



— 70 years —
1950-2020



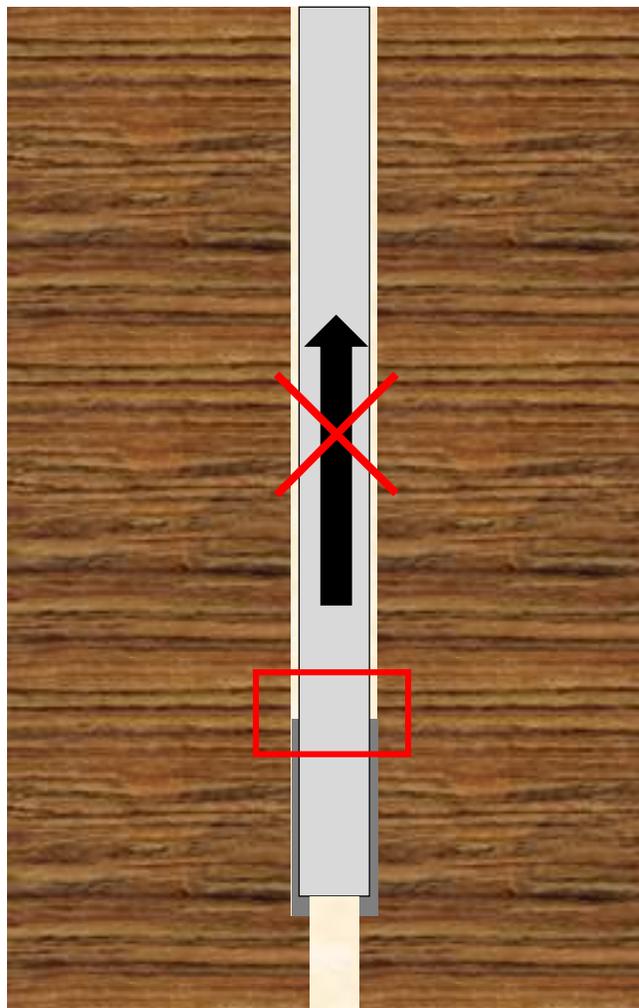
PROGRESSIVE ROCK DEFORMATION & ROCK-CASING CONTACT AROUND WELLBORE IN BINGHAM VISCOPLASTIC ROCK

Xiyang XIE^{1,2}, Erling FJÆR^{1,2}

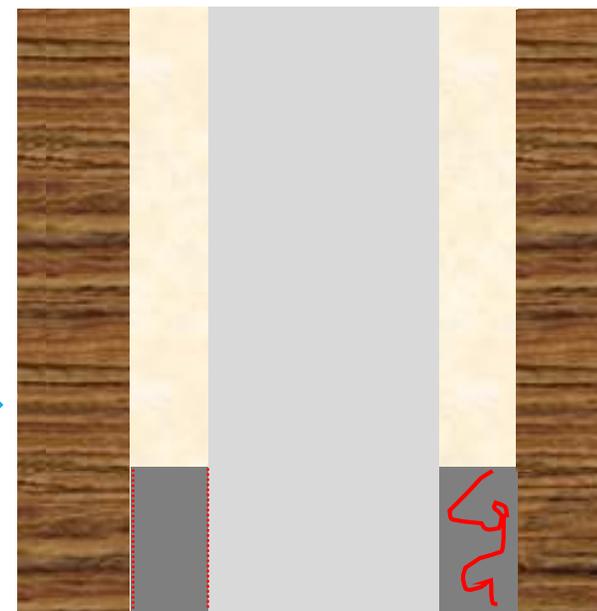
1. SINTEF, Trondheim, Norway

2. Norwegian University of Science and Technology, Trondheim, Norway

Well Abandonment



I am Shale!
creep



cement degradation

Pressure drawdown in casing
annulus triggers the borehole
closure.

pressure drawdown



stress concentration



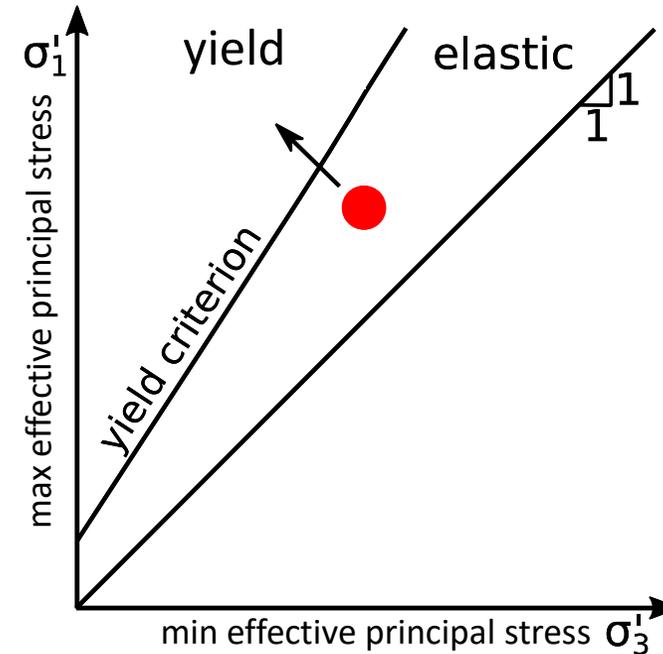
increase deviatoric stress



(time-dependent)

Rock yields with irreversible deformation.

(around the borehole)

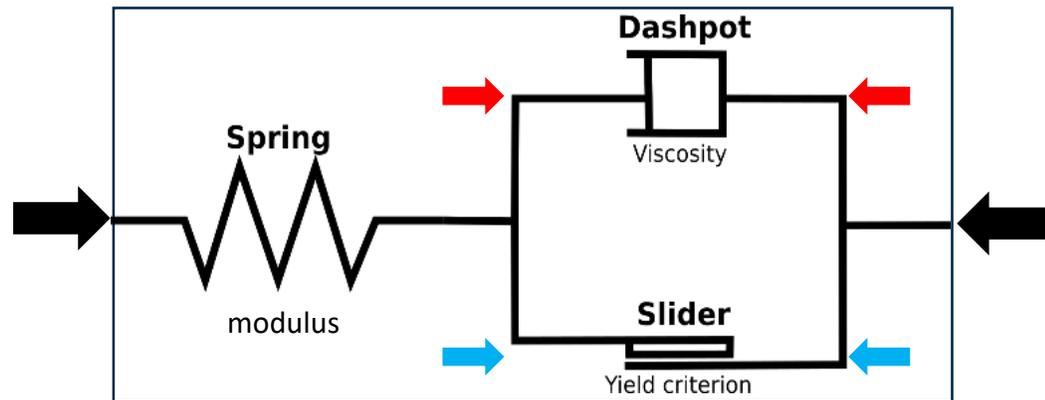


Why time-dependent?

Lab results of time-dependent borehole closure will come in the end of the presentation.

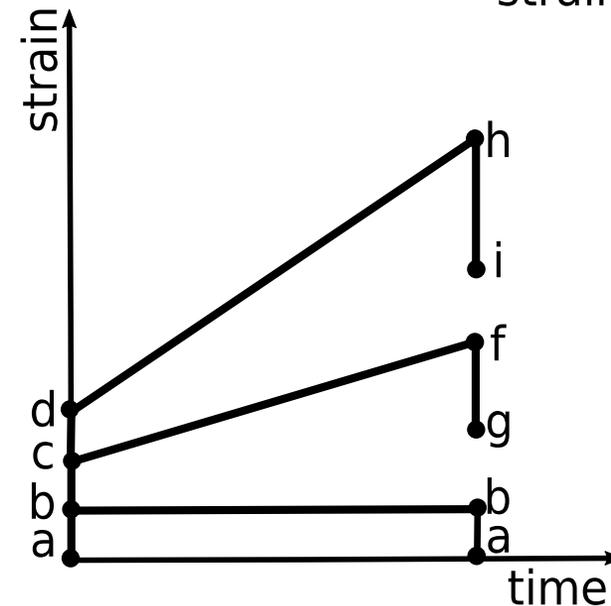
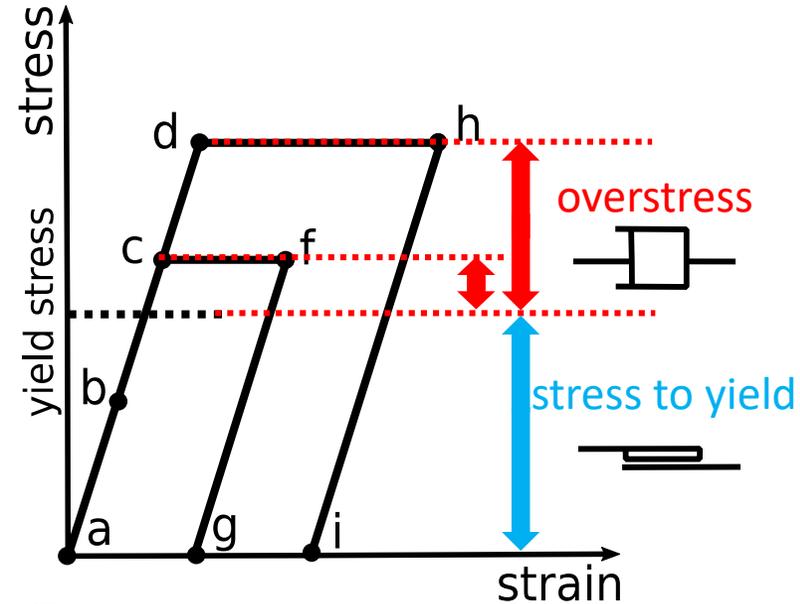
Bingham viscoplastic model (C++ UDM)

In 1-dimensional stress space:

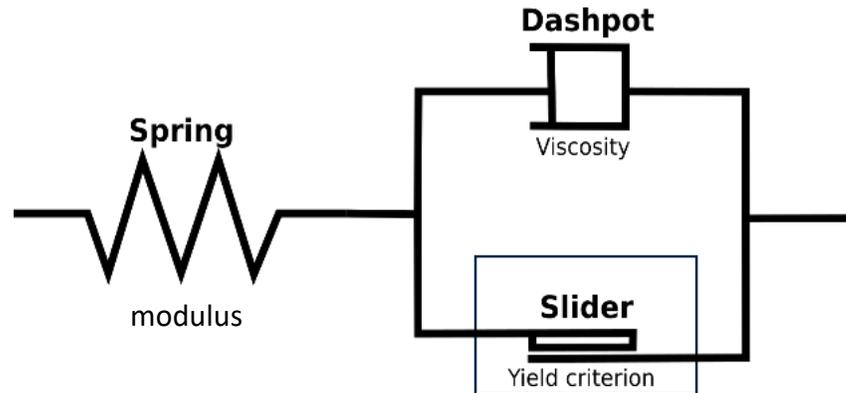


In 2-dimensional stress space:

- Deviatoric stress triggers the Bingham viscoplastic behavior.
- The volumetric behavior of the rock is elastic in compression.

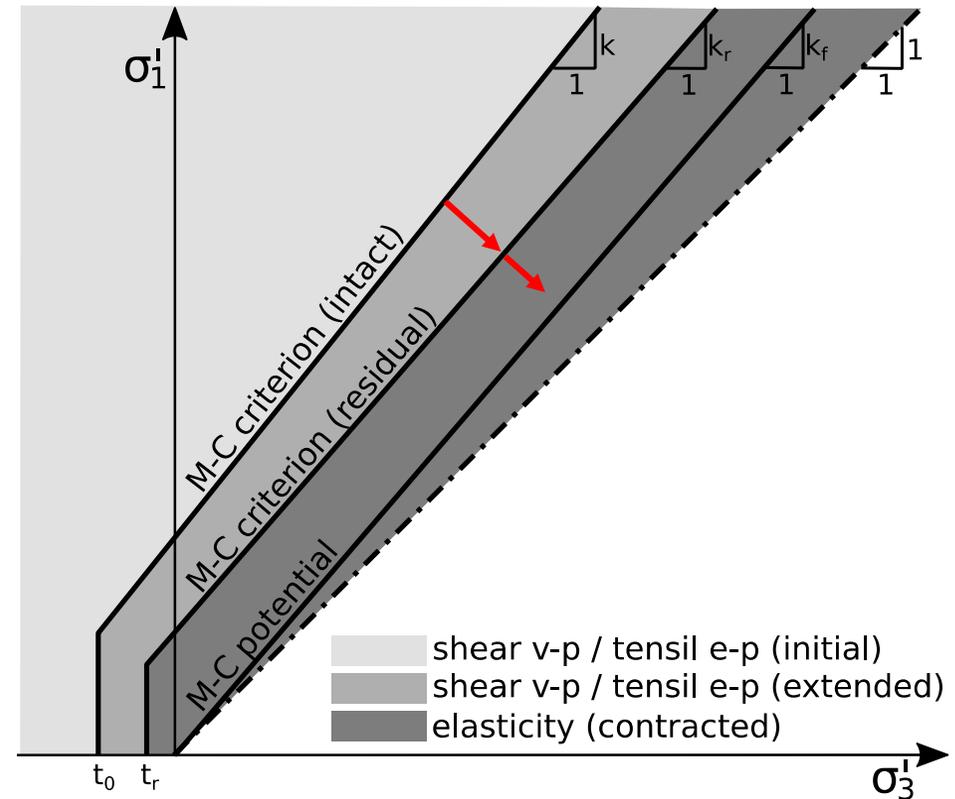


Bingham viscoplastic model (C++ UDM)



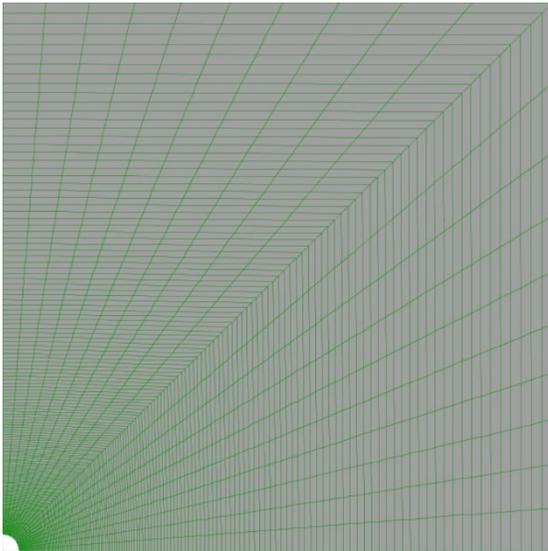
Features of Mohr-Coulomb yield criterion:

- Double-yield surface
- Softening / hardening
- Non-associated flow rule
- Tensile cutoff

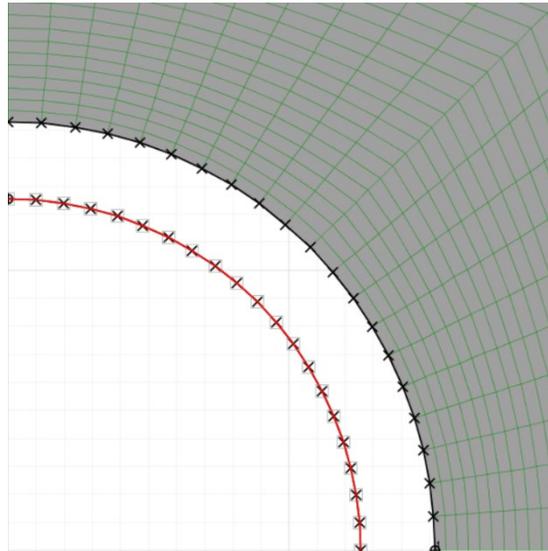


Geometry

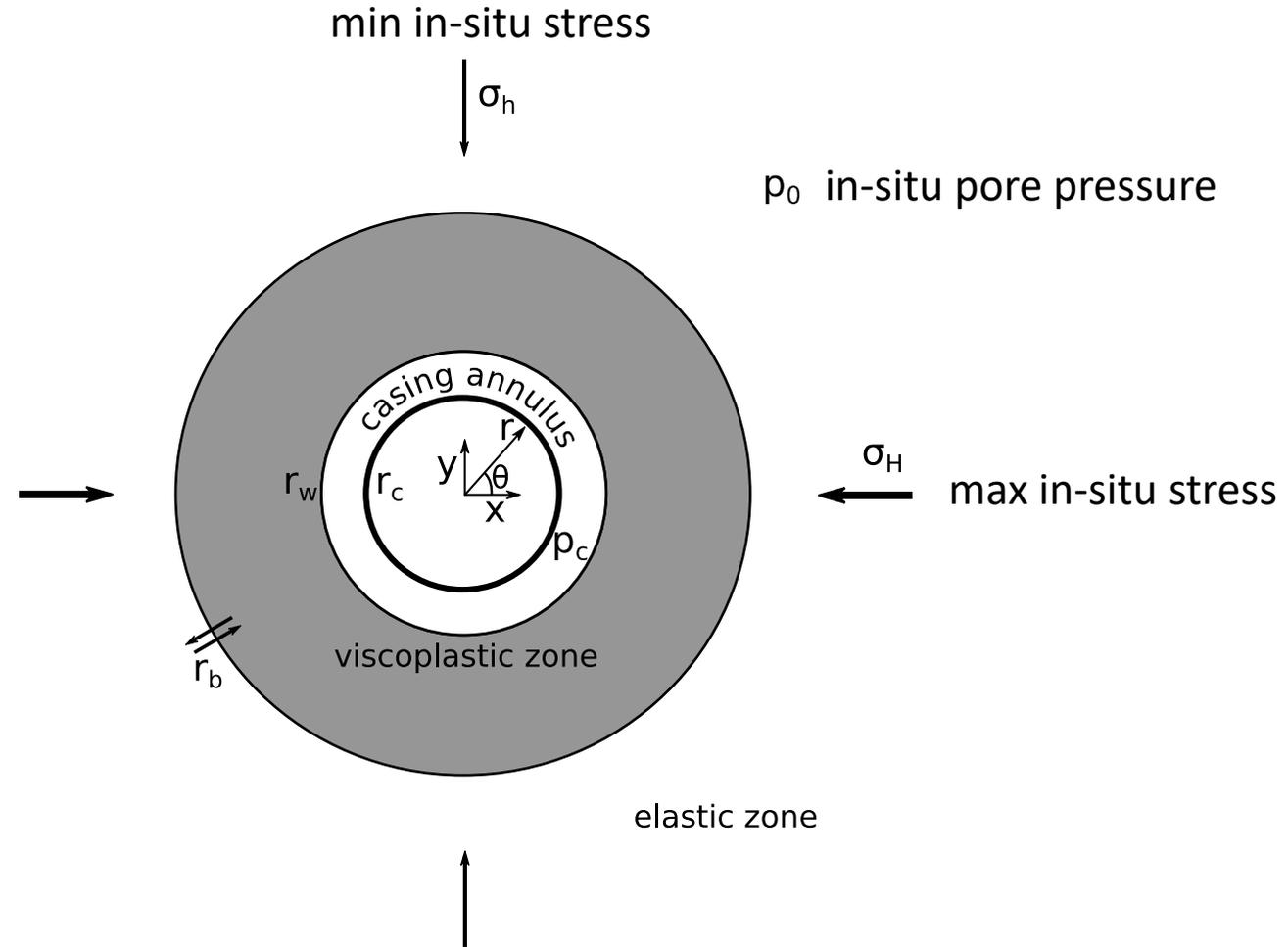
- Isotropic / anisotropic in-situ stress
- In-situ pore pressure
- Coaxial casing inside the borehole



mesh (165 x 20)



mesh close to the borehole

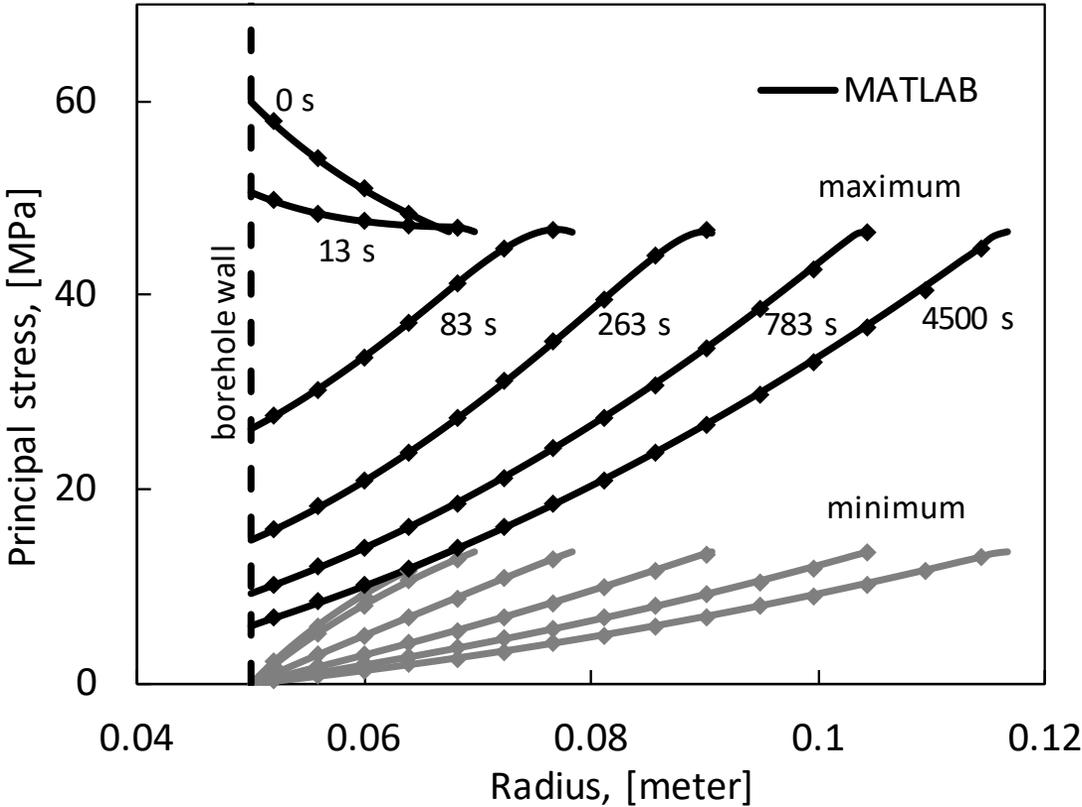
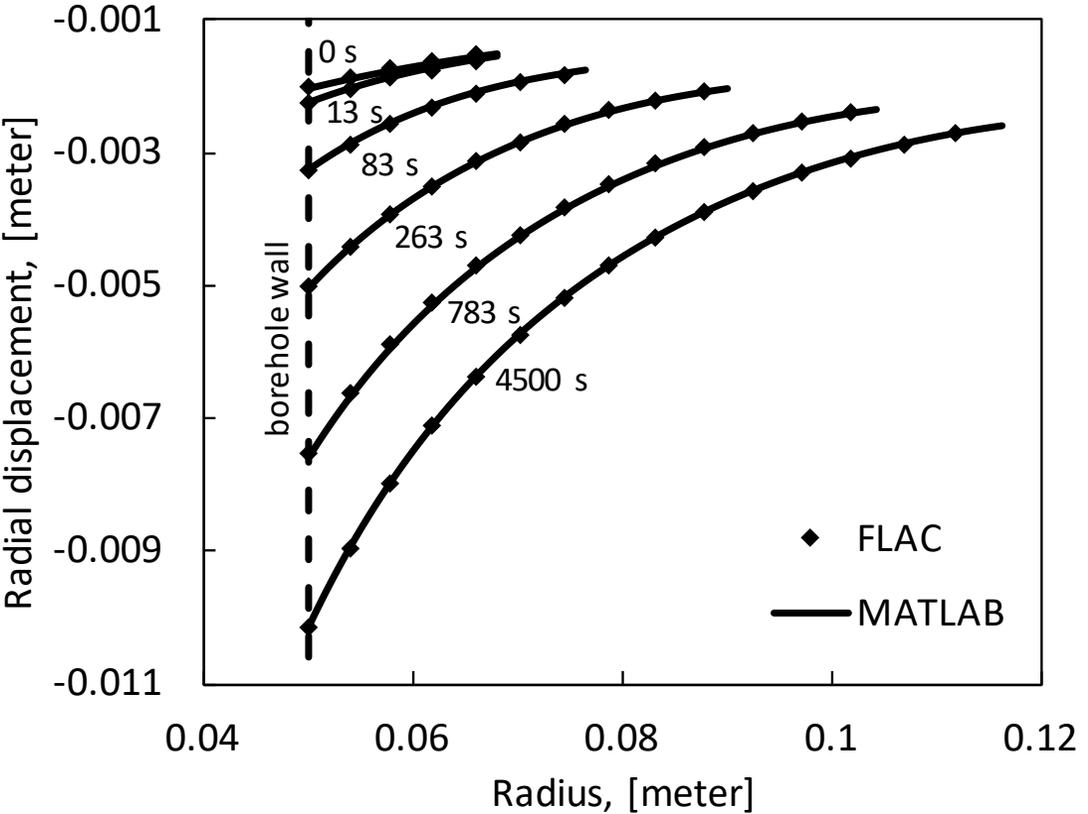


Simple simulations

- Compare FLAC and MATLAB without pore pressure

Inputs	Value	Unit
Borehole radius	0.05	m
Young's modulus	1.00	GPa
Poisson's ratio	0.35	-
Uniaxial compressive strength	6	MPa
Friction angle	30	Degree
Dilation angle	11.6	Degree
Viscosity	10.0	GPa·s
In-situ stress	30.0	MPa
Borehole pressure	0	MPa

Compare FLACTM and MATLABTM results



MATLABTM simulation: Xie et al., Geomechanics for Energy and the Environment, 2019.



Application simulations

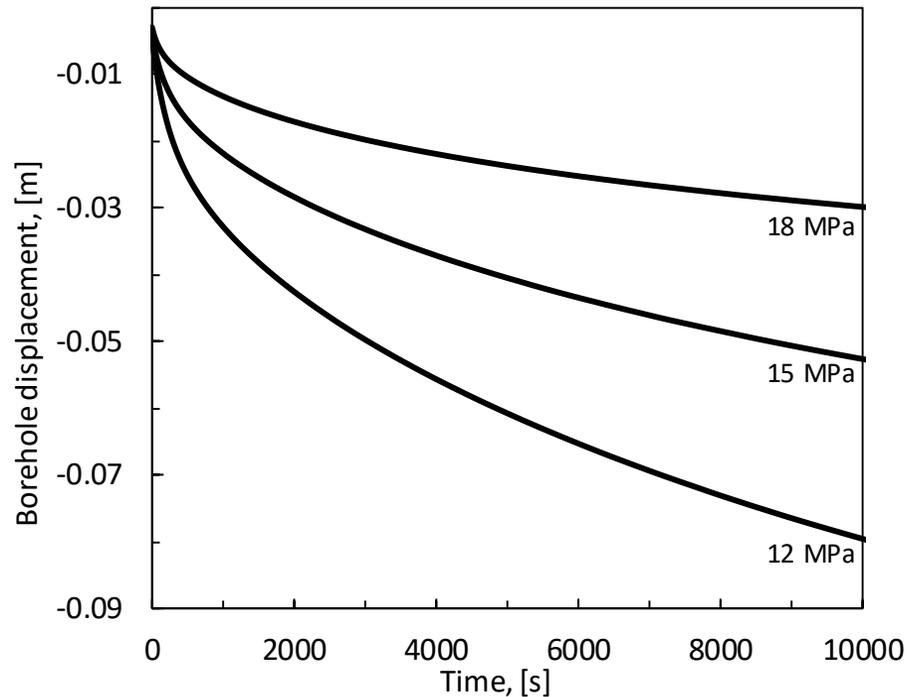
Inputs	Value	Unit
Young's modulus of the rock frame	0.80	[GPa]
Poisson's ratio of rock frame	0.30	[-]
Friction angle (intact)	15.03	[degree]
Dilation angle (intact)	11.54	[degree]
Cohesion (intact)	1.53	[MPa]
Tensile strength (intact)	1.00	[MPa]
Rock viscosity (intact)	10	[GPa·s]
Porosity	0.15	[-]
Permeability	0.022	[mD]
Water density	1000	[kg/m ³]
Water bulk modulus	2.25	[GPa]
In-situ stress	30	[MPa]
In-situ pore pressure	18	[MPa]
Biot coefficient	1	[-]
Borehole radius	15.56	[cm]
Outer radius of casing	12.54	[cm]
Gap of casing annulus	3.02	[cm]

Viscoplastic strain	Cohesion	Friction	Dilation	Viscosity
[-]	[MPa]	[degree]	[degree]	[GPa·s]
0	1.53	15.03	11.54	10
$1 \cdot 10^{-10}$	1.40	13.00	10.00	10
0.1	1.00	9.00	6.00	5
>0.1	1.00	9.00	6.00	5

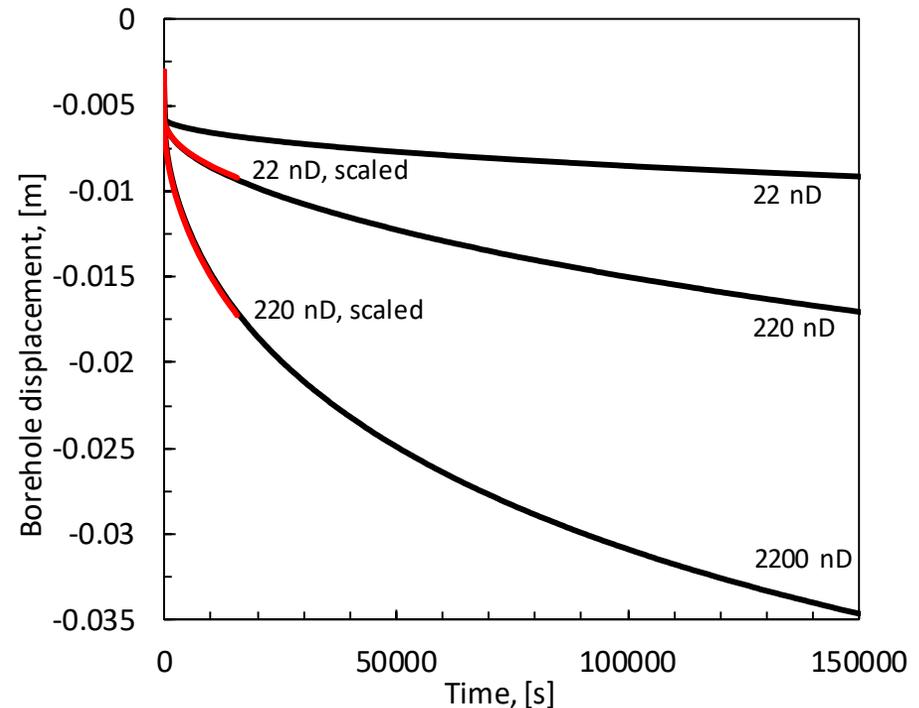
Tensile plastic strain	Cutoff
[-]	[MPa]
0	1.00
$1 \cdot 10^{-10}$	1.00
0.1	0.50
>0.1	0.50

Before rock-casing contact (isotropic in-situ)

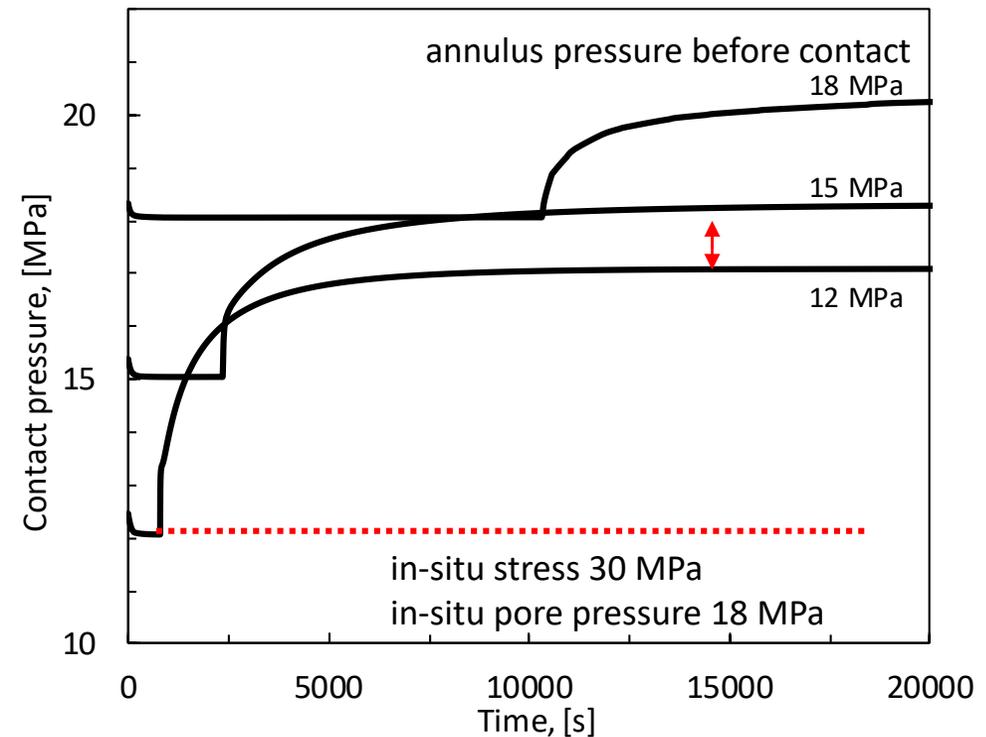
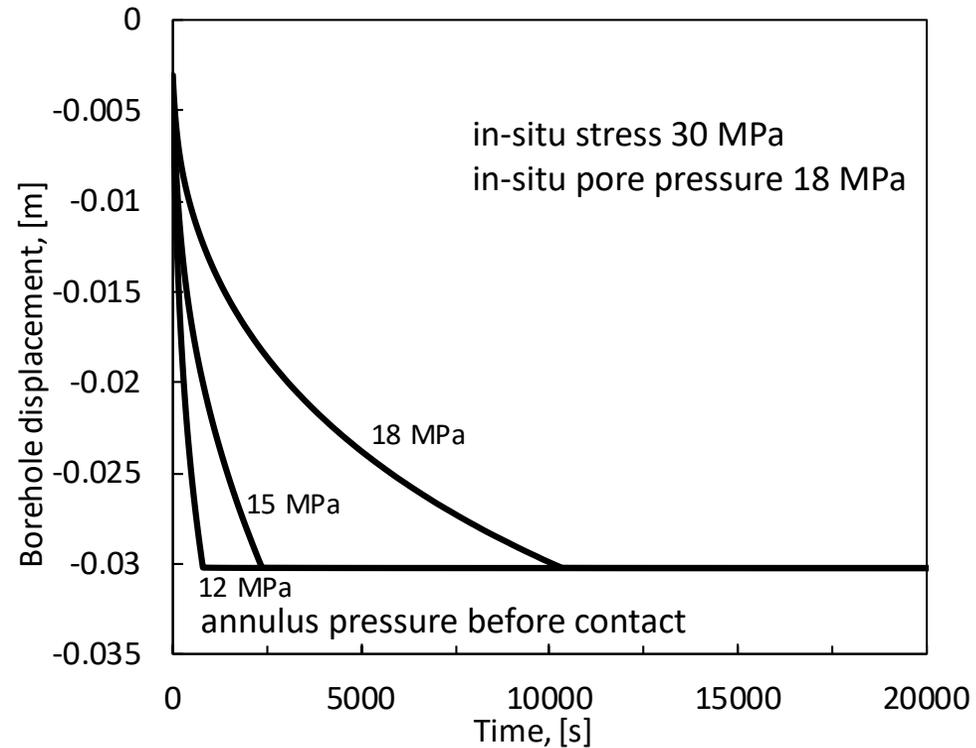
Annulus pressure



Permeability

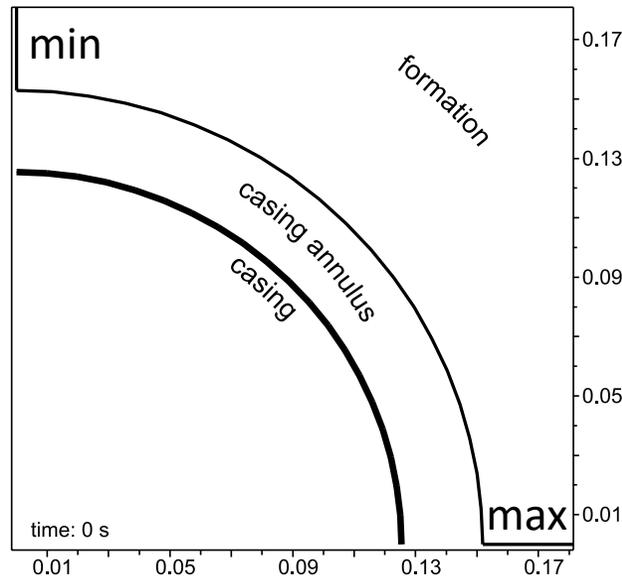


After rock-casing contact (isotropic in-situ)

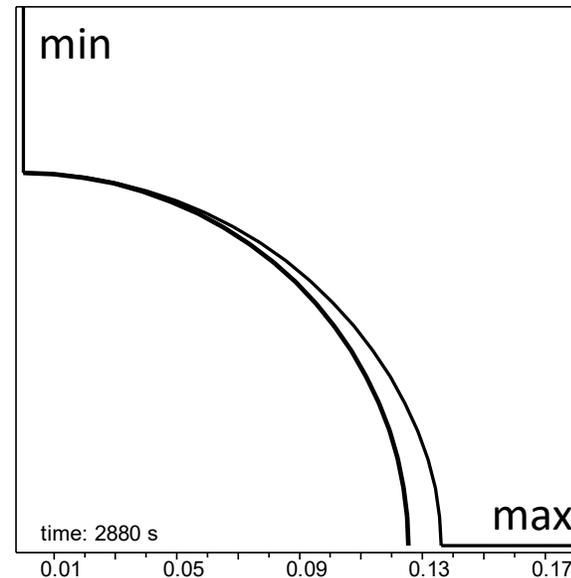


After rock-casing contact (Anisotropic in-situ)

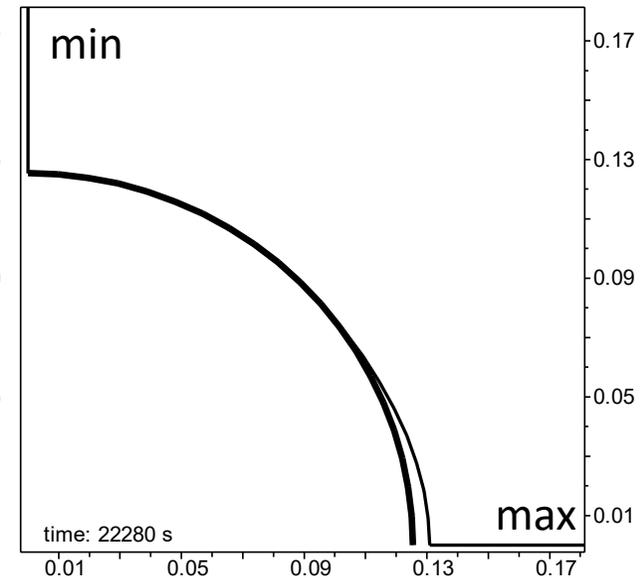
minimum horizontal stress (vertical in pic): 28 MPa
maximum horizontal stress (horizontal in pic): 32 MPa
pressure drawdown to: 17 MPa



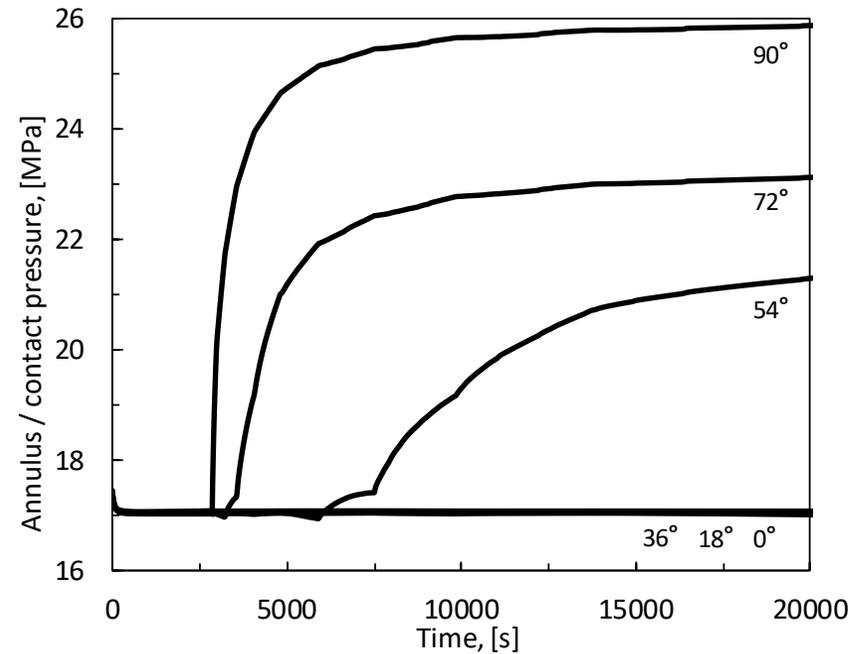
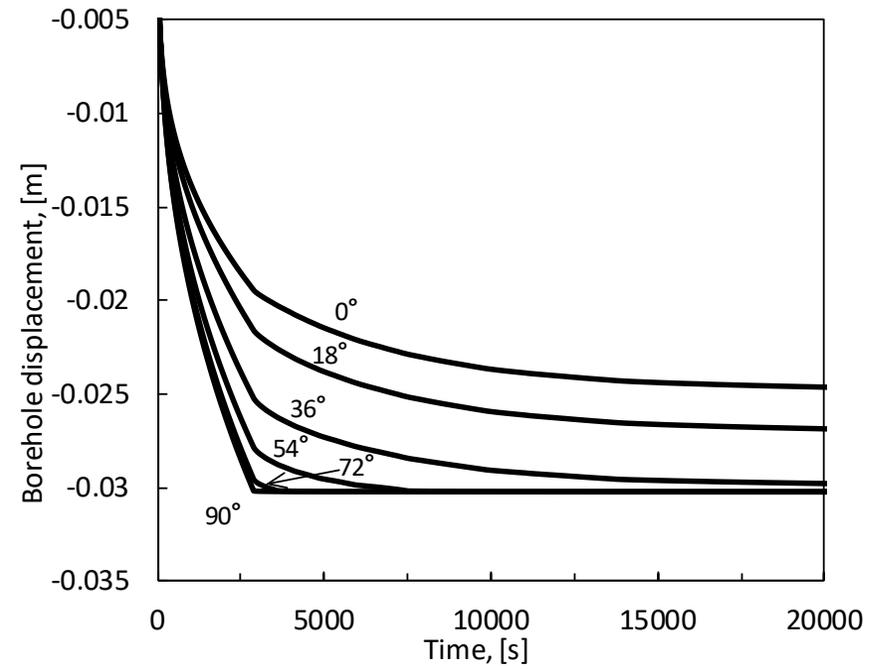
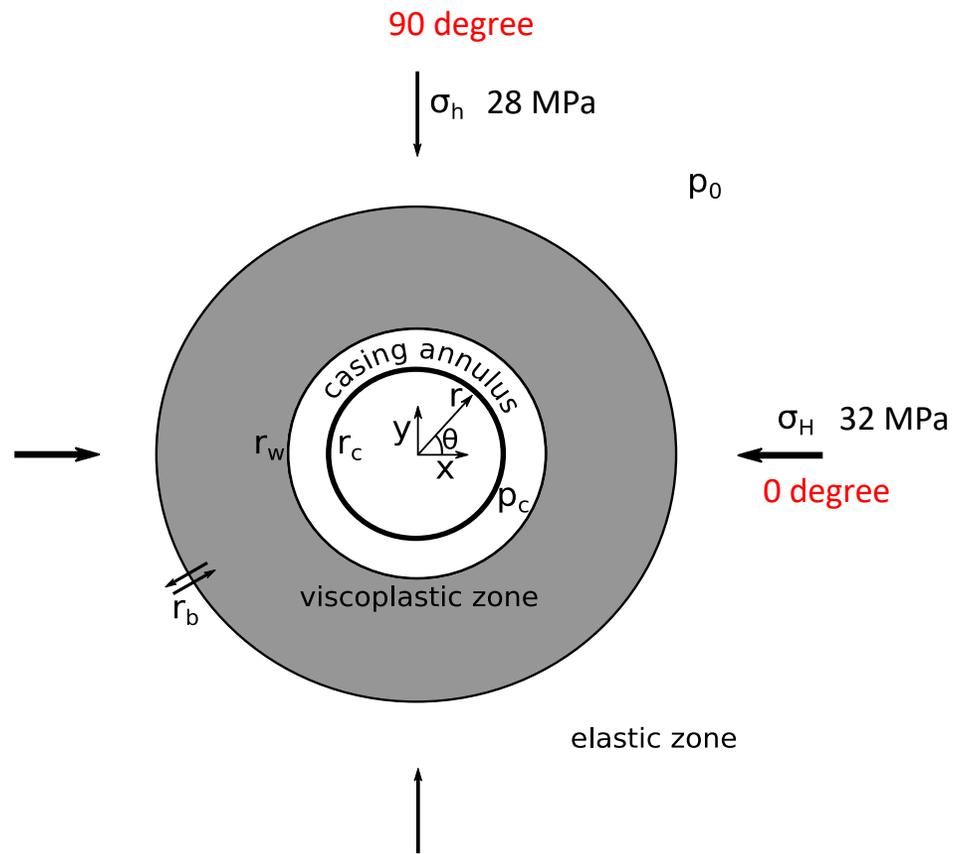
0 second:
Pressure drawdown at annulus



2880 seconds:
Rock-casing contact in one direction

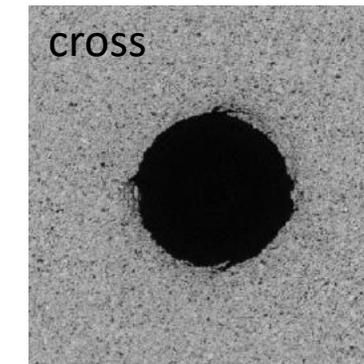
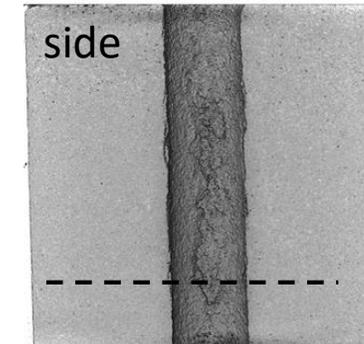
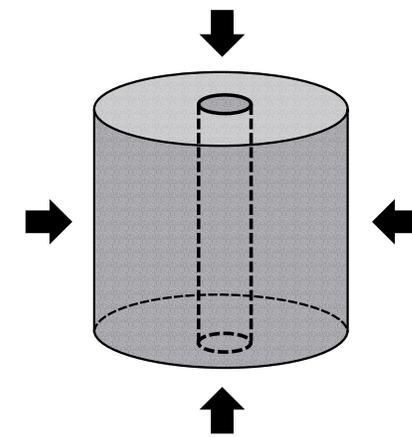
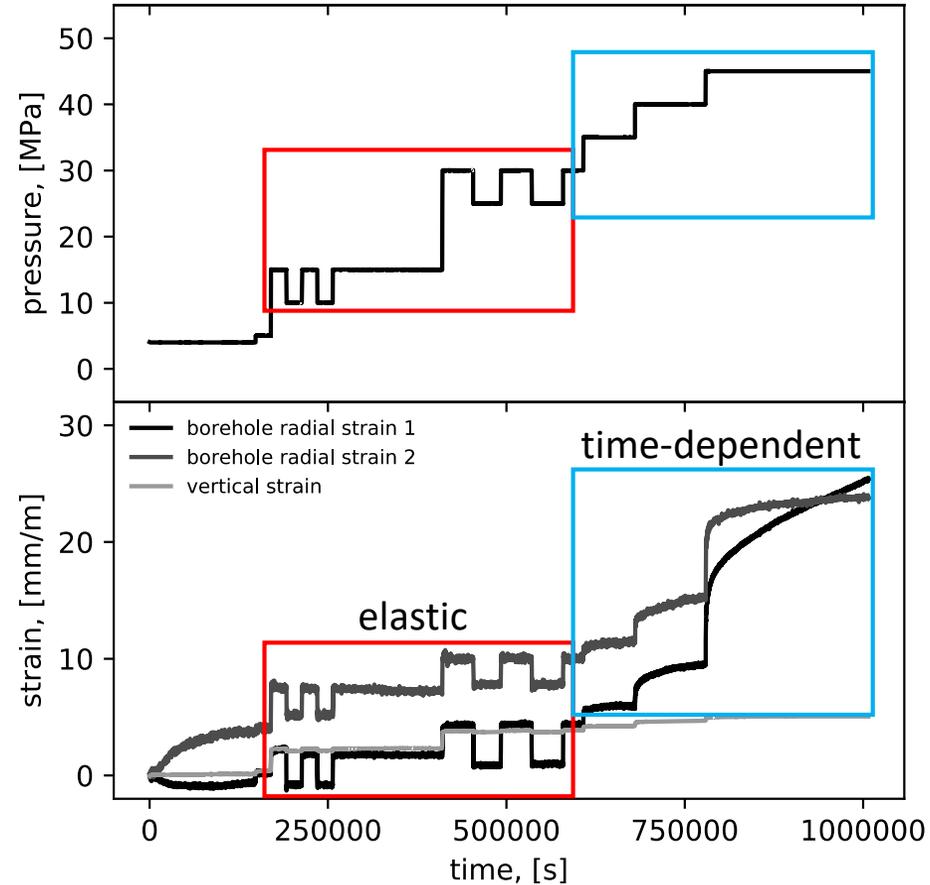


22280 seconds:
Borehole closure at large time

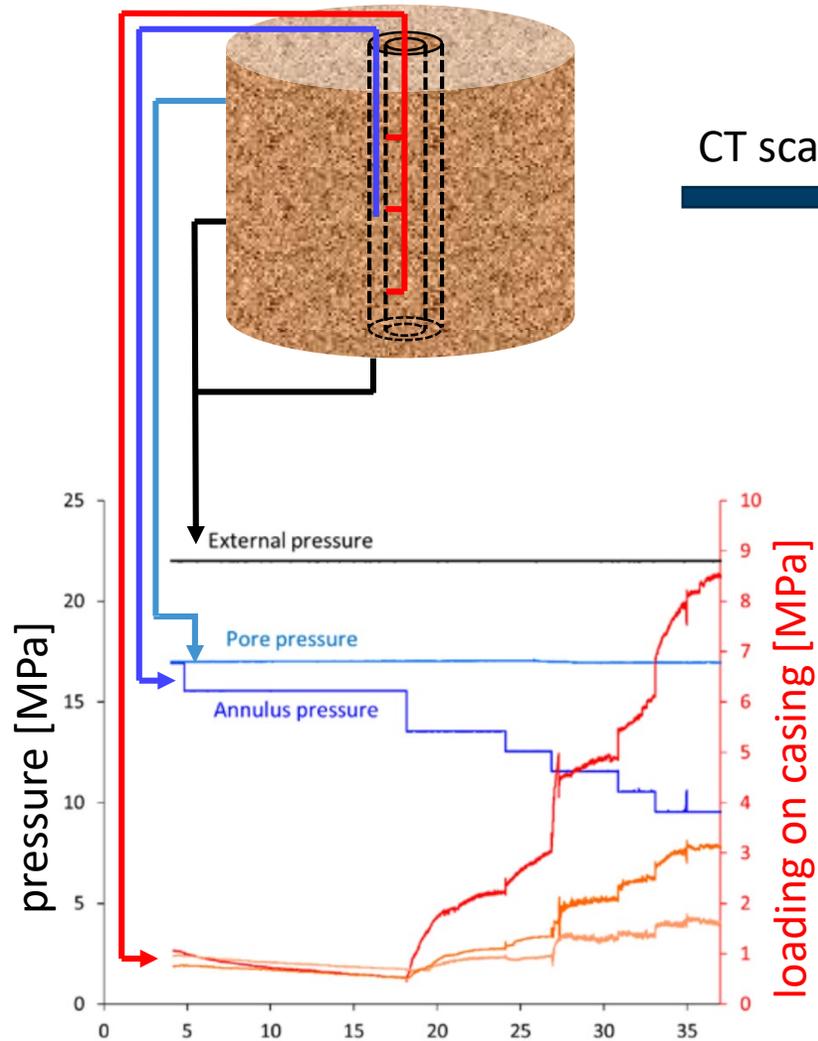


Hollow cylindrical creep test

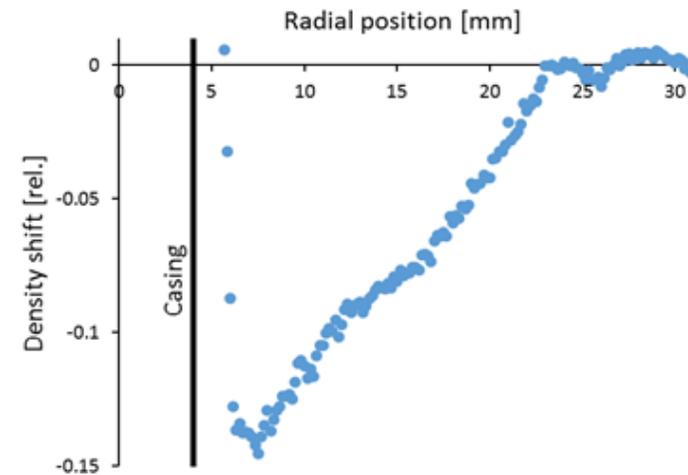
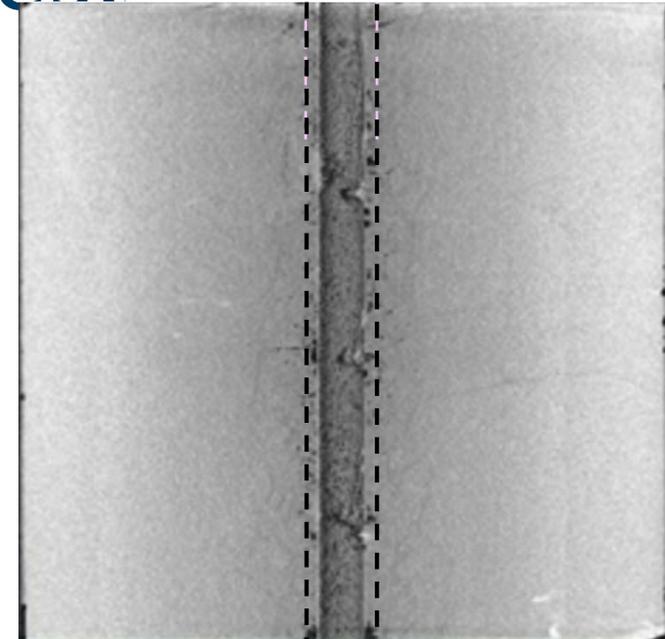
- dried Castlegate sandstone
- external loading test:
wellbore pressure = 0
- displacement on the borehole wall (two directions perpendicular to each other)



Hollow cylindrical creep test



(Fjær et al., ARMA 18-1146)



dilation-induced density decrease

We learned...

- Lower annulus pressure accelerates borehole closure but restrains the recovery of contact pressure.
- With anisotropic in-situ stress, annulus closure happens first along the direction of minimum in-situ stress; Early rock-casing contact can delay or restrain the contact in other directions.

Acknowledgement

- Itasca Education Partnership

Especially the thank to Dr. Christine Detournay, Jin Wang, and Judy Zetterlund in Itasca Consulting Group for all the help.

- Shale Barrier Toolbox

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— 70 år —
1950-2020

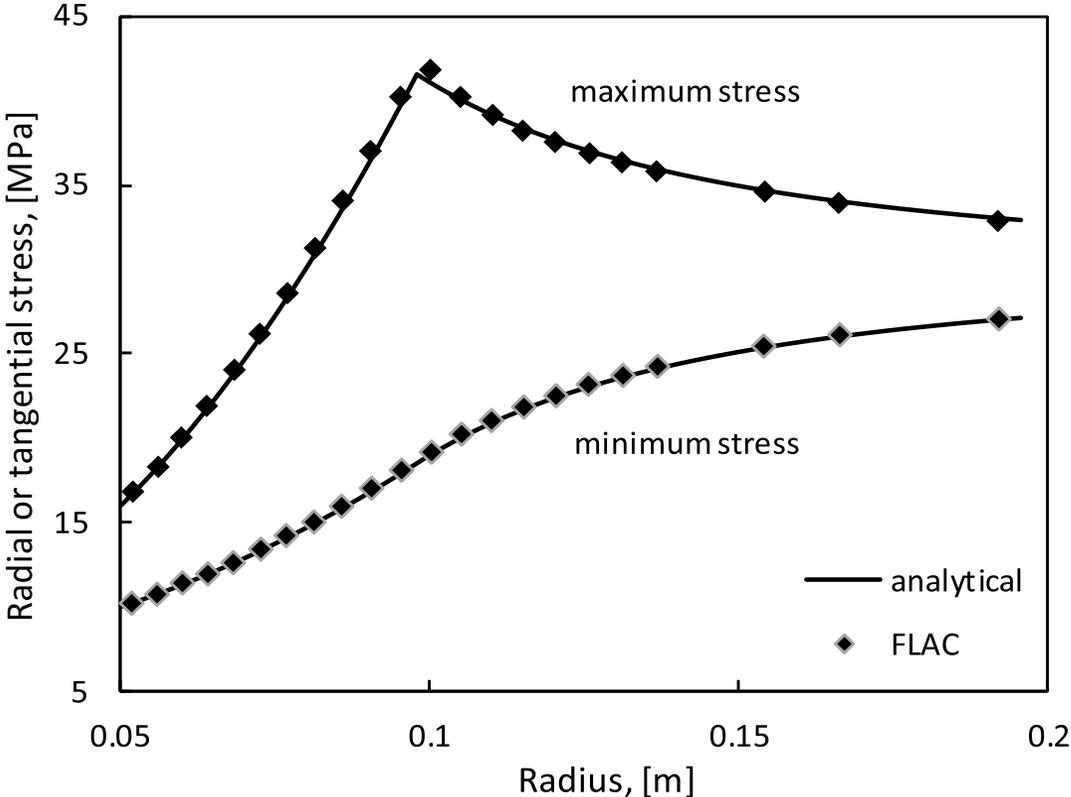
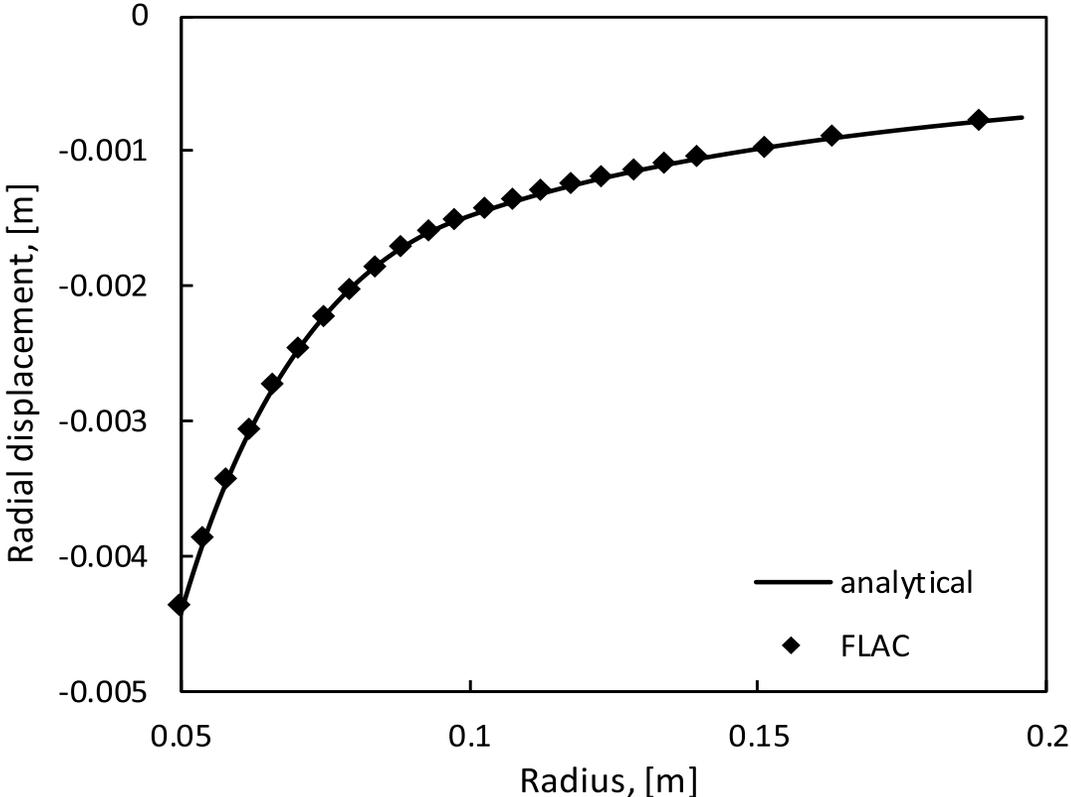
Teknologi for et bedre samfunn

March 17-18, 2020, Radisson Blu Royal Garden Hotel, Trondheim, Norway

SINTEF Petroleum Conference

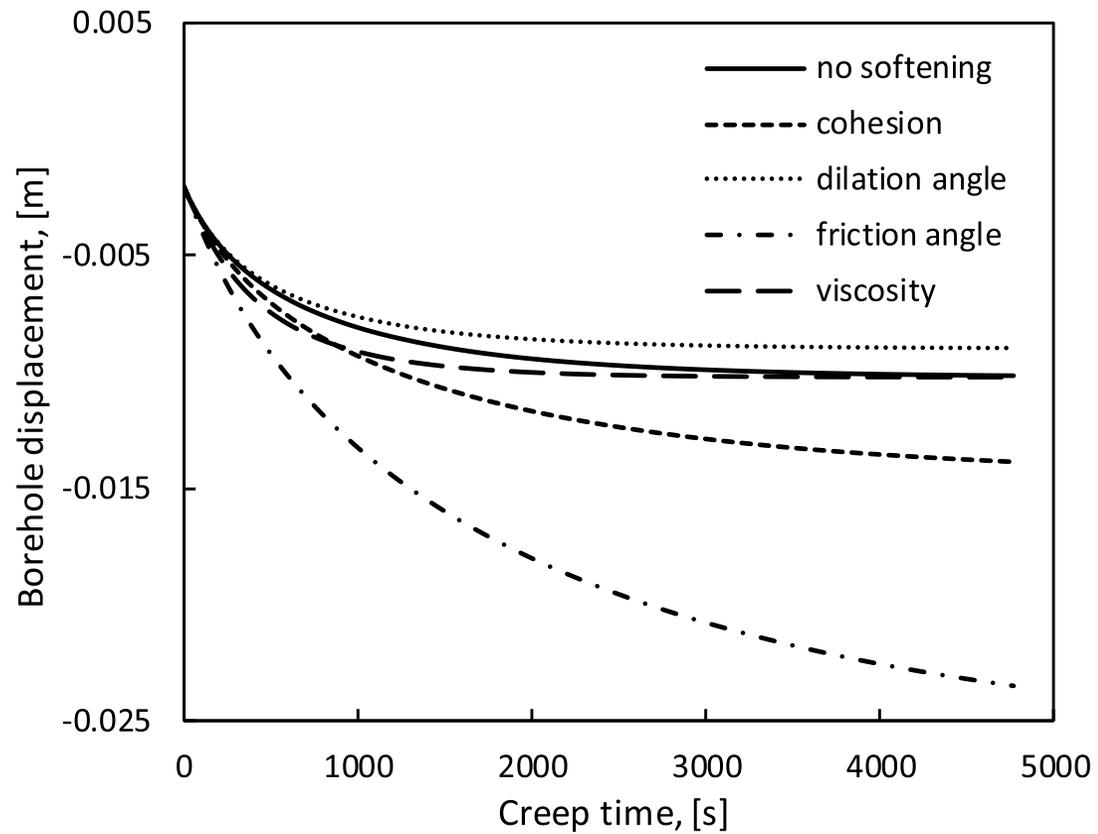
Low carbon technologies for the upstream oil and gas industry

Constant pore pressure



In-situ pore pressure = wellbore pressure = 10 MPa

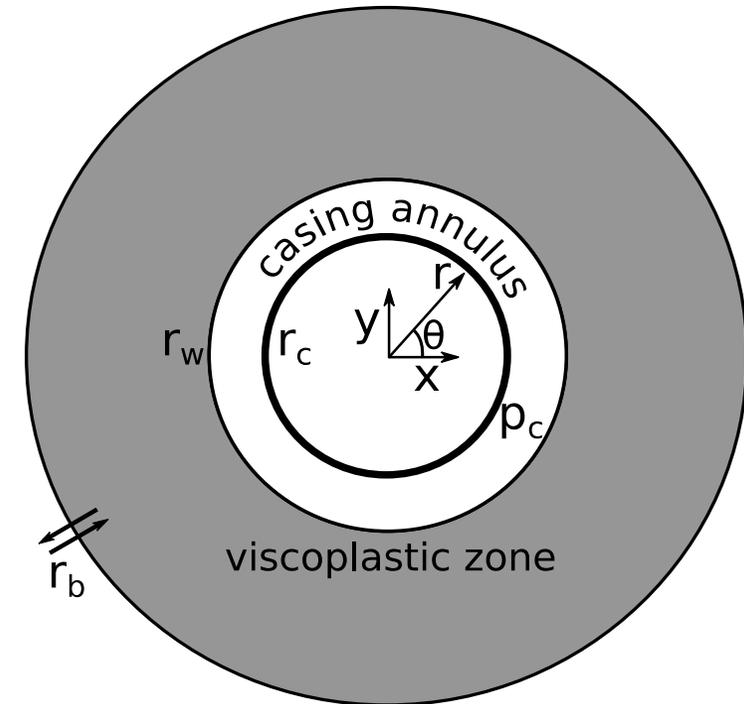
Softening

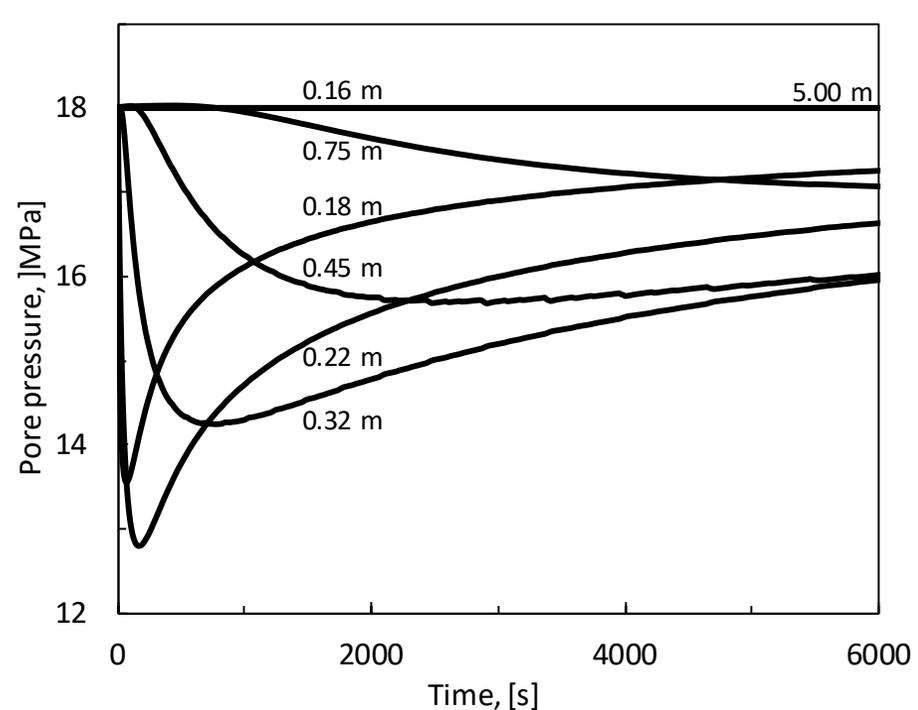
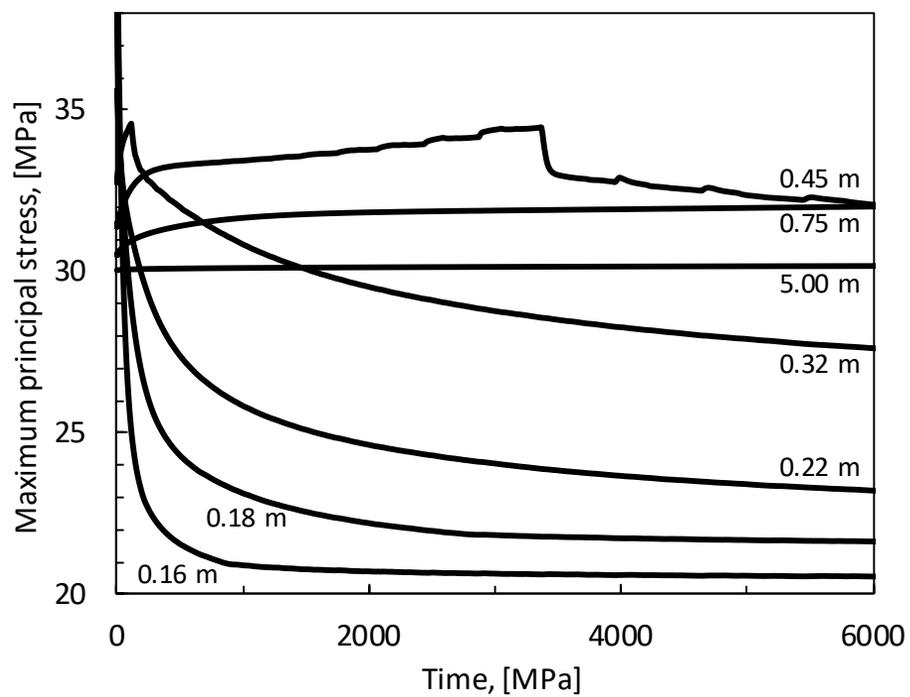
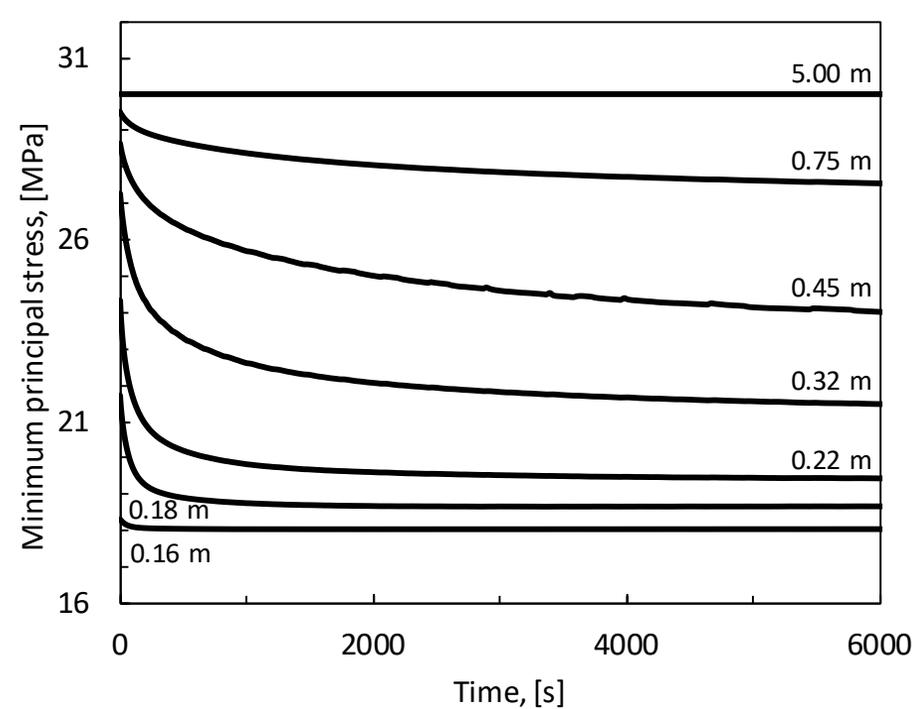
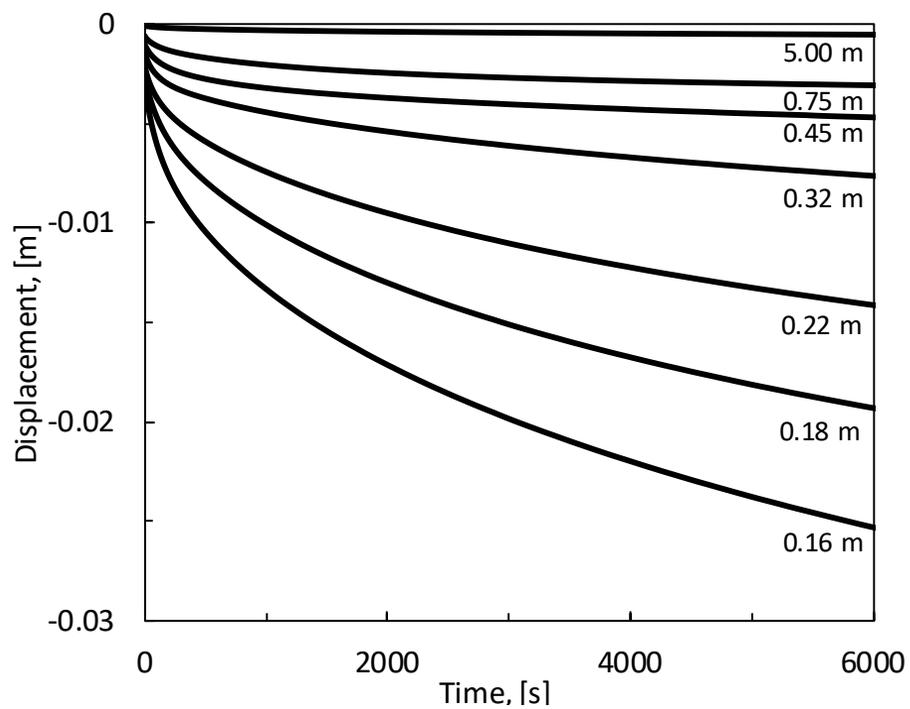


Viscoplastic strain	Cohesion	Friction	Dilation	Viscosity
[-]	[MPa]	[°]	[°]	[GPa·s]
0.00	1.73	30	11.6	10
0.05	1.23	20	5.6	5

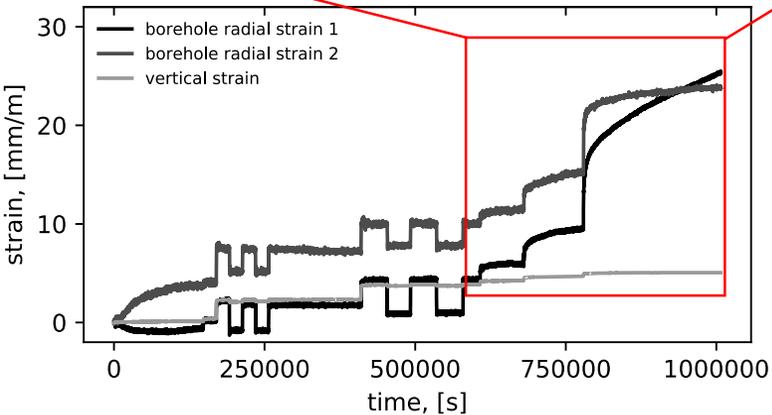
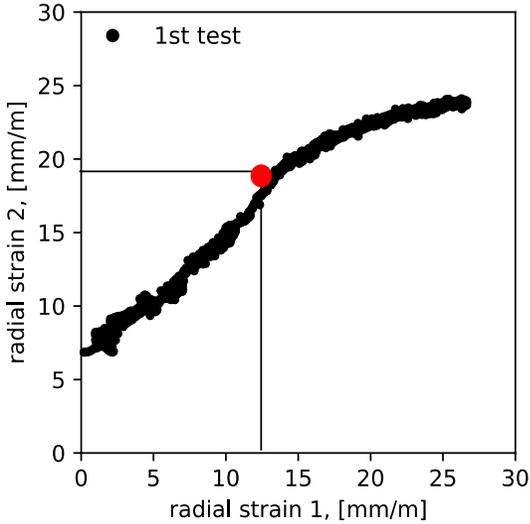
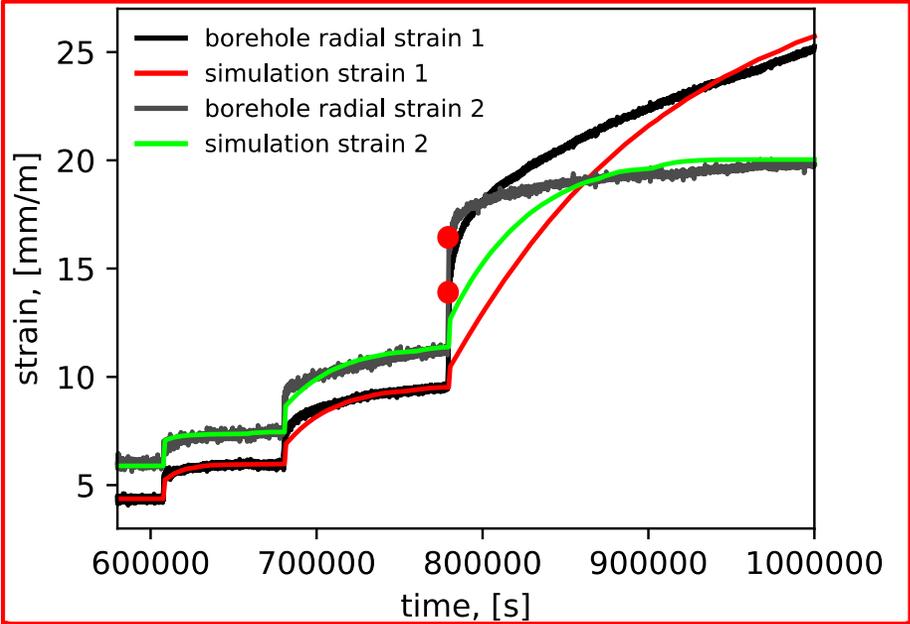
Small/large strain condition

Gap	Asymptotic contact pressure		Difference
	MATLAB	FLAC	
[mm]	[MPa]	[MPa]	[%]
3.00	4.22	3.97	5.9
4.00	2.96	2.50	15.5
4.86	2.21	1.65	25.2



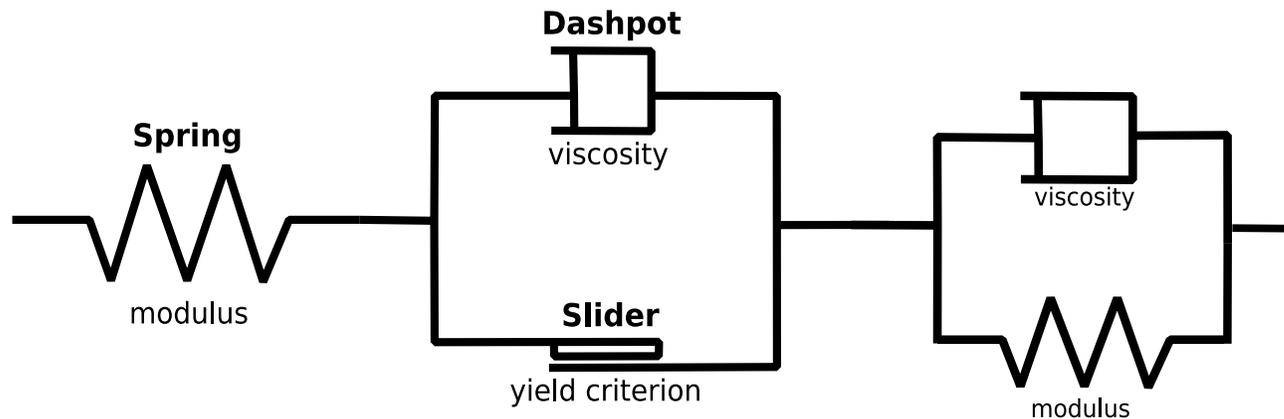


Compare with lab data



The Bingham model in FLAC™ can catch rock yield but not local failure.

Bingham (viscoplastic) → Bingham-Kelvin (viscoelastic-viscoplastic)



In a larger picture...

