GEOMECHANICS FOR GEOPHYSICISTS

Discrete Particle Modeling of Rock Behaviour

Rune M Holt (NTNU & SINTEF)

Idar Larsen (SINTEF)

Liming Li (SINTEF)

Trondheim, 26 April 2012

Why?

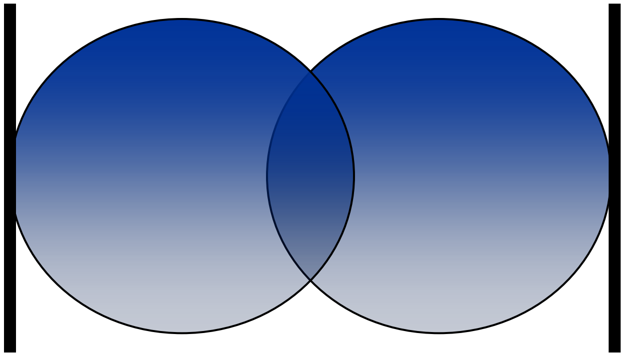
- Main idea is to develop a Numerical Laboratory, where stress dependent rock properties can be measured from 3D (or 2D) microstructure images.

- Useful when no or insufficient amount or quality of core material is available.

- Useful for understanding of rock behaviour, enabling simpler models to be developed, incorporating the right physics.

Discrete Particle Model

- Deformation is modeled using a Discrete Element Method (DEM)
- Key elements: Spherical particles (in 3D); Disks (in 2D)
- Overlap permitted (”soft contact”)
- Use linear, Hertzian or user-defined contact laws to calculate elastic deformation between spheres

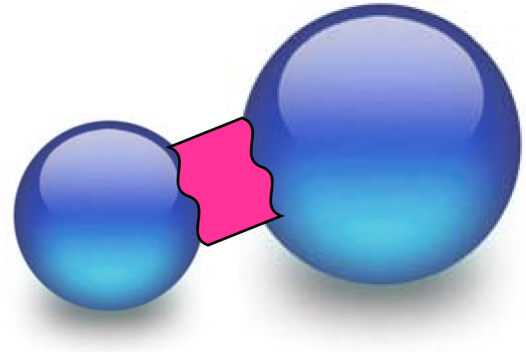


In addition: Walls

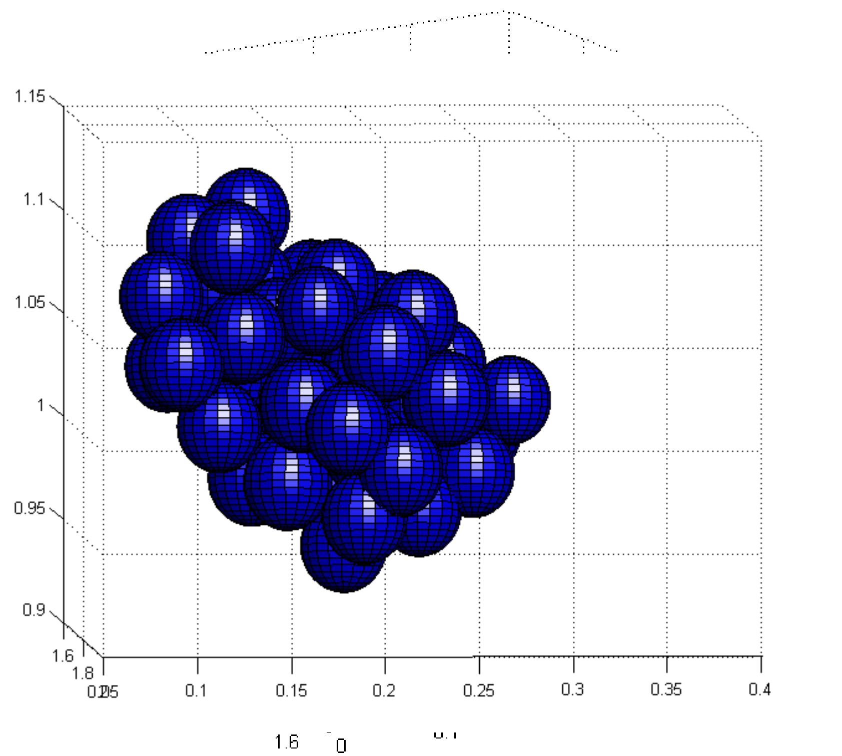
We use PFC (”Particle Flow Code”); Potyondy & Cundall, Int. J. Rock Mechanics 2004

SINTEF NTNU

Discrete Particle Model



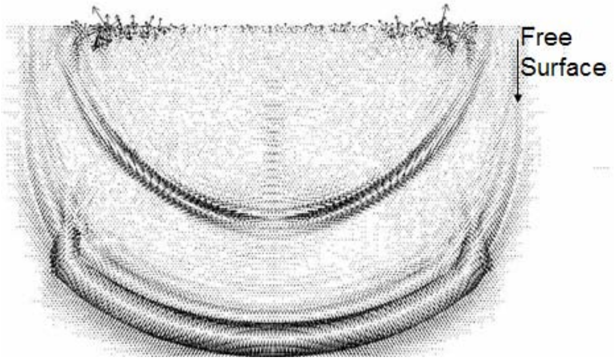
- ❑ Cement between particles is simulated through ”parallel bonds”
- ❑ Bonds are defined through
  - ❖ shear & normal stiffness
  - ❖ shear & normal strength
  - ❖ Extent of contact (transfer of moment)
- ❑ Spheres are clustered to creat grains



Discrete Particle Model

- Force and moment equilibrium ensured fo each contact in a cycling and time-stepping approach

- Discrete Particle Modelling represents a fully dynamic approach to computing complex behaviour of bonded rock based on contact law between individual particles

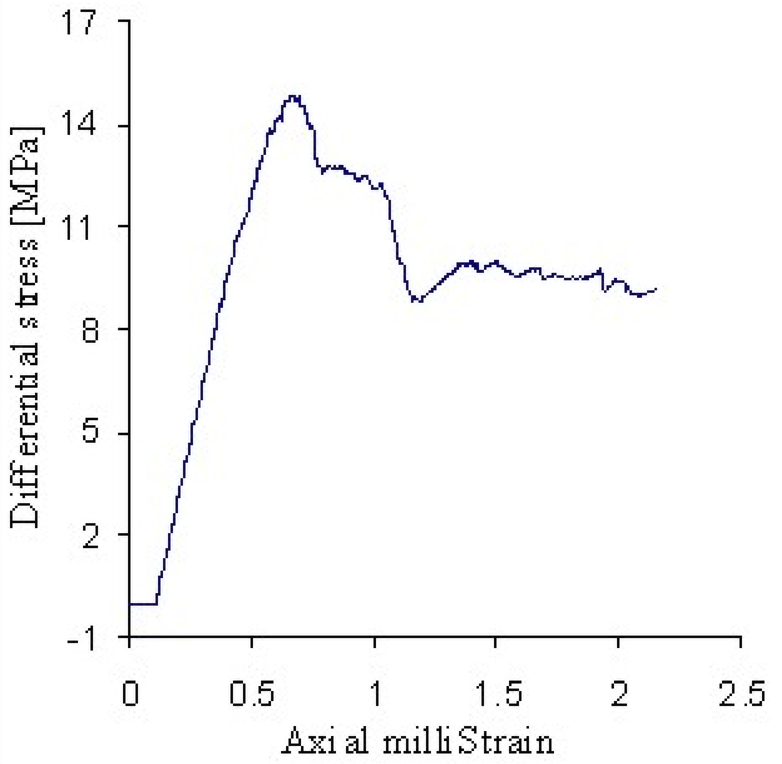


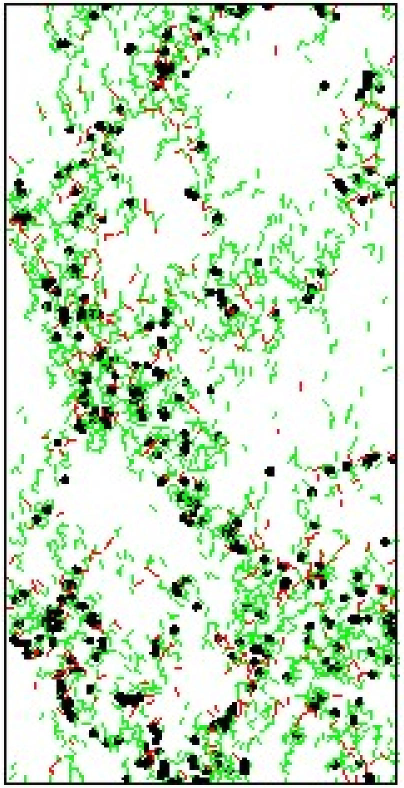
SINTEF NTNU

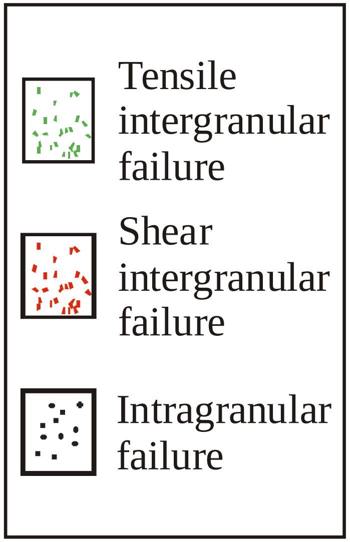
Deformation and failure

A 2D model with multi-disk clusters under biaxial stress

(Development of a shear band at low confinement 4 MPa)





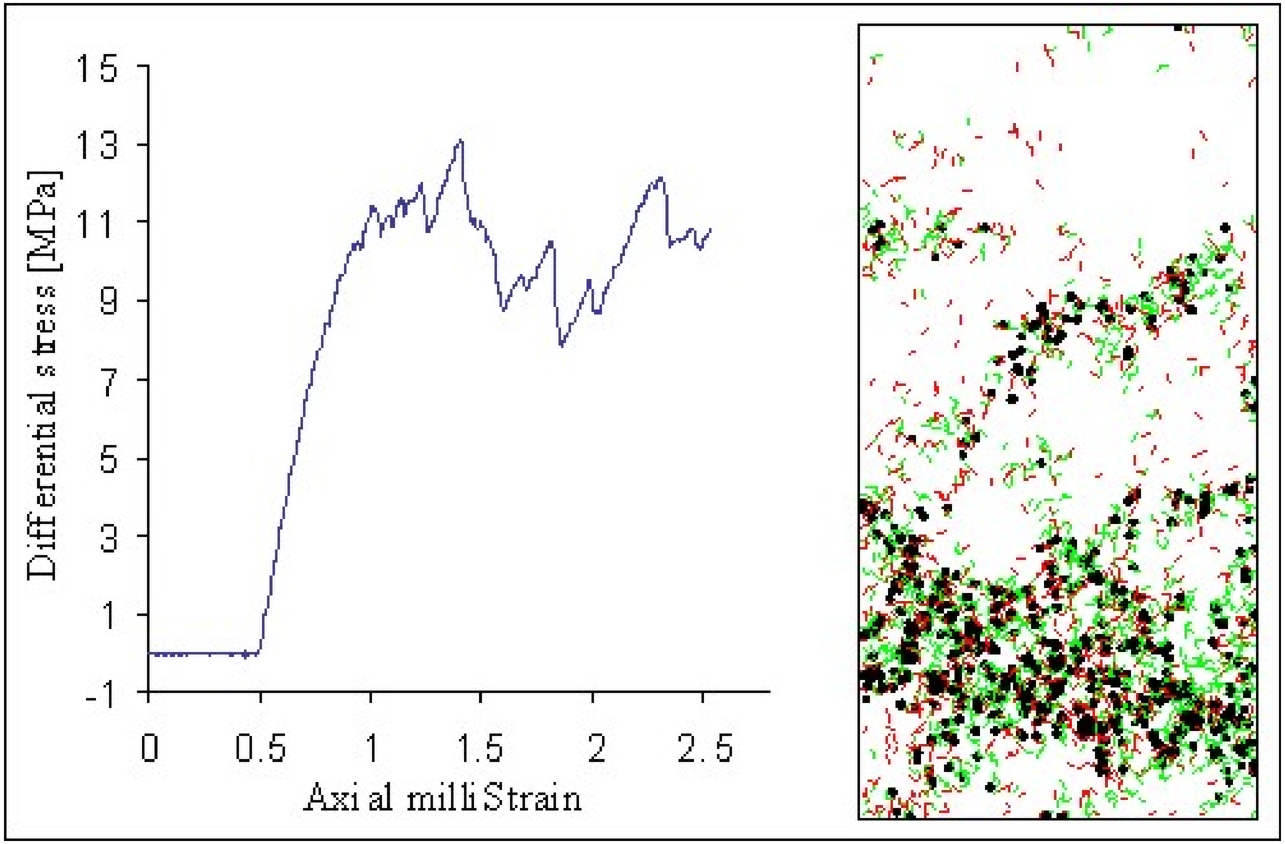


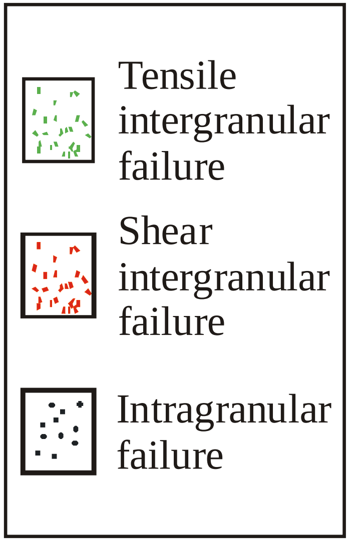
SINTEF NTNU

Deformation and failure

A 2D model with multi-disk clusters under biaxial stress states

(Development of a compaction band at high confinement 18 MPa)



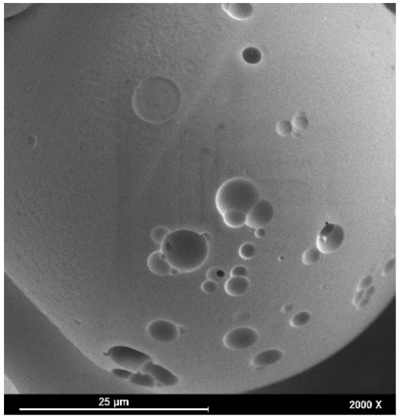


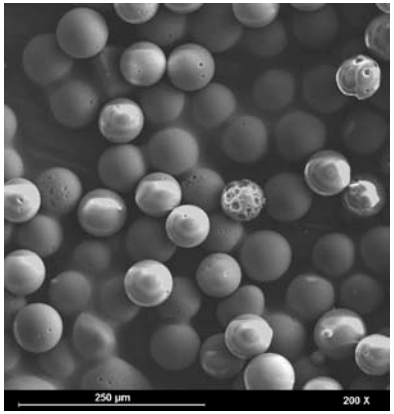
As observed in Castlegate sst by Olsson & Holcomb (2000)!

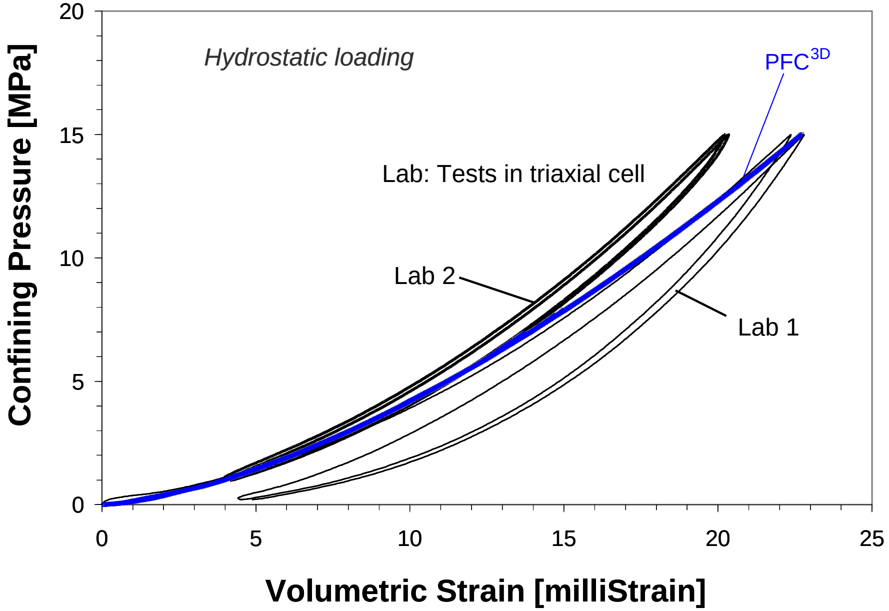
SINTEF NTNU

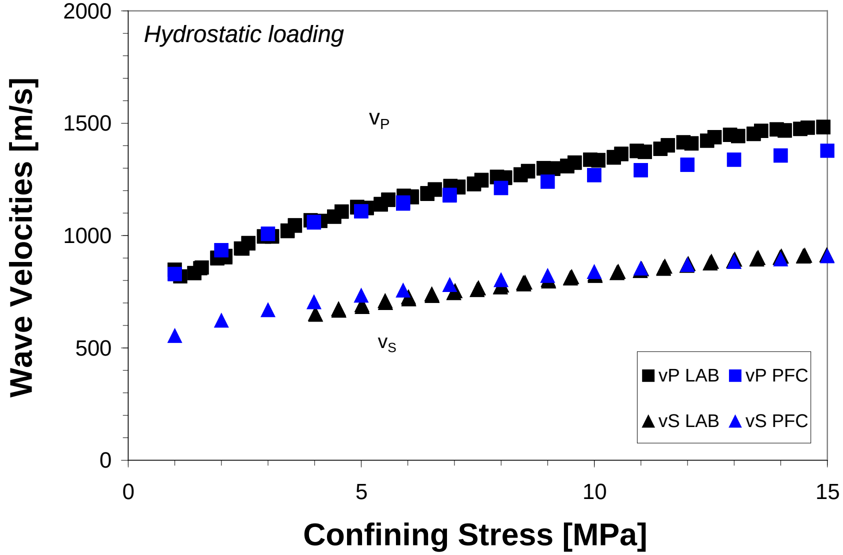
Comparison with experiments

Experiments with uncemented glass beads give satisfactory [but not perfect] fit to data, [almost] without adjustable parameters





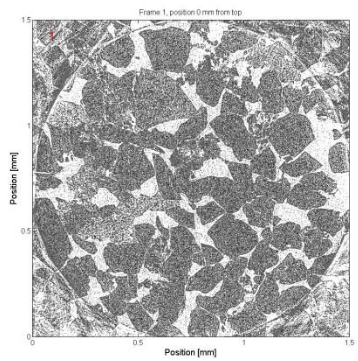




SINTEF NTNU

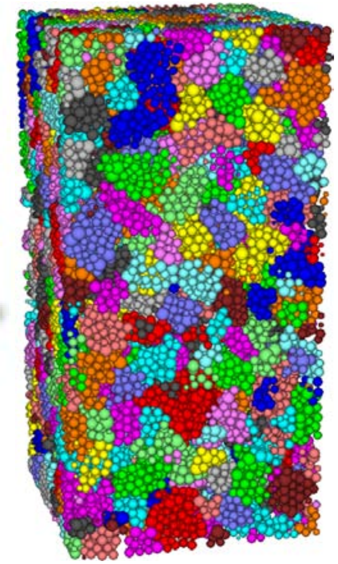
Generation of a microstructure-based model for sandstone

Sandstone specimen (may be from disintegrated core material or drill cuttings)



3D micro-CT image

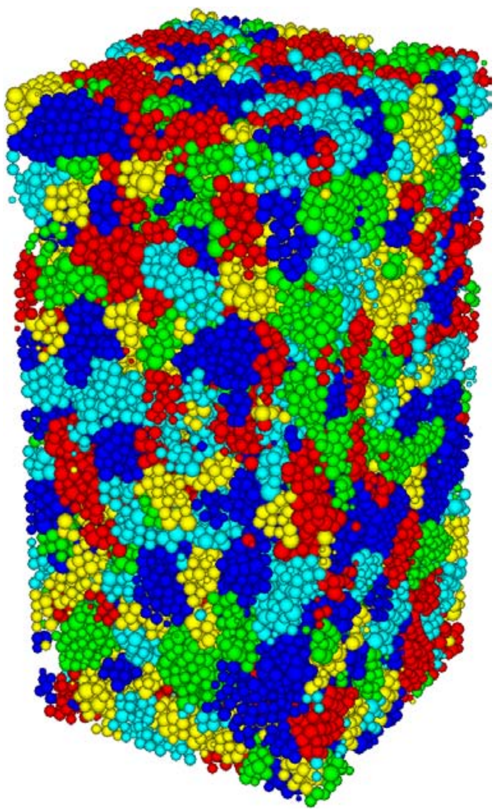
Segmented 3D micro-CT data



Discrete element model of the sandstone (Each sand grain is represented by a cluster of elements of the same color)

SINTEF NTNU

Using clusters of elements to represent grains



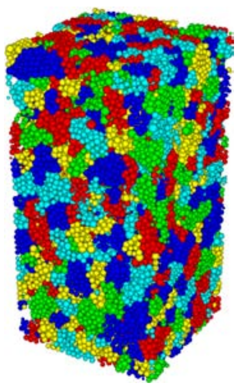
Two sets of bonding parameters:

Intergranular bonds: for a pair of elements which belong to two different grains.

Intragranular bonds: for a pair of elements which belong to the same grain.

Model calibration to determine input parameters

Fit the results of different lab tests with real rock specimens using the same model (same parameters).



Model generation

Load the model hydrostatically to different pressures

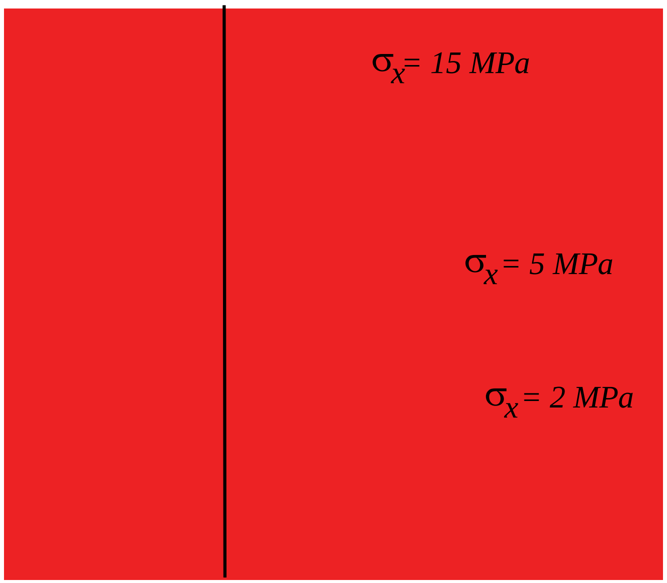
Triaxial test with 15 MPa confining stress

Triaxial test with 5 MPa confining stress

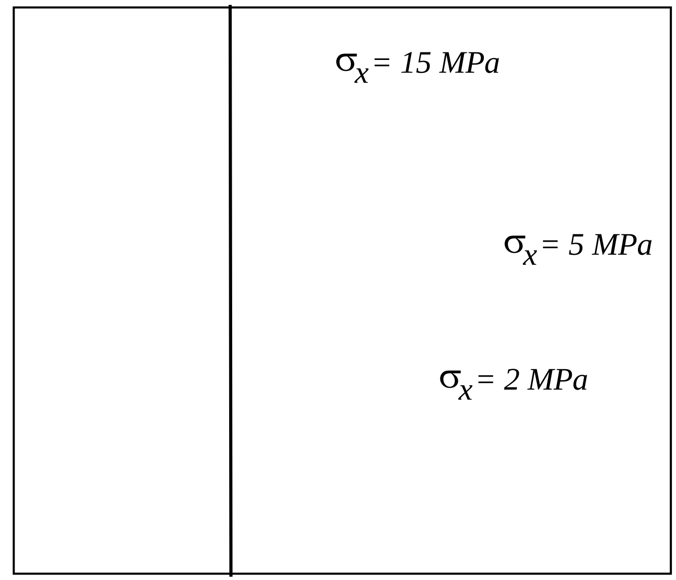
Triaxial test with 2 MPa confining stress

Comparison of simulation results and data measured on Castlegate sst.

Stress vs. strain

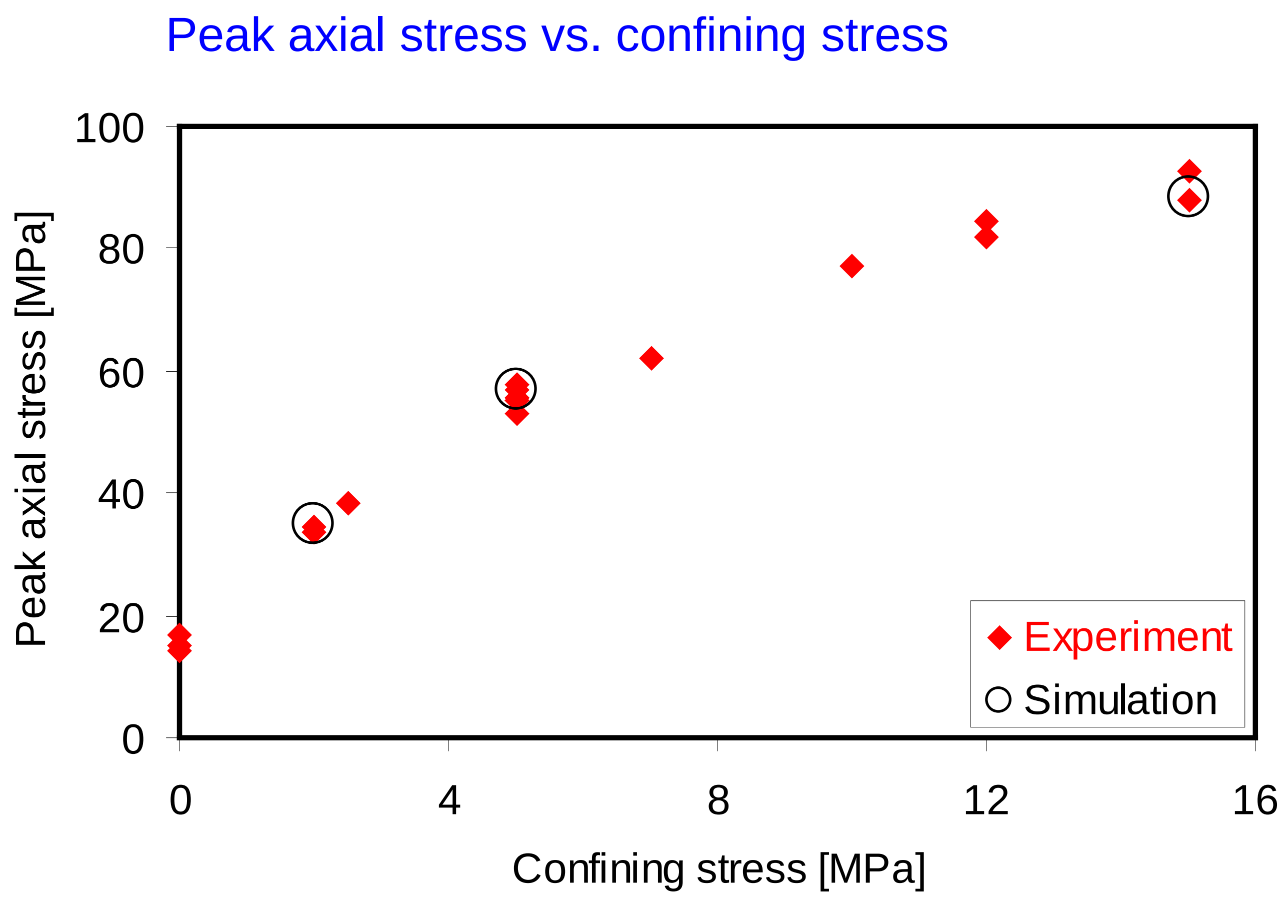


Experiment



Simulation

Comparison of simulation results and data measured on Castlegate sst.

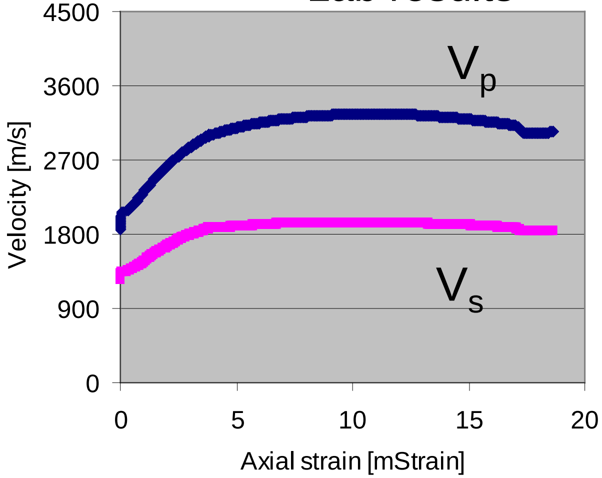


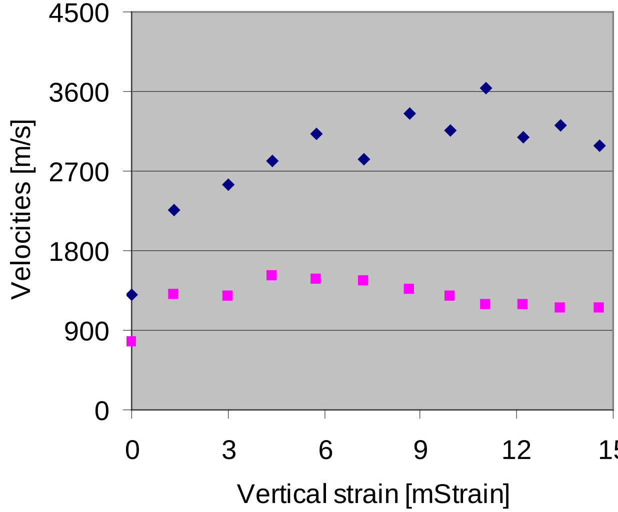
SINTEF NTNU

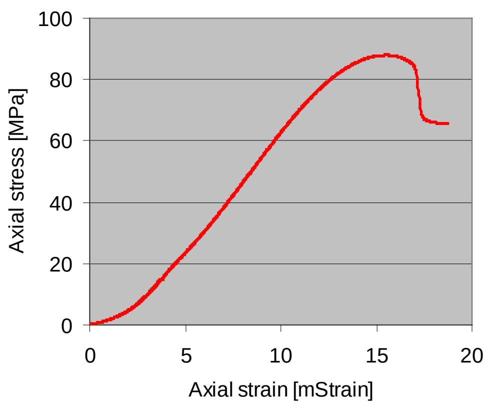
Comparison of simulation results and data measured on Castlegate sst.

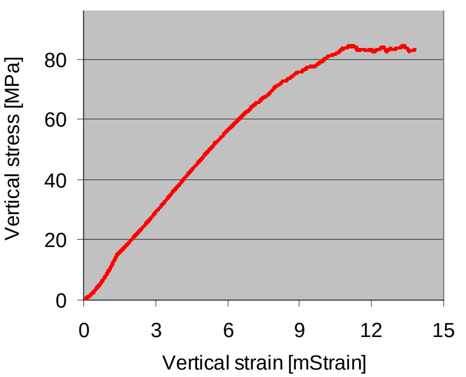
Velocities in a triaxial test (confining pressure 15 MPa)

Lab results





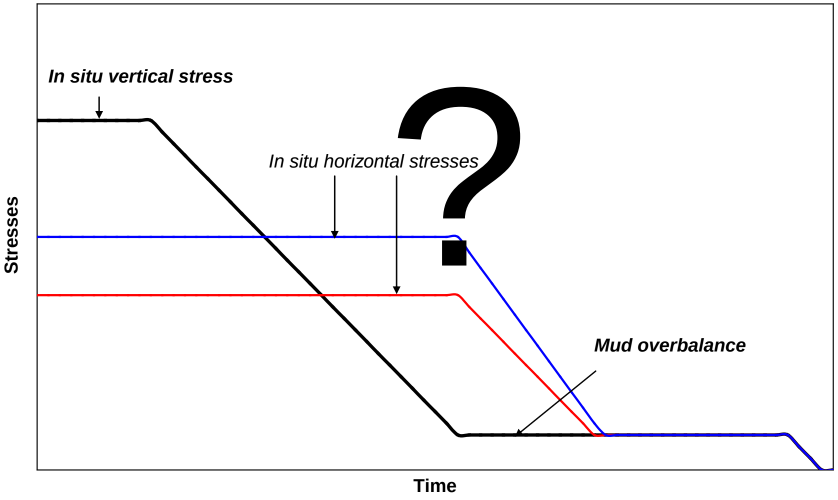


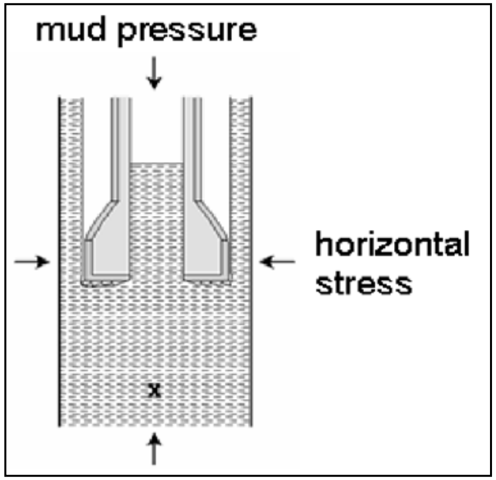


SINTEF NTNU

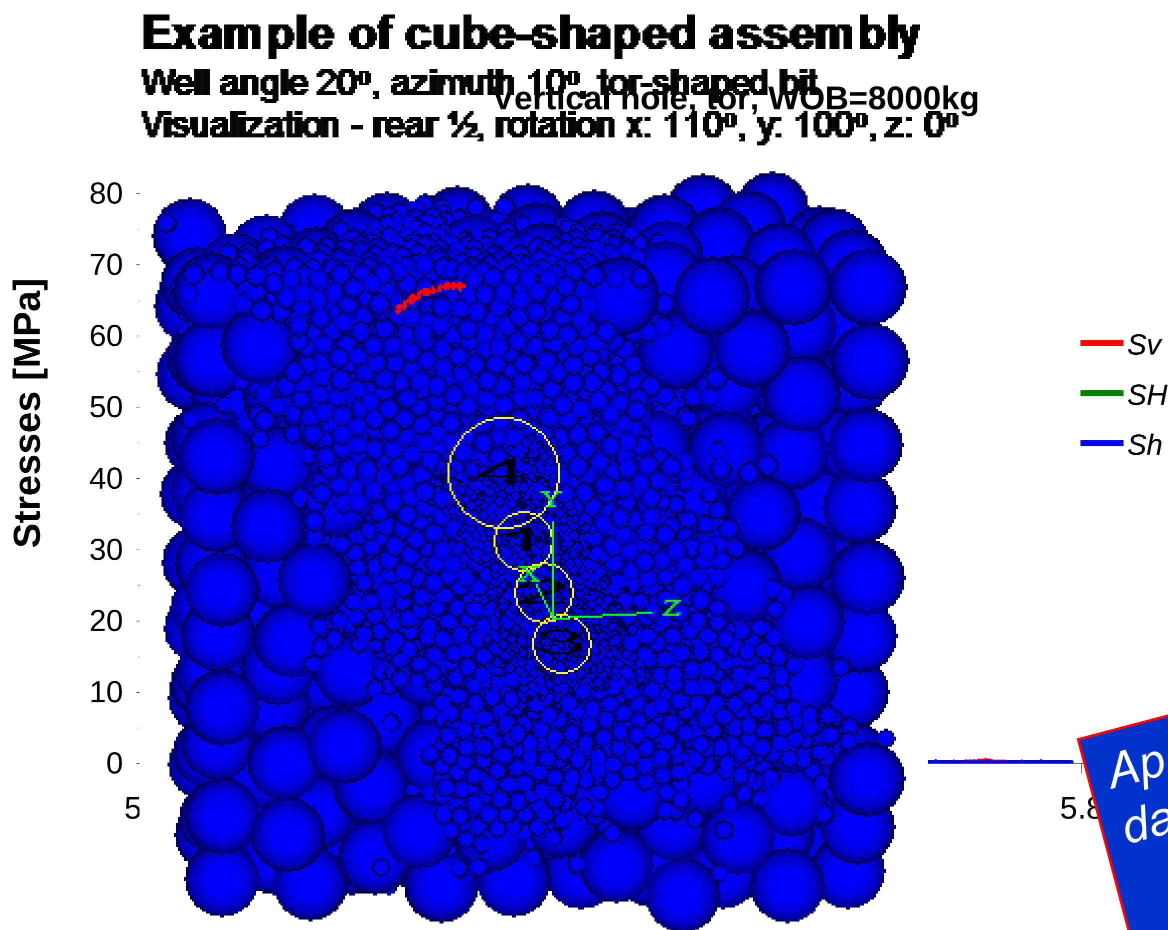
Stress Path during Coring

- ❑ Source of core alteration, affecting rock mechanical & wave velocity measurements
- ❑ Source of Stress Memory (Kaiser effect in AE), potential tool for stress determination





Stress Path during Coring
PFC^{3D} Simulation



Study effect of:

Rock properties

Hole angle

Bit shape

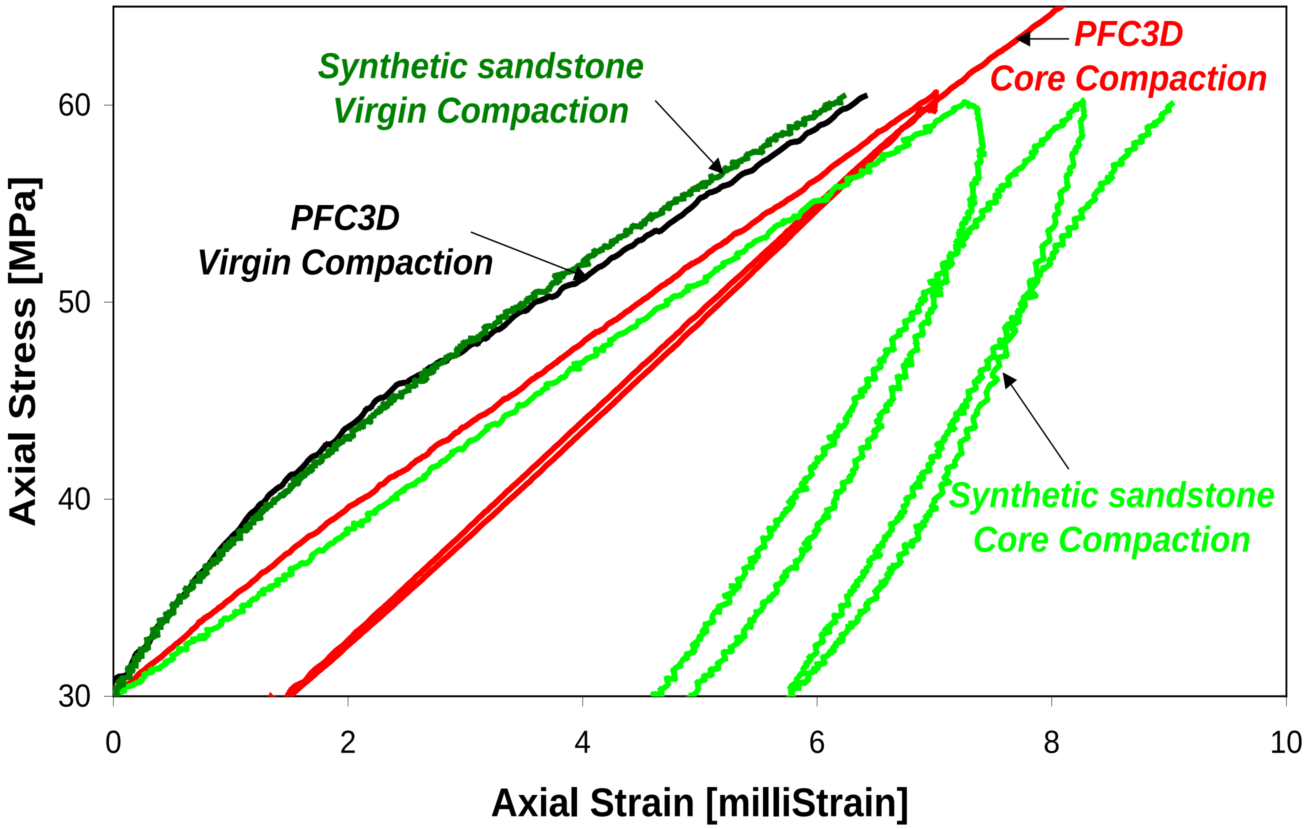
WOB

Apparent stress path is less damaging than anticipated

Gorodkov et al, Rock Stresses 2006

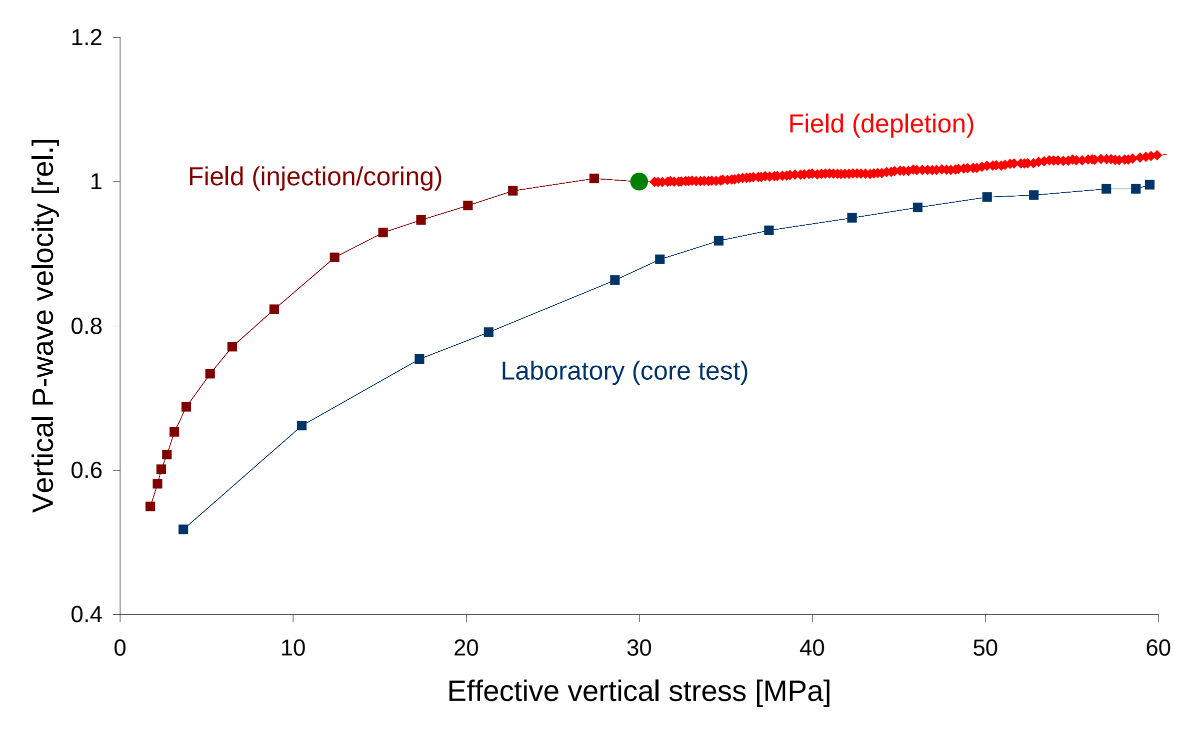
SINTEF NTNU

Particle Modelling:
PFC^{3D} Virgin vs. Core Compaction



Reservoir Rocks: Synthetic Sandstone

Laboratory modelling of
***In situ* vs. Core Behaviour**



We observe:

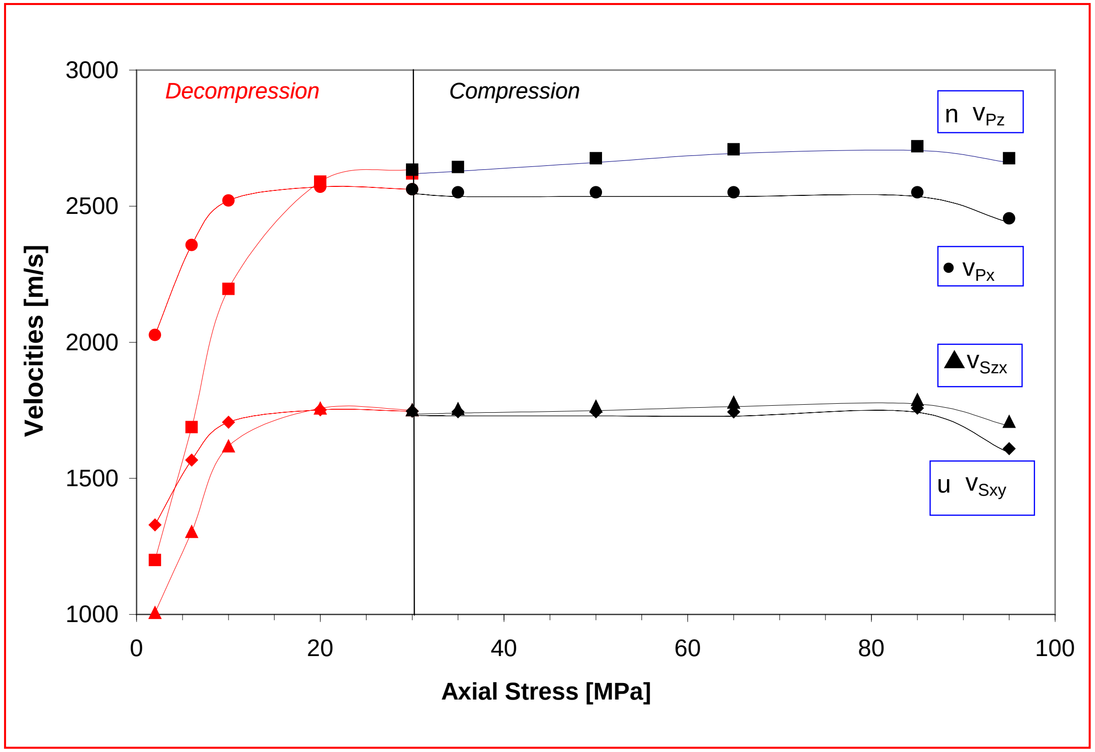
Low stress sensitivity during virgin loading (depletion) – effect of cementation

Significant stress sensitivity during unloading (inflation) and reloading (core measurement) – effect of cement bond breakage

Synthetic sandstone formed by cementation under simulated *in situ* stress conditions (here: 30 MPa vertical, 15 MPa horizontal)

Reservoir Rocks: Synthetic sandstone

In situ Behaviour from numerical modelling



We observe:

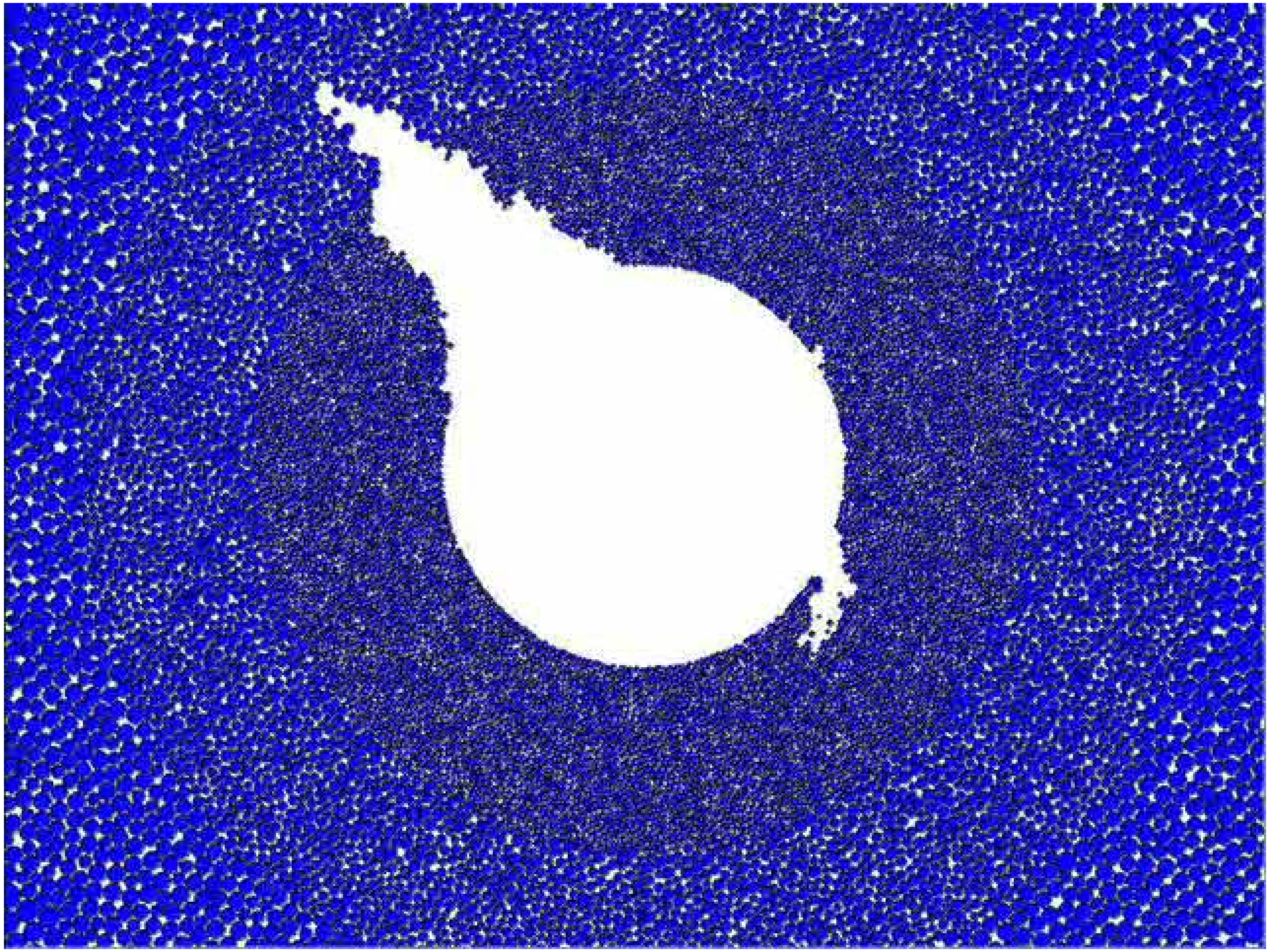
Qualitatively the same repsonse to loading & unloading as seen in the physical experiments

Notice Stress-Induced Anisotropy (also in lab!), and velocity decrease at high stress due to bond breakage

PFC^{3D} simulation performed with spherical particles; bonds inserted under 30 MPa axial & 15 MPa lateral stress

Courtesy of Lars M Moskvil

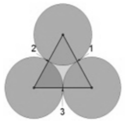
Sand Production / Well Stability

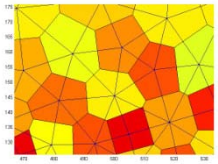


SINTEF NTNU

DEM on larger scale

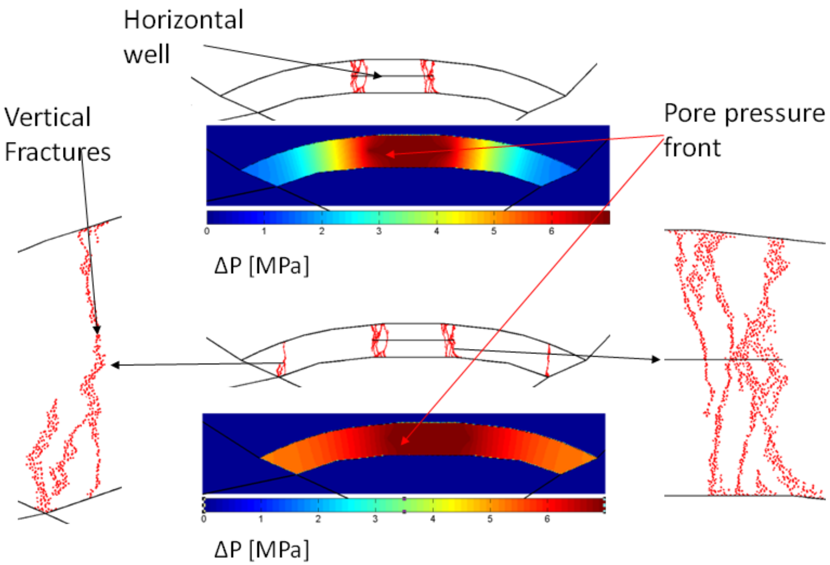
- Initial work with PFC on basin scale led to Modified DEM

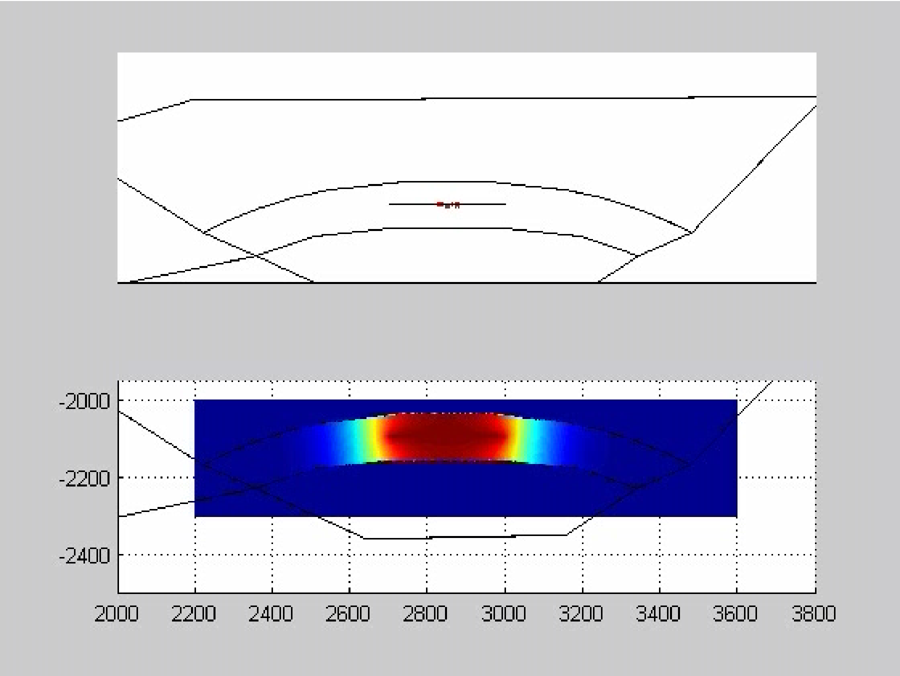




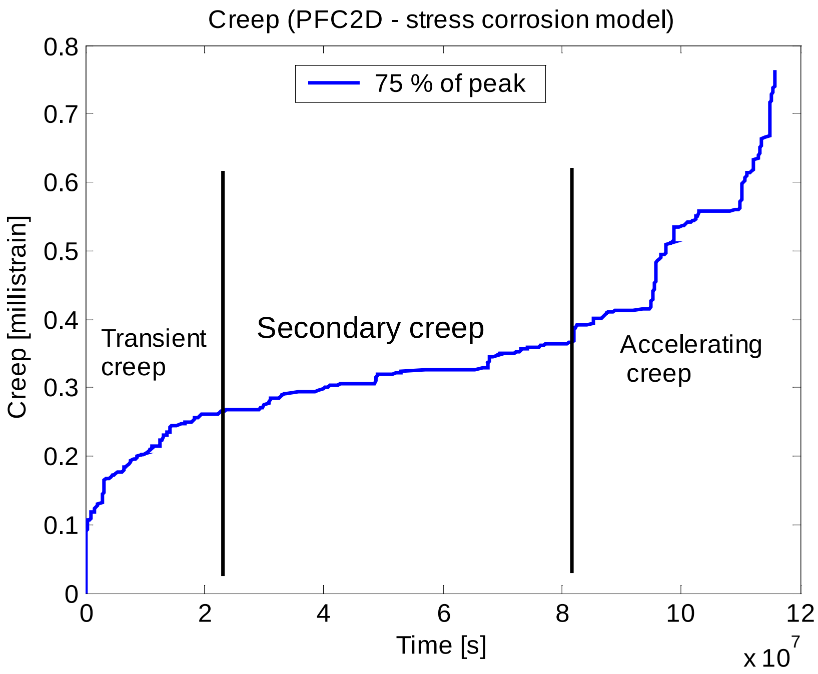
PhD Study by Haitham Alassi

- Permit realistic modelling of fracture development and fault (re-) activation during injection (or depletion) - Link to 4D seismics





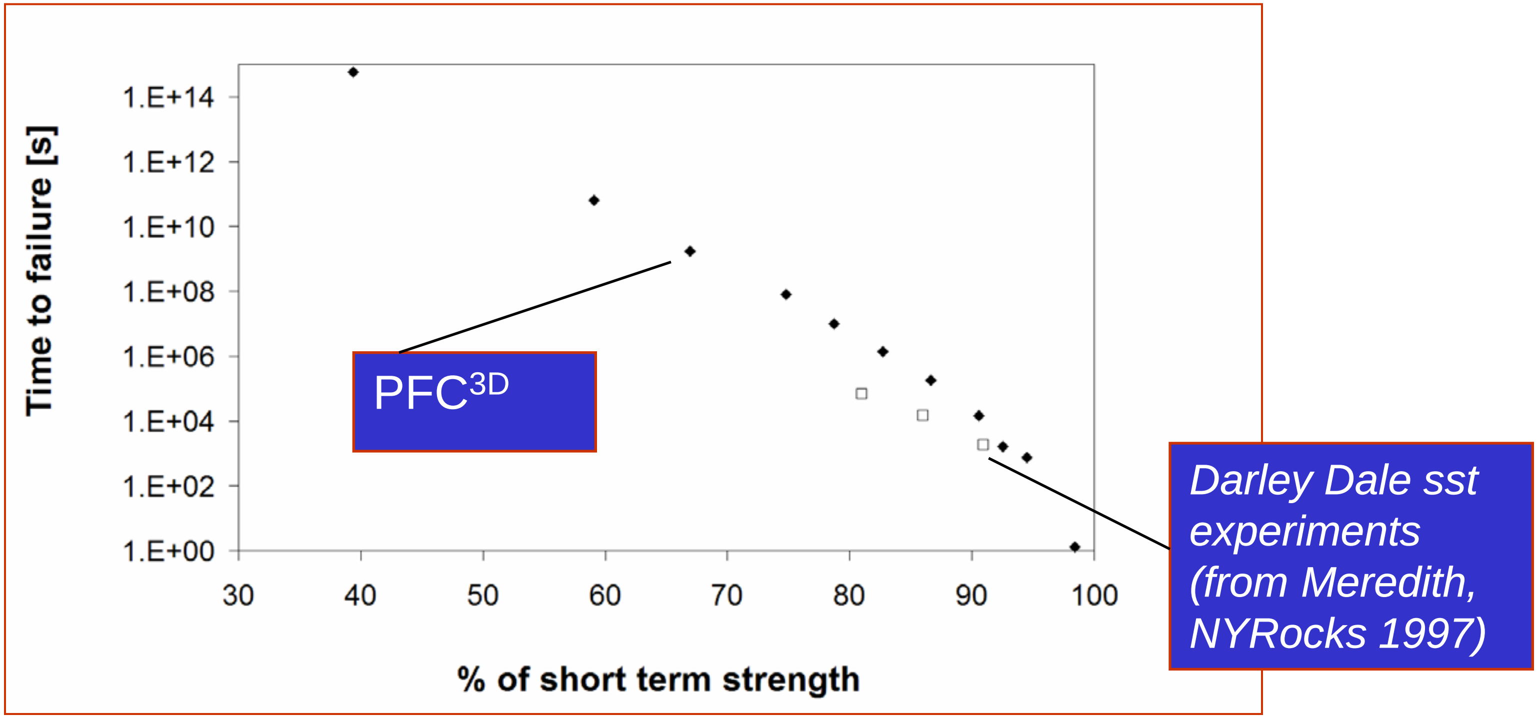
- **Creep is implemented to mimick stress-induced corrosion by reducing the parallel bond extent depending on the stress level relative to bond strength at each contact**



The model captures the three commonly observed phases of transient, secondary and accelerating (tertiary) creep

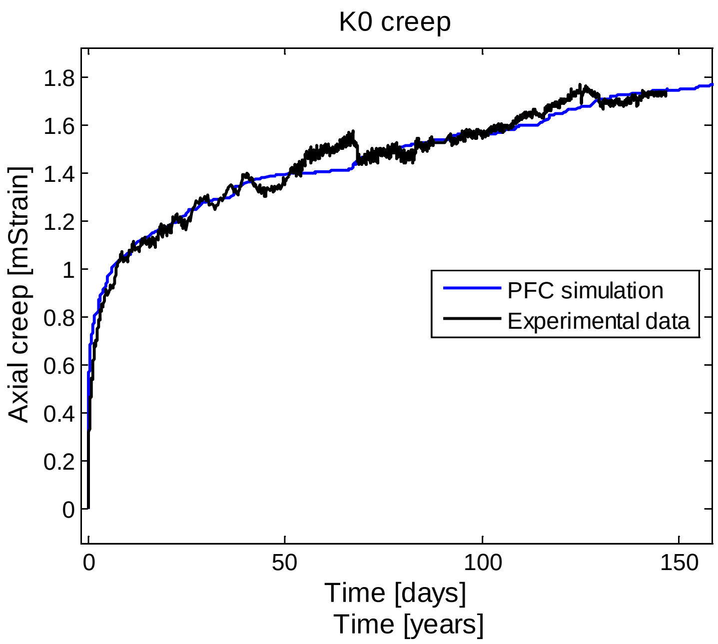
A similar approach has been presented by Potyondy (2005)

Time dependent deformation



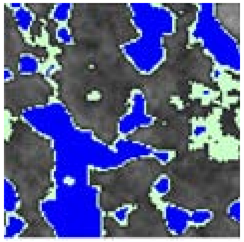
- Long-term behaviour may be assessed from short-term simulations
- Challenges: Appropriate calibration of microscopic creep parameters
- Other physical mechanisms may play a vital role over long time scales

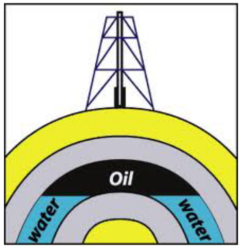
❑ A Tool for the Future...



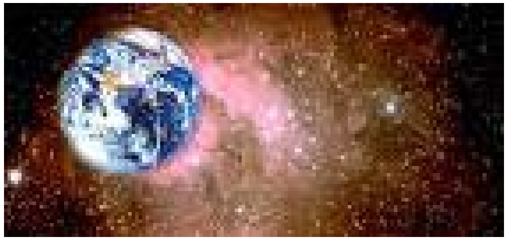
Dance me through the end of the pore

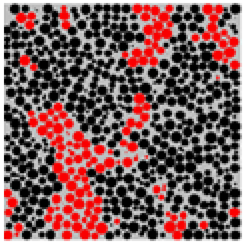
Lyrics: Rune M. Holt

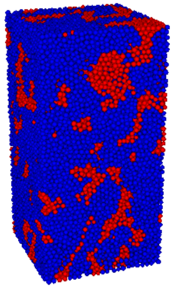


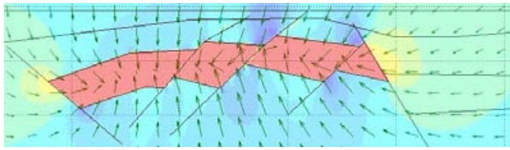


From the land of a lonely pore
next to a solid grain
We digest their contacts
- squeeezed by contracts -
With courage and pain
we compute the strain
and derive the strength of a full sized core!
It is not in vain
- maybe it's insane -
But one day we may capture the reservoirs -
built by discrete balls,
surrounded by walls,
seismic waves moving in a silent waltz.
Our dream is to model the Earth and the Stars!









SINTEF NTNU

Acknowledgements

Financial support to SINTEF's PETЯUS & PETЯUSCA projects:

Chevron
ConocoPhillips
Det norske
RWE Dea
Shell
Statoil
Petrobras (only PETЯUS)

Cooperation:

Numerical Rocks