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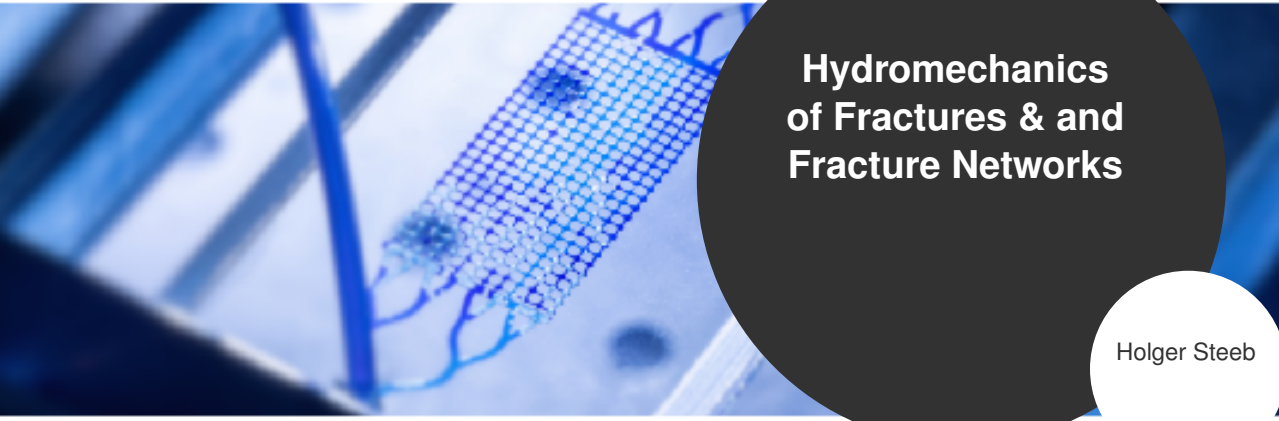

Hydromechanics of Fractures & and Fracture Networks

Holger Steeb

SFB 1313

P|M|L
Porous Media Lab

SimTech

Fracture characteristics

- aspect ratio: ratio of fracture length to fracture width $r_f = l/\delta$
- investigation of fractures with ratios $r_f \gg 10^5$
- transmissivity & storativity
- fractures embedded in matrix: hydro-mechanical coupling (inverse pressure response)

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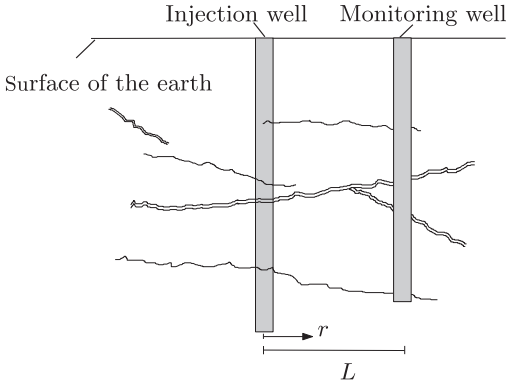
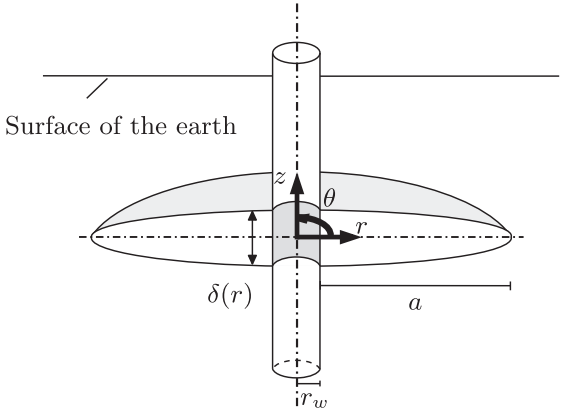
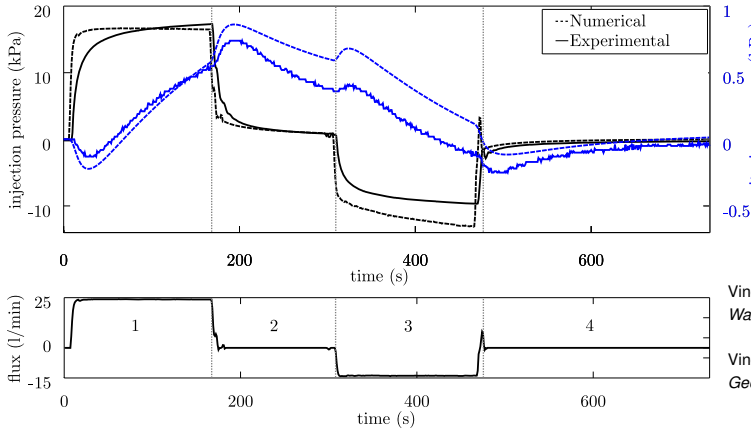
Fracture characteristics - typical borehole configuration





Numerical vs. experimental observations

- pressure evolution at injection borehole (black lines) & monitoring borehole (blue lines)
- numerical solutions (dashed lines) and field data (solid lines)
- vertical dashed lines: (1) injection, (2) pause, (3) production, and (4) pause



Vinci, Renner, Steeb (2014)
Water Resour. Res, **50**, 1616-1635

Vinci, Steeb, Renner (2015)
Geophys. J. Int., **200**, 1613-1626

Fracture characteristics - modelling issues

- coupling of governing PDEs (fracture - (poro)elastic matrix)
- aspect ratio of fracture leads to discretization problem for (D)irect (N)umerical (S)imulations (meshing, # of DOFs)
- coupling techniques of fracture and solid matrix needs to be identified

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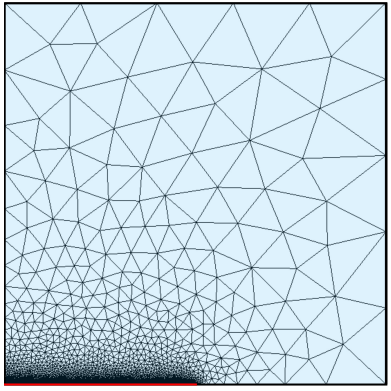
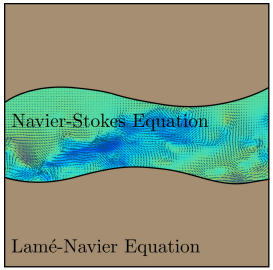
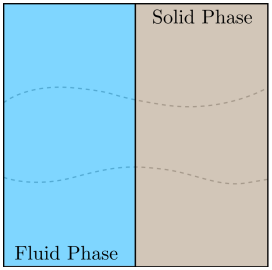


Modelling fractures - a matter of complexity



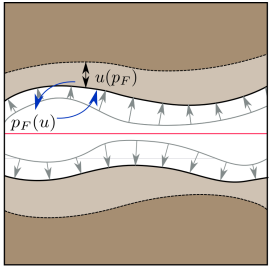
DNS

- strong coupling conditions at interface free flow - solid matrix
- fluid properties are not restricted (e.g. Re-number)
- efficient/necessary for e.g. discretizations with $r_f \ll 10^4$



poroelastic approach

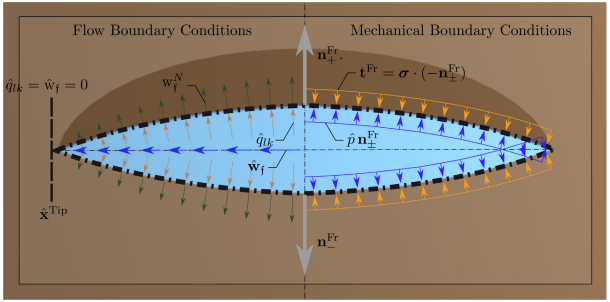
- modeled with Biot's poroelastic equations
- coupling due to coarse-grained momentum interaction
- large defs. within fracture lead to extended formulations

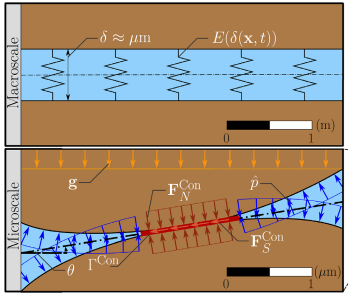


hybrid-dimensional

- introduces a priori assumptions for fluid domain
- naturally covers large deformations within fractures (BCs)
- also efficient for high aspect ratios $r_f \gg 10^5$

Modelling fractures - a matter of complexity





… some modelling aspects (hybrid-dimensional approach)

- **incl. effective fracture stiffness / effective stress concept**
- leak-off effects (porous rock)
- deformable fracture & poro-elastic rock & fluid flow in fracture

Governing equation - hybrid-dimensional formulation

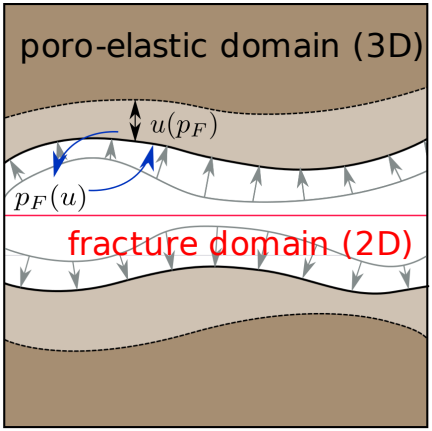
$$\frac{\partial p}{\partial t} - \left[\frac{\delta^2}{12\,\eta^{\mathfrak{f}R}}\right]\left(\frac{\partial p}{\partial x}\right)^2 - \left[\frac{\delta}{12\,\eta^{\mathfrak{f}R}\,\beta^{\mathfrak{f}}}\right]\frac{\partial p}{\partial x}\frac{\partial \delta}{\partial x} - \left[\frac{1}{12\,\eta^{\mathfrak{f}R}\,\beta^{\mathfrak{f}}}\right]\frac{\partial}{\partial x}\left(\delta^2\,\frac{\partial p}{\partial x}\right) + \left[\frac{1}{\delta\,\beta^{\mathfrak{f}}}\right]\frac{\partial \delta}{\partial t} = \frac{w^{\mathfrak{f}R,N}}{\delta\,\beta^{\mathfrak{f}}}$$

1. transient
2. quadratic (nonlinear)
3. convection
4. diffusion
5. coupling

Vinci, Renner, S. (2014) *Water Resour. Res.*, **50**, 1616-1635

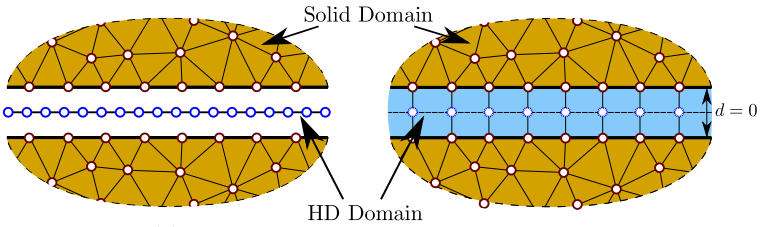
Governing equation - hybrid-dimensional formulation

How do we couple now the (3D) poro-elastic domain with the (2D) fractures?



Governing equation - hybrid-dimensional formulation

- FE approach: strong coupling vs. weak (staggered) coupling

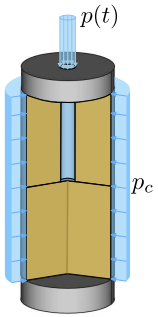


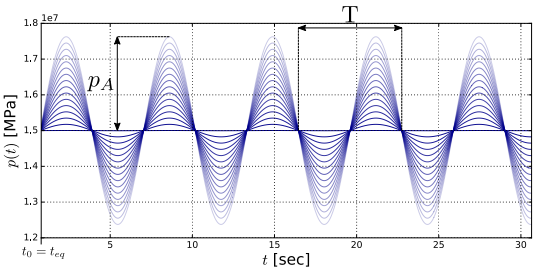
Schmidt, S. (2019) *Int. J. Geomath. (GEM)*, **10**, Doi:10.1007/s13137-019-0127-5

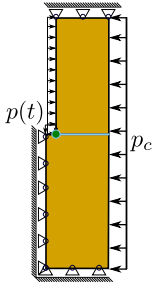
- FE approach: Biot's equations

Adachi et al. (2007) *Int. J. Rock Mech. Min. Sci.*, **44**, 739-757
Segura (2008) *Int. J. Num. An. Met. Geom.*, **32**, 2083–2101

Modelling for **lab scale** experimental analysis

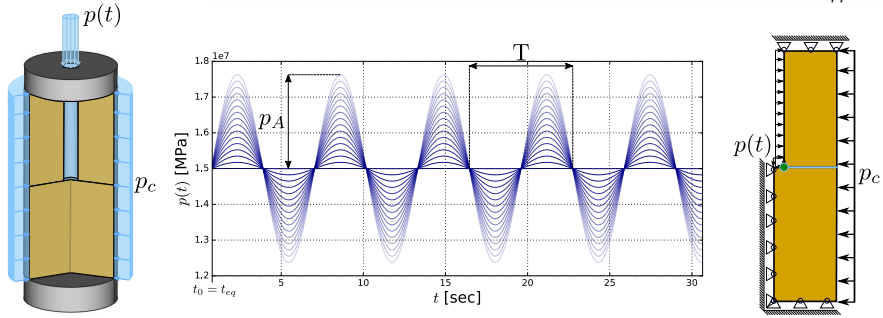






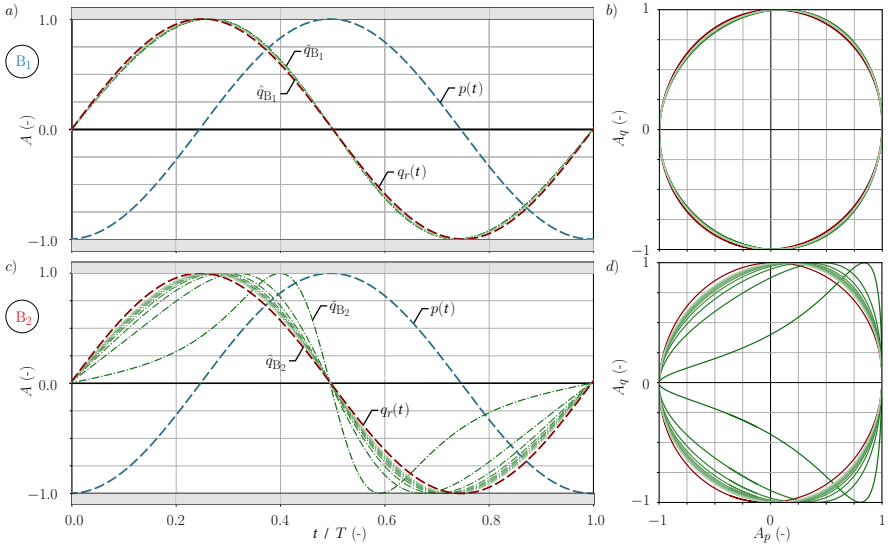
Modelling for **lab scale** experimental analysis

Schmidt, Steeb, Renner (2023)
Pure Appl. Geophys., **180**, 2841-2860

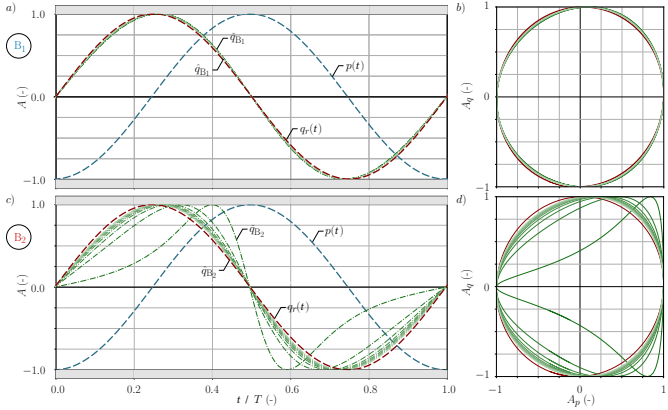


- sample dimension r = 15 mm, h = 75 mm
- equilibrium state for confining pressure (20 MPa) and constant upstream pressure (15.0 MPa)
- fracture stimulated by $p(t)$ = 15.0 MPa - 2 π p_A $\sin(t - t_{eq})$

Modelling for **lab scale** experimental analysis



Modelling for **lab scale** experimental analysis



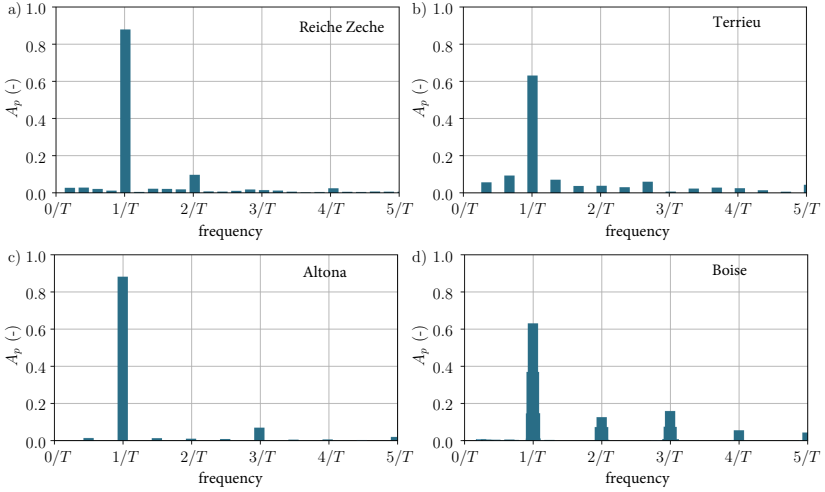
- large fracture deformations lead to **non-linear** relationship between pressure and flux
- permeabilty variations result in **non-constant pressure-flux phase shifts** within one period T

From **lab scale** (back) to **field scale**

Investigation of the records of (different) field studies that employed harmonic pumping

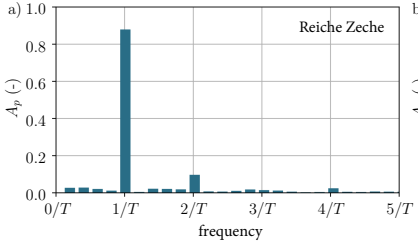
- **Reiche Zeche** underground-research laboratory (RZ), Freiberg, Germany (Renner et al., 2021)
- **Terrieu karstic field**, near Montpellier, France (Fischer et al., 2018)
- **Altona Flat Rock Site**, Clinton County, NY, USA (Guiltinan and Becker, 2015)
- **Boise Hydrogeophysical Research Site**, Boise, ID, USA (Rabinovich et al., 2015)

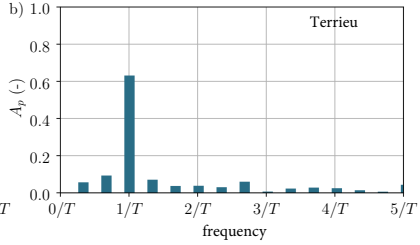
From **lab scale** (back) to **field scale**



From **lab scale** (back) to **field scale**

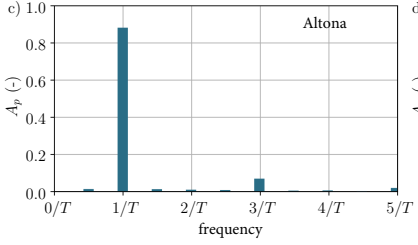
(stiff) crystaline rock
gneiss

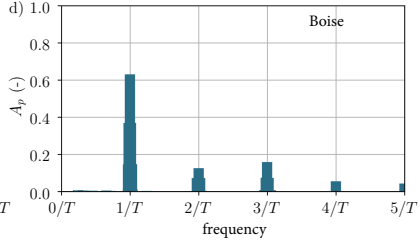




(soft) karstic rock

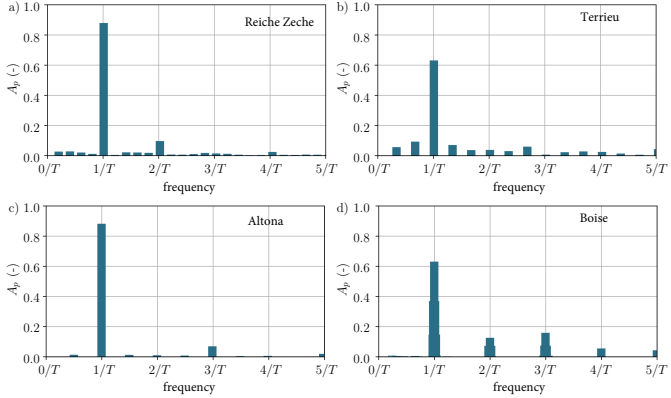
(stiff) sandstone





(soft) unconfined acquifer
sand / gravel

From **lab scale** (back) to **field scale**



- hydro-mechanical coupling (could) lead to distinct non-linear effects
- higher harmonics could be explained by non-linearities

take home message:

* linear/non-linear hydro-mechanics of fractures

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* harmonic (pumping) tests could lead to non-linearities & overtones

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- . . . but experimental characterization of fractures is also not trivial

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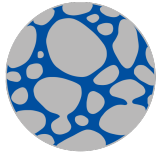
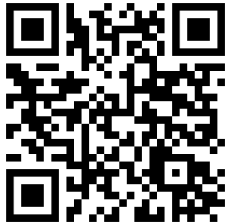
* linear/non-linear hydro-mechanics of fractures
* harmonic (pumping) tests could lead to non-linearities & overtones
* modeling fractures could be complex
* . . . but experimental characterization of fractures is also not trivial
* if you are interested - have a closer look at SFB 1313 & PML





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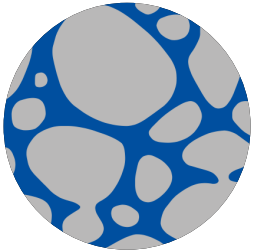
Thank You!



Holger Steeb

E-Mail holger.steeb@mechbau.uni-stuttgart.de
Phone +49 711 685-66346
Fax +49 711 685-66347

University of Stuttgart
Institute of Applied Mechanics (MIB)
Collaborative Research Center SFB 1313
Stuttgart Center of Simulation Science (SC SimTech)
70569 Stuttgart