Poroelastic stresses and pore pressure in media with anisotropic permeability and its implications on fault reactivation.

COOLSTRESS TIEFE GEOTHERMIE

SPONSORED BY THE Federal Ministry of Education and Research

Karlsruhe Institute of Technology

Tatia Sharia[1], Andreas Rietbrock[1], Birgit Müller[2], Thomas Niederhuber[2].

[1] Geophysical Institute (GPI), Karlsruhe Institute of Technology (KIT), Hertzstrase 16, Karlsruhe, 76187, Germany
[2] Institute of Applied Geosciences, Karlsruhe Institute of Technology (KIT), Adenauerring 20b, Karlsruhe, 76131, Germany

Introduction

Fault reactivation depends on the orientation of faults and effective stress state where the latter can be modified by changes in pore pressure. Additionally, total stress is linked to pore pressure through poroelastic coupling. The analytical solution for pore pressure and stress evolution for isotropic media was developed by Rudnicki (1986)[1]. We investigate the coupling processes in media of isotropic and anisotropic permeability using analytical solutions and 3D FEM. We compare analytical solutions of pore pressure for isotropic and anisotropic case. We use the FEM results to derive stresses in anisotropic media and calculate Coulomb failure stress changes and slip tendencies.

Methodology

We use generic 3D numerical models built in COMSOL Multiphysics.
Hydraulic anisotropy uses a diagonal permeability tensor, with 190 mD along the x- and z-axes, and 10 times larger value along the y-axis. Other material parameters correspond to Berea sandstone [2]. The point injection of 120 l/s fluid is at the center of the model.

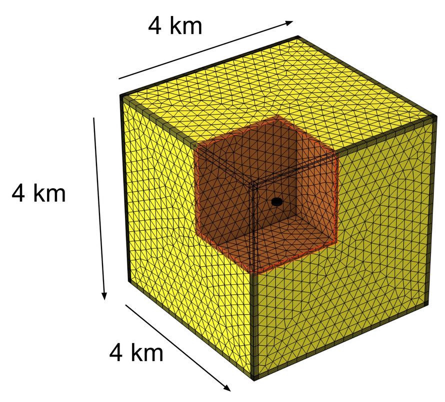

Fig. 1 Numerical Model Dimensions

We use infinite elements to model unbounded media.

Changes in Coulomb Failure Stress Δ CFS

We investigated the evolution of ΔCFS with time and fault orientation.

- For vertical faults aligned parallel to the y-axis (the direction of higher permeability) ΔCFS along the y-axis propagates more rapidly in the anisotropic case (Fig. 3a). For 10 years, the results converge with the isotropic solution (Fig. 3b). In the perpendicular direction, the anisotropic isolines extend over smaller area.

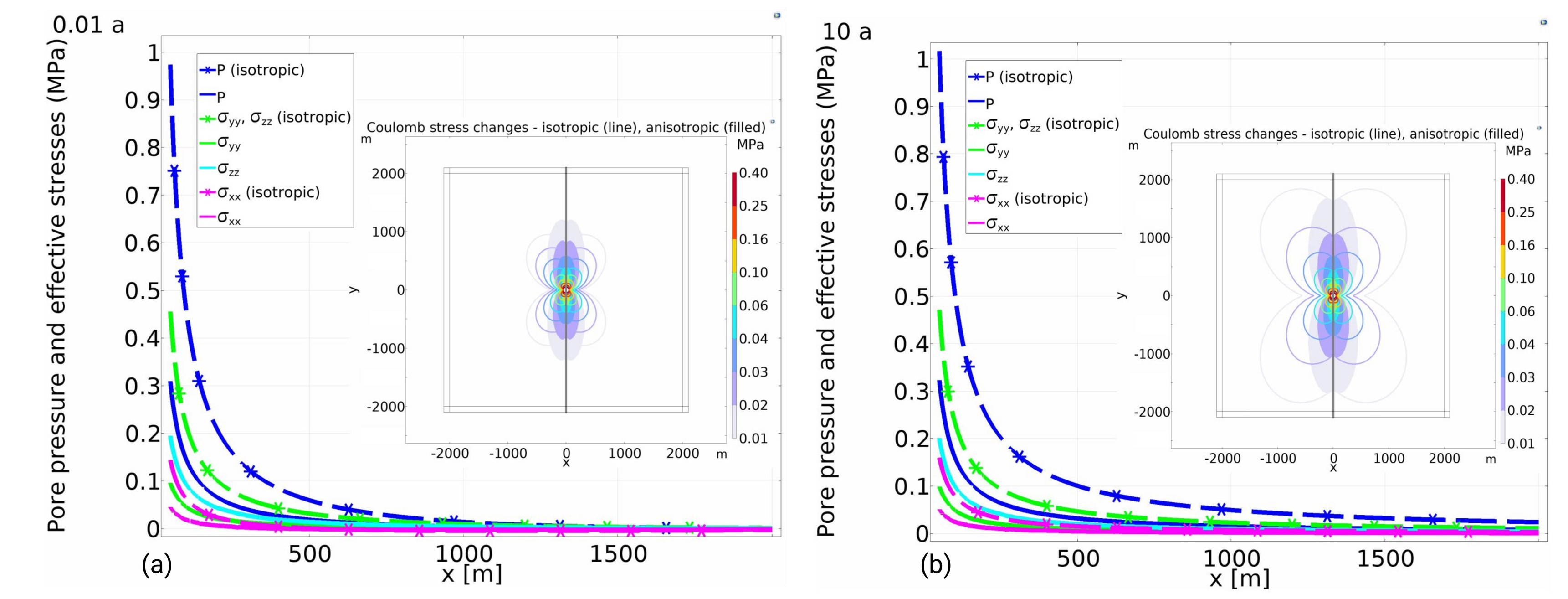

Fig. 3: Comparison of areas of Coulomb Failure stress on vertical planes parallel to the y-axis (axis of high permeability) for different injection times in isotropic and anisotropic media. The individual stress and pressure components along x-axis are displayed in the line plots.

- For vertical faults with different orientations (Fig. 4), the distribution of ΔCFS in the isotropic case rotates with fault orientation. In the anisotropic case, the areas defined by specific ΔCFS thresholds (e.g., 0.01 MPa) vary significantly. This variation could influence the size of the fault segment susceptible to reactivation.

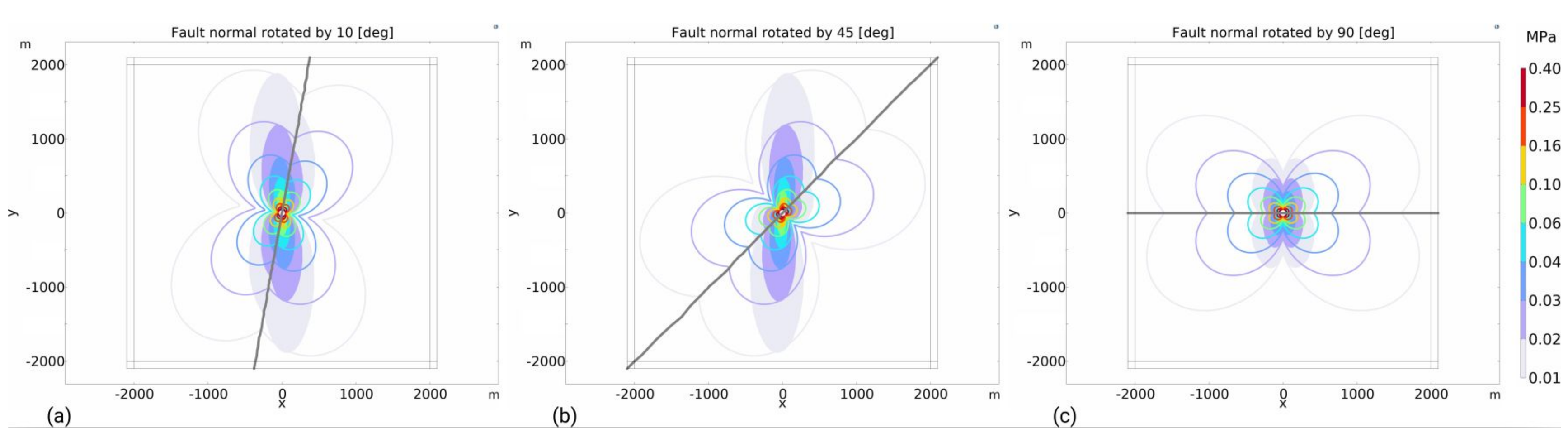

Fig. 4: As Fig. 3 but for vertical faults rotated by 10, 45 and 90 degrees with respect to the y-axis for a 10 year injection.

Conclusion and Outlook:

- In anisotropic media the difference in spatial and temporal evolution of pore pressure strongly depends on the considered location (Fig. 2). The resulting stress fields exhibit similar distribution patterns to those of pore pressure (Fig. 3).
- The permeability anisotropy induces a concentration of positive Coulomb Failure stress changes along the axis of high permeability (Fig.4). Its effect on slip tendency seems to be small on considered case, it requires further study.
- These stress changes should be considered in projects of wastewater injection or geothermal circulation in fractured reservoirs especially near critically stressed faults.

Pore Pressure in Anisotropic Medium

The analytical solution for pore pressure evolution in anisotropic media resulting from continuous point fluid injection into an unbounded domain has been derived [4]:

$$p(x,y,z,t) = \frac{q_v\gamma}{4\pi\sqrt{k_{xx}k_{yy}k_{zz}}\sqrt{\frac{x^2}{k_{xx}}+\frac{y^2}{k_{yy}}+\frac{z^2}{k_{zz}}}} \times erfc\left(\frac{1}{2\sqrt{t/(S\gamma)}}\sqrt{\frac{x^2}{k_{xx}}+\frac{y^2}{k_{yy}}+\frac{z^2}{k_{zz}}}\right)$$

q_v - Volumetric injection rate
k_{ii} - Permeability
γ - Viscosity
S - Specific storage

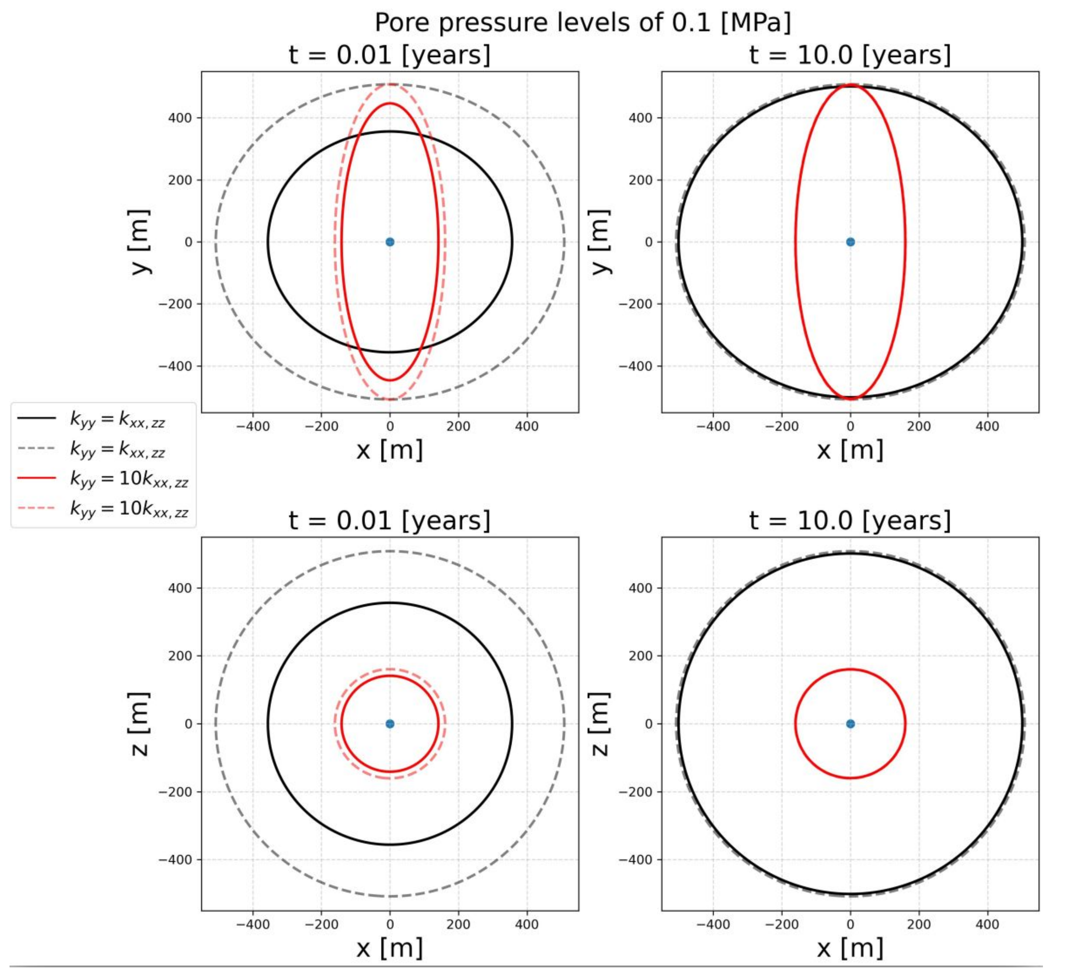

Fig. 2: Pore pressure isolines for different injection times in isotropic and anisotropic media. Black lines correspond to isotropic case, red lines correspond to anisotropic one with 10 times higher permeability at y direction. Dashed lines are steady state limits of the pressure values.

Results:

- xy plane: pore pressure evolution in anisotropic medium is faster in direction of k_{yy}. The steady state value converges to isotropic case.
- xz plane: Areas of p >= 0.1 MPa are reduced in comparison of isotropic case.
- Overall volume with p >= 0.1 MPa has decreased by factor of 10 in anisotropic case.

Comparison of Slip Tendencies for Isotropic and Anisotropic Media

Fault reactivation can also be assessed using Slip Tendency [3], defined as the ratio of shear stress to normal stress on a fault. Fig. 5 presents slip tendencies and stress distributions after 10 years of fluid injection, shown as a function of fault orientation at specific locations along the y-axis and x-axis, respectively. This is based on a background stress field with Sx=26 MPa , Sy=46 MPa and Sz=46 MPa and P=20 MPa.

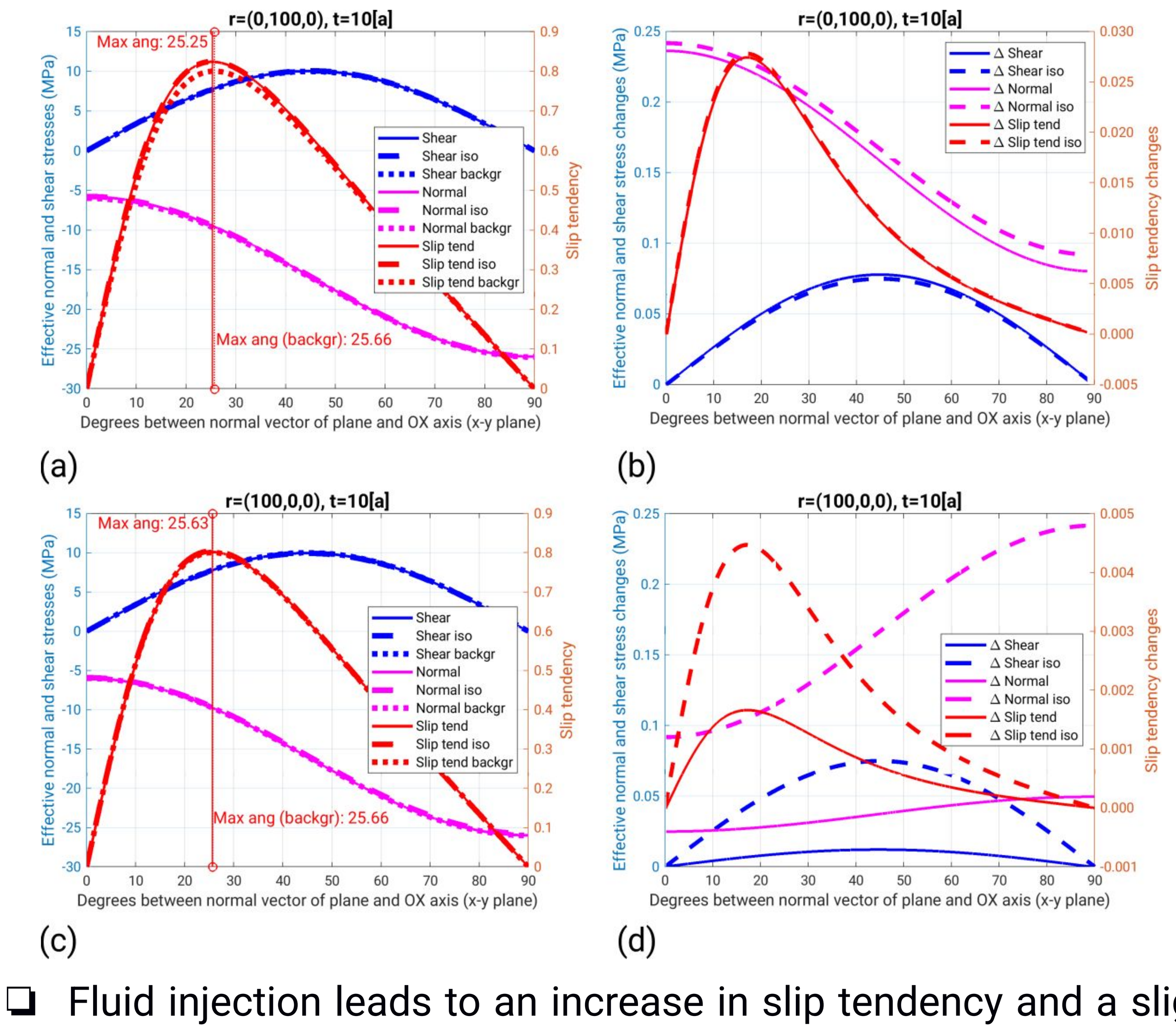

Fig. 5:

a) and c) Slip Tendency and stresses at location r = (0, 100, 0)[m] and (100, 0, 0)[m] for 10 years injection into an anisotropic medium with $k_{yy}=10k_{xx,zz}$ and a medium with isotropic permeability $k_{yy}=k_{xx,zz}$

b) and d) Stress and slip tendency changes at location (0, 100, 0)[m] and (100, 0, 0)[m].

Dotted lines indicate the case of the background stress field without injection.

Dashed lines indicate isotropic medium and solid lines anisotropic medium with injection.

- Fluid injection leads to an increase in slip tendency and a slight rotation of the fault orientation associated with the maximum slip tendency at the point along the y-axis. Along the x-axis, changes in slip tendency and optimal fault orientation are minimal.
- The effect of permeability anisotropy on slip tendency of different fault orientations is minor.

References:
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[3] Alan Morris, David A. Ferrill, D.Brent Henderson; Slip-tendency analysis and fault reactivation. Geology 1996;; 24 (3): 275–278
[4] Tatia Sharia, Thomas Niederhuber, Birgit Müller, and Andreas Rietbrock, Pore pressure evolution in media with isotropic and anisotropic permeability - 3D numerical models and analytical solutions, 2025. (in prep)

Acknowledgement: This work was carried out as part of the COOLStress project (grants 03G0935A) sponsored by the federal ministry of education and research.