem
  - Review the context of the research problem
- Define the variables
- Analytical model
- Model verification
- Sensitivity analysis
- Application to North-Central, Oklahoma

Model



Failure Criteria

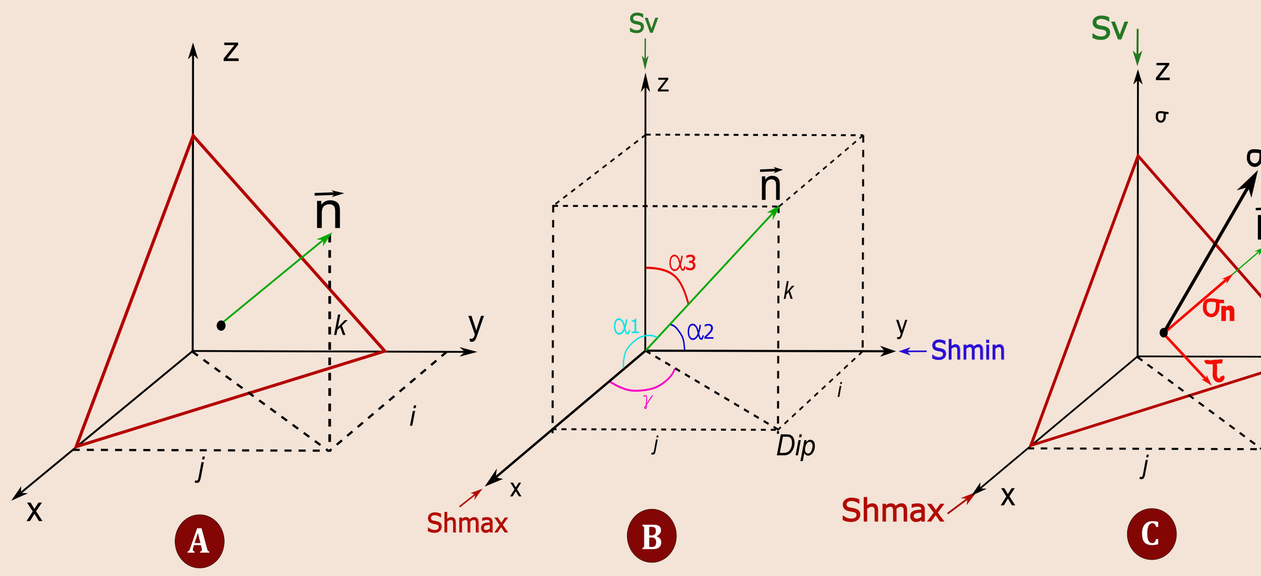
1) Mohr - Coulomb Criteria

$$|\tau s| = So + \mu(\sigma_n - \alpha P_p)$$

2) Modified Slip Tendency

$$Tsm = \frac{\tau}{\tau slip} \geq 1$$

Fig. 3: The analytical model studies the parameters that have the greatest impact on the reactivation of faults. The model seeks to determine, graphically and numerically, the reactivation of faults under high potential scenarios, taking into account the in situ stresses (σ1, σ2, σ3), pore pressure (Pp), Biot´s coefficient (α), friction and cohesion coefficients and the geometry of fault planes (strike and dip).
The criterias for reactivation of faults included in the model were the Mohr-Coulomb graphic method and the numerical method of Modified Slip Tendency (Tsm).



$$\text{I. } \begin{bmatrix}\sigma_{rx}\\ \sigma_{ry}\\ \sigma_{rz}\end{bmatrix} = \begin{bmatrix}\sigma_x & \tau_{yx} & \tau_{zx}\\ \tau_{xy} & \sigma_y & \tau_{zy}\\ \tau_{xz} & \tau_{yz} & \sigma_z\end{bmatrix}\begin{bmatrix}\cos\alpha_1\\ \cos\alpha_2\\ \cos\alpha_3\end{bmatrix}$$

$$\text{II. } \sigma_r = \langle \sigma_{rx}, \sigma_{ry}, \sigma_{rz} \rangle$$

$$\text{III. } \sigma_n = \sigma_r \cdot \vec{n}$$

$$\text{IV. } \tau = \sqrt{\sigma_r^2 - \sigma_n^2}$$

Fig. 4: To represent the fault in 3-D we use a normal vector (n) to the fault plane (A). The angles formed between the normal vector and each of the main stresses (Sv, Shmax, Shmin) are called director cosines (α1, α2, α3), and define the orientation of the fault plane with respect to stress field (B). Then, to find the principal stress (σr) acting on the fault plane (Eq. II), we multiplied the normal vector by matrix (Eq. I). Finally, with this principal stress and the normal vector we calculated the normal and shear stresses (C) (Eq. III and IV) necessary to execute the model.

Model verification

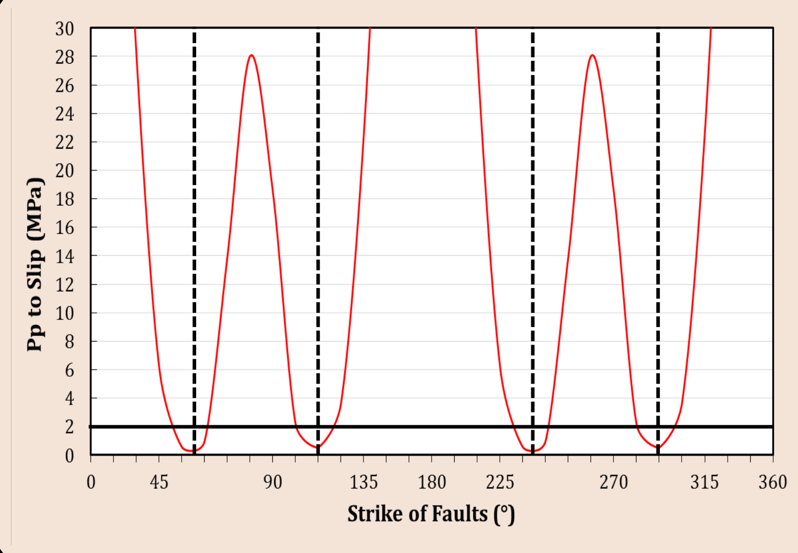


Fig. 5: We used the data from Walsh and Zoback (2016) to compared and verify our model.
The authors defined 6 areas to carry out their study, however, we only use the data from area 6 to execute the model. We use their data as the input for our model and we obtained consistent results. Both models recognized that fault planes with dip of 89° and strikes of 55°, 110°, 235°, 290° approximately, are the most prone to the reactivation with minimum changes in the pore pressure between 0.3 - 2 Mpa.

Sensitivity analysis

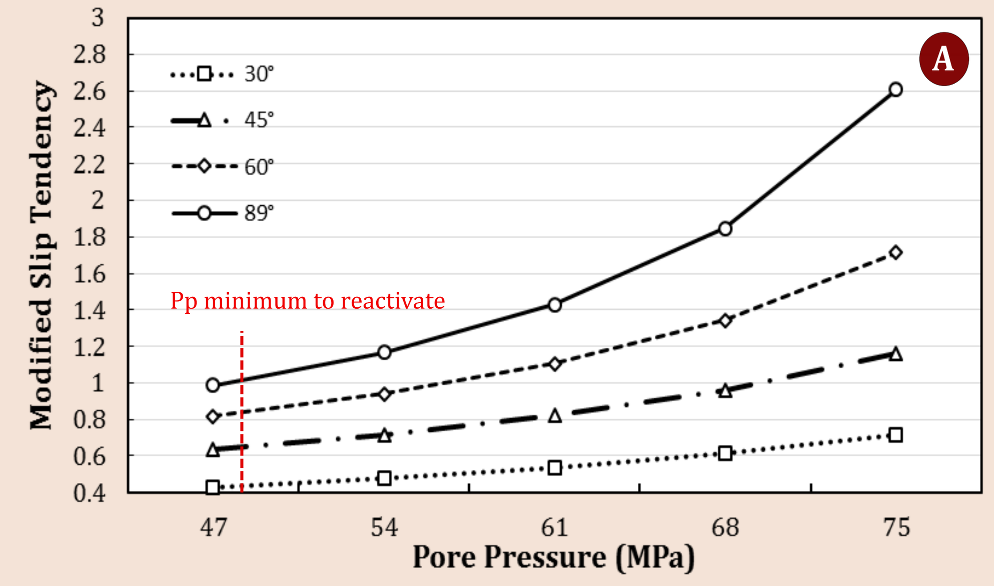
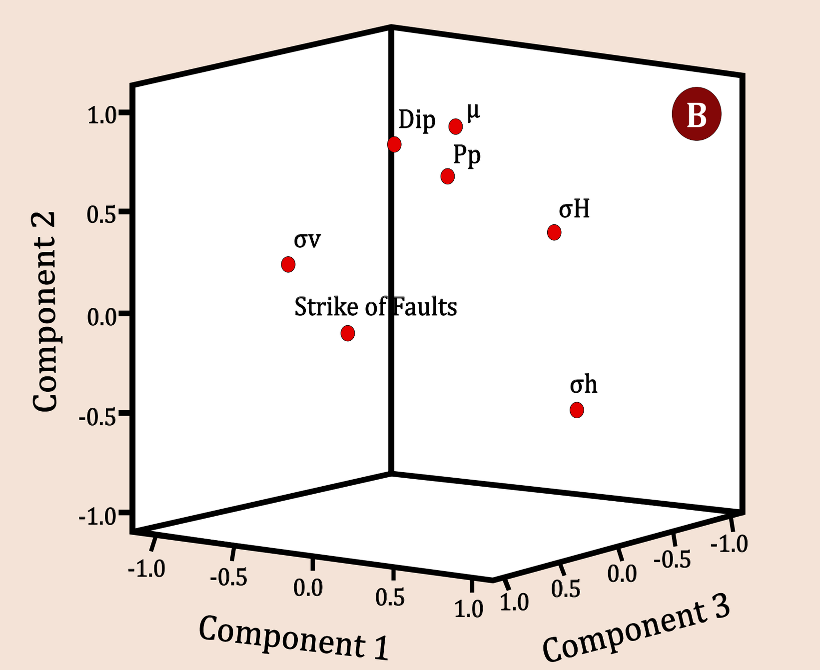


Fig. 6: The geometry of the fault (Strike and Dip), the pore pressure (Pp), the effective stresses and the coefficient of friction were the variables with the most influence on the sensitivity analysis.
We observed that for the case study in which the model was applied, the planes with high dip values will be prone to reactivation with slight changes in the pore pressure (A).

A principal component analysis (PCA) of the variables showed that, although there is a correlation between some of the original variables, others do not correlate and are grouped into different components (PC1, PC2, PC3) (B), each of them being responsible for the risk of reactivation due to their individual variations.

Principal Component Analysis



Correlation matrix

	σv	σH	σh	Pp	μ	Strike of fault	Dip
σv	1.000	-.794	-.899	.003	.164	-.185	.186
σH	-.794	1.000	.447	.230	.267	.233	.296
σh	-.899	.447	1.000	-.164	-.437	.105	-.487
Pp	.003	.230	-.164	1.000	.392	.054	.282
μ	.164	.267	-.437	.392	1.000	-.167	.499
Strike of fault	.185	.233	.105	.054	-.167	1.000	-.058
Dip	.186	.296	-.487	.282	.499	.058	1.000

	PC1	PC2	PC3
Standard deviation	1.6250	1.4343	1.0005
Proportion of Variance	0.3772	0.2939	0.1430
Cumulative Proportion	0.3772	0,6711	0.8141

Conclusions

- The coefficient of friction (u), the dip of the fault and the pore pressure (Pp) were the parameters that influenced the most in fault reactivation.

- The planes with high dip values are prone to reactivation with slight changes in the Pp.

- The coefficient of friction is related to the lithology of the rock. Therefore, the rock is an important criterion on fault reactivation.

Acknowledgements

All Consortium Members

- Hawkes, C.D., McLellan, P.J., Zimmer, U. and Bachu, S., 2004, January. Geomechanical factors affecting geological storage of CO2 in depleted oil and gas reservoirs: risks and mechanisms. In Gulf Rocks 2004, the 6th North America Rock Mechanics Symposium (NARMS). American Rock Mechanics Association.
-Walsh III, F.R. and Zoback, M.D., 2016. Probabilistic assessment of potential fault slip related to injection-induced earthquakes: Application to north-central Oklahoma, USA. Geology, 44(12), pp.991-994.
- Zoback, M.D., 2010. Reservoir geomechanics. Cambridge University Press.