April 19, 2010

ROSE

ROck SEismic research project

NTNU

Norwegian University of Science and Technology

IMPACT OF PORE FLUID ON THE NONLINEAR ACOUSTIC WAVE PROPAGATION

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   - Results and conclusions
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Project description

- Subject
- Method
- Objective

'Nonlinear elastic waves for estimation of properties of geologic materials'

The SURF technique = Second-order UltRasound Field technique

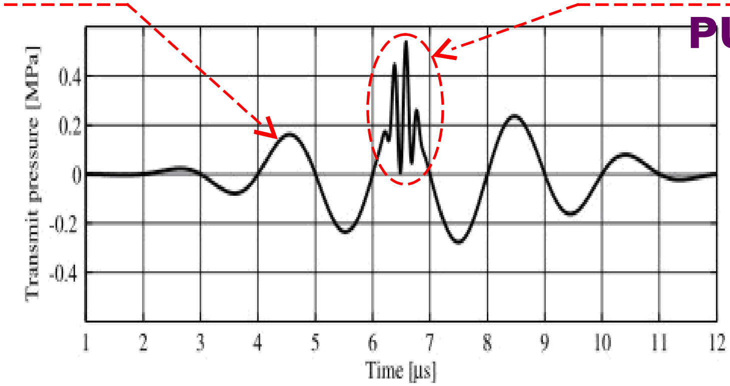
*The primary goal is an adaptation of the SURF method to the petroleum industry use – **new diagnostic tool***

The method was developed in 2002 at the Department of Circulation and Medical Imaging, NTNU. It is currently used for medical ultrasound imaging

SURF => the dual-band technique => relies on simultaneous transmission of two frequency pulse complexes in the same direction

MANIPULATION PULSE

LF Low frequency pulse



IMAGING PULSE

HF High frequency pulse

(Angelsen et al., 2007)

The centre frequency separation typically from 1:7 to 1:10

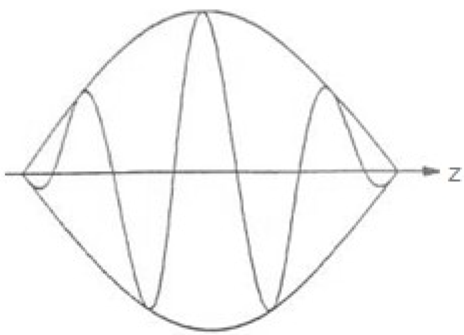
PhD project

Project description

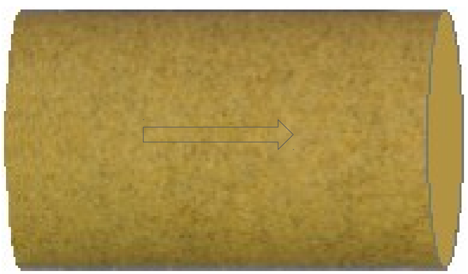
The ***low-frequency (manipulation) pulse*** *is used to manipulate the elastic properties of the material e.g., rock.*

Manipulation pulse generates a local change in the speed of sound

Transmitted

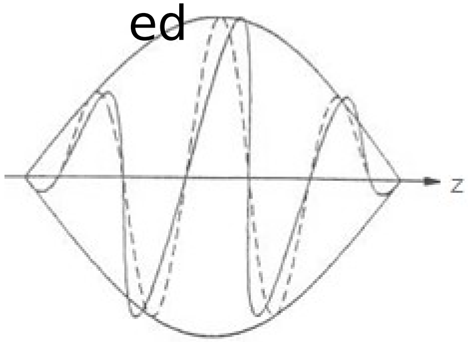


Sinusoidal wave



ROCK

Received



Distorted wave

The LF wave distortion affects the propagation of the ***high-frequency (imaging) pulse****. That pulse is used to record the elastic properties of rock*

Preliminary project

Research motivation

Verification of reasonability of the SURF method implementations into the rocks testing

It is realised by the creating the similar conditions as occure during the SURF measurements

In preliminary test => the manipulation puls is replaced by the oscillations of the mechanical uniaxial stress

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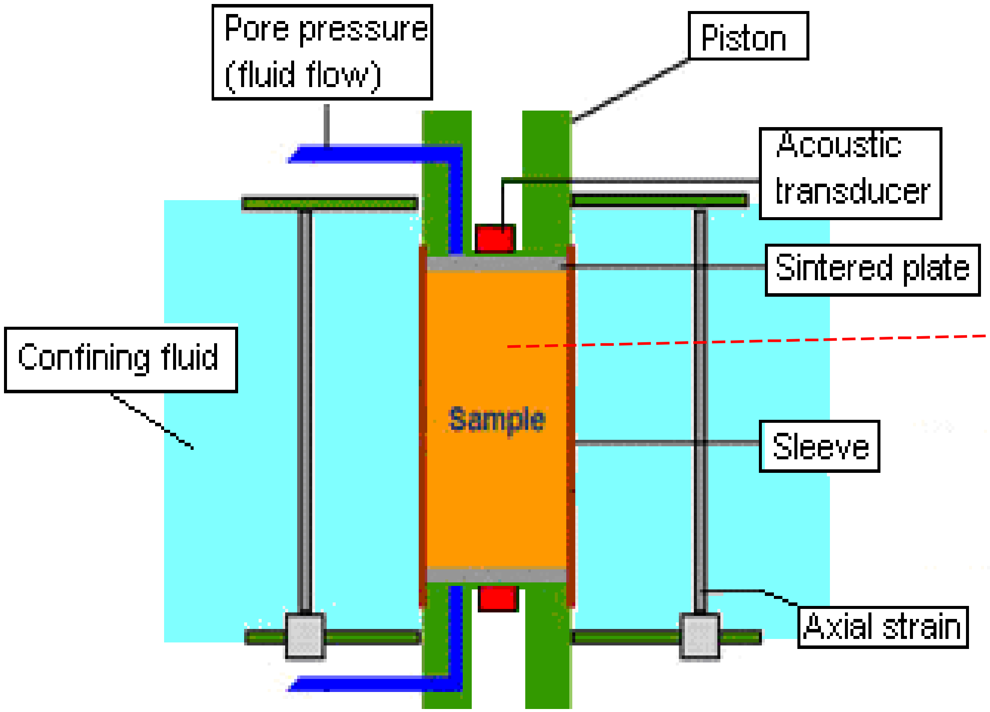
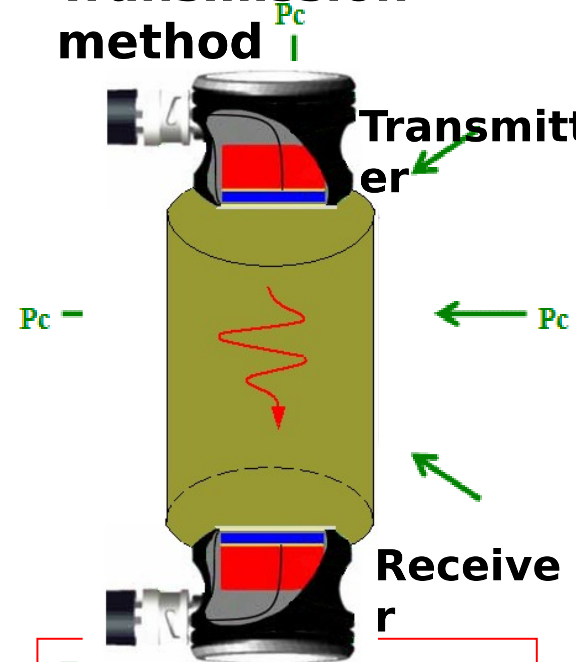
Experimental set-up

Tests => a combination of the ***quasi-static*** and ***dynamic*** measurement methods



Triaxial test system

Transmission method

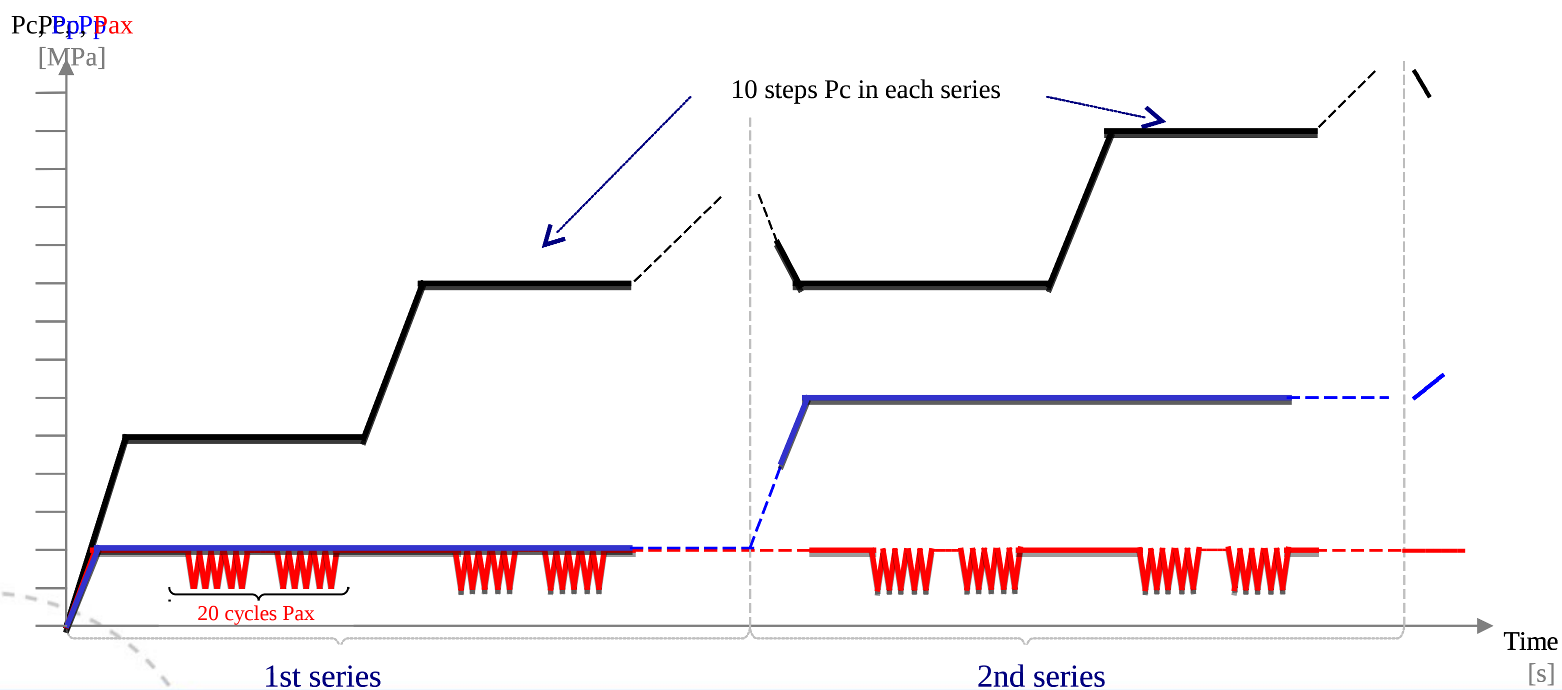


Pc - confining pressure
Pp - pore pressure
σax - axial stress

f = 500 kHz
Single-sine pulse

Stress protocol

Pp	Pc										
2	**5**	**9**	13	17	21	25	29	33	37	41	← 1 series
6	**9**	**13**	17	21	25	29	33	37	41	45	← 2 series
10	13	17	21	25	29	33	37	41	45	49	← 3 series
14	17	21	25	29	33	37	41	45	49	53	← 4 series
18	21	25	29	33	37	41	45	49	53	57	← 5 series
22	25	29	33	37	41	45	49	53	57	61	← 6 series
26	29	33	37	41	45	49	53	57	61		← 7 series
30	33	37	41	45	49	53	57	61			← 8 series
34	37	41	45	49	53	57	61				← 9 series
38	41	45	49	53	57	61					← 10 series



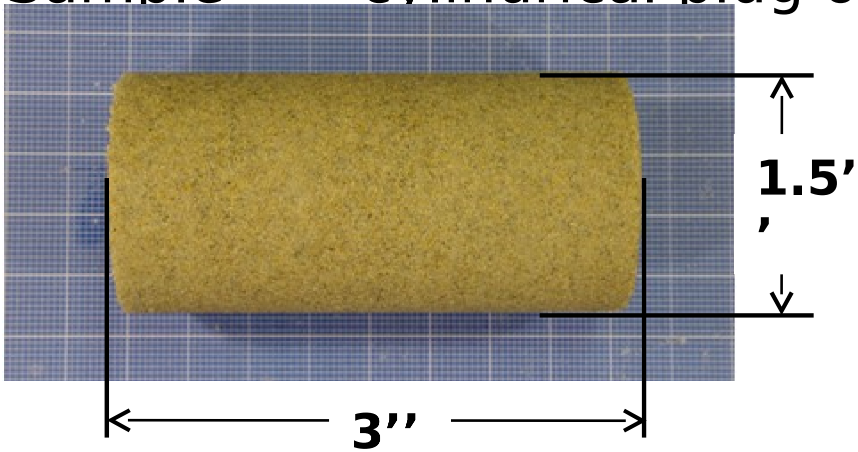
The additional requirments for test

Undrained conditions – the pore fluid is not allowed to escape - variable pore pressure P_p

K0 mode – the radial strain is keep at zero or negligible value during loading of axial stress P_{ax} - realised by adjusting the confining pressure P_c

Specimen:

Sample => cylindrical plug of **Castlegate sandstone**



Castlegate sandstone is a weak, high porous (~ 27%), outcrop rock. It consist of 70% quartz, 30% feldspar and other rock fragments, and a low clay content

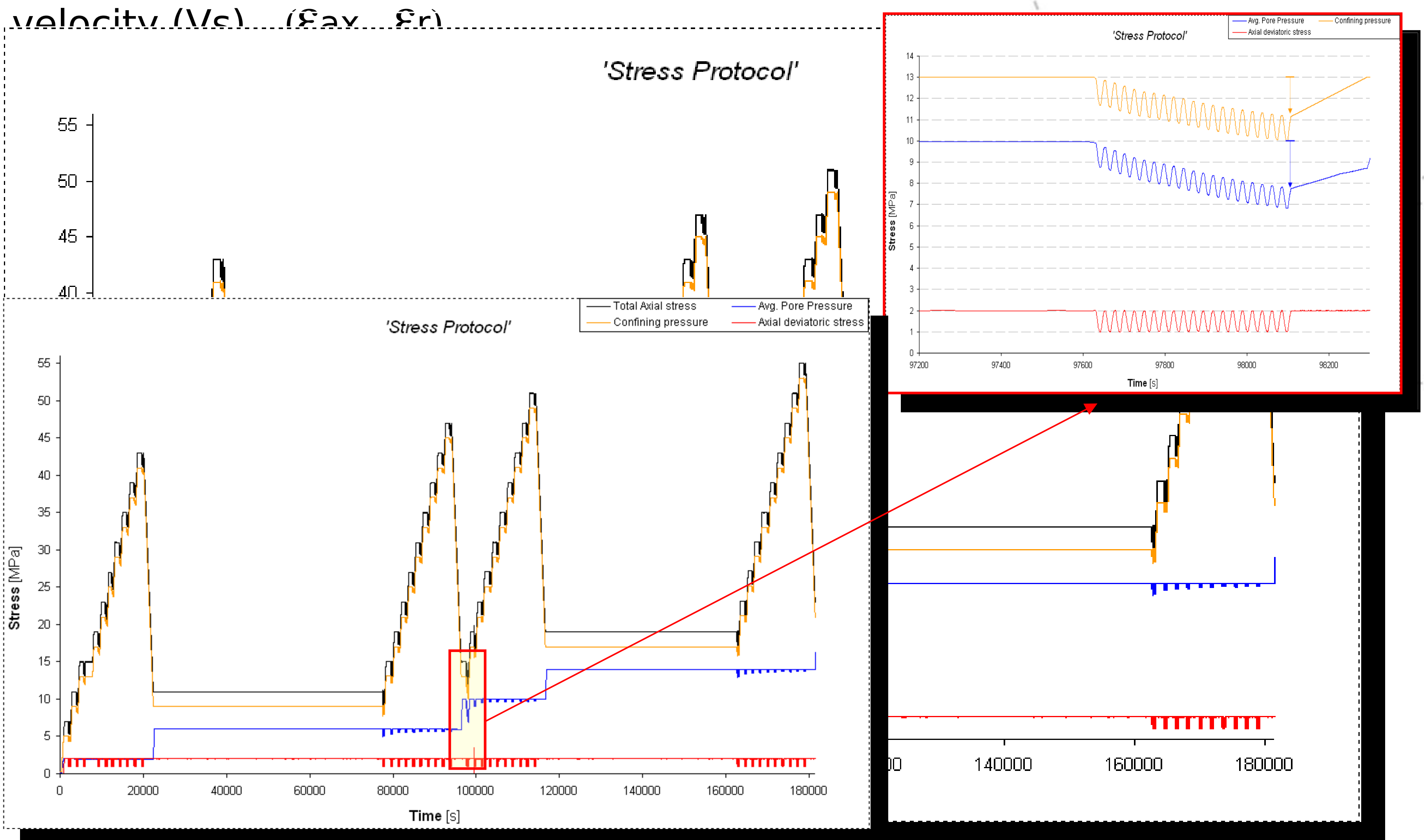
Saturation:

Pore fluid => **Brine** (3.5%) and **Oil** (Kerosene)

Measurements – monitored parameters

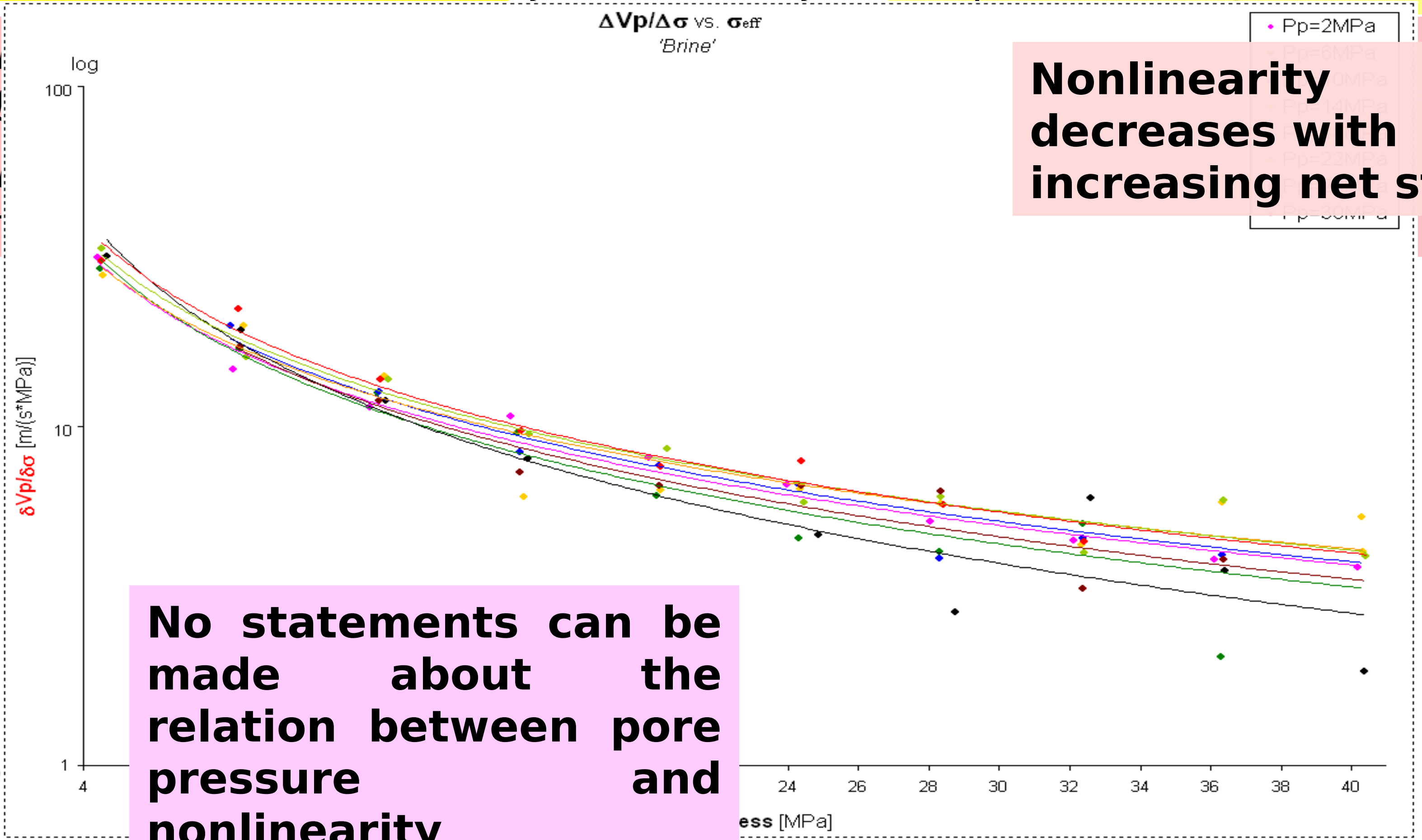
Triaxial cell => Axial and radial strains (εax, εr)

Acoustic cell => Axial P-wave velocity (Vp) and Axial S-wave velocity (Vs)



Tested parameter

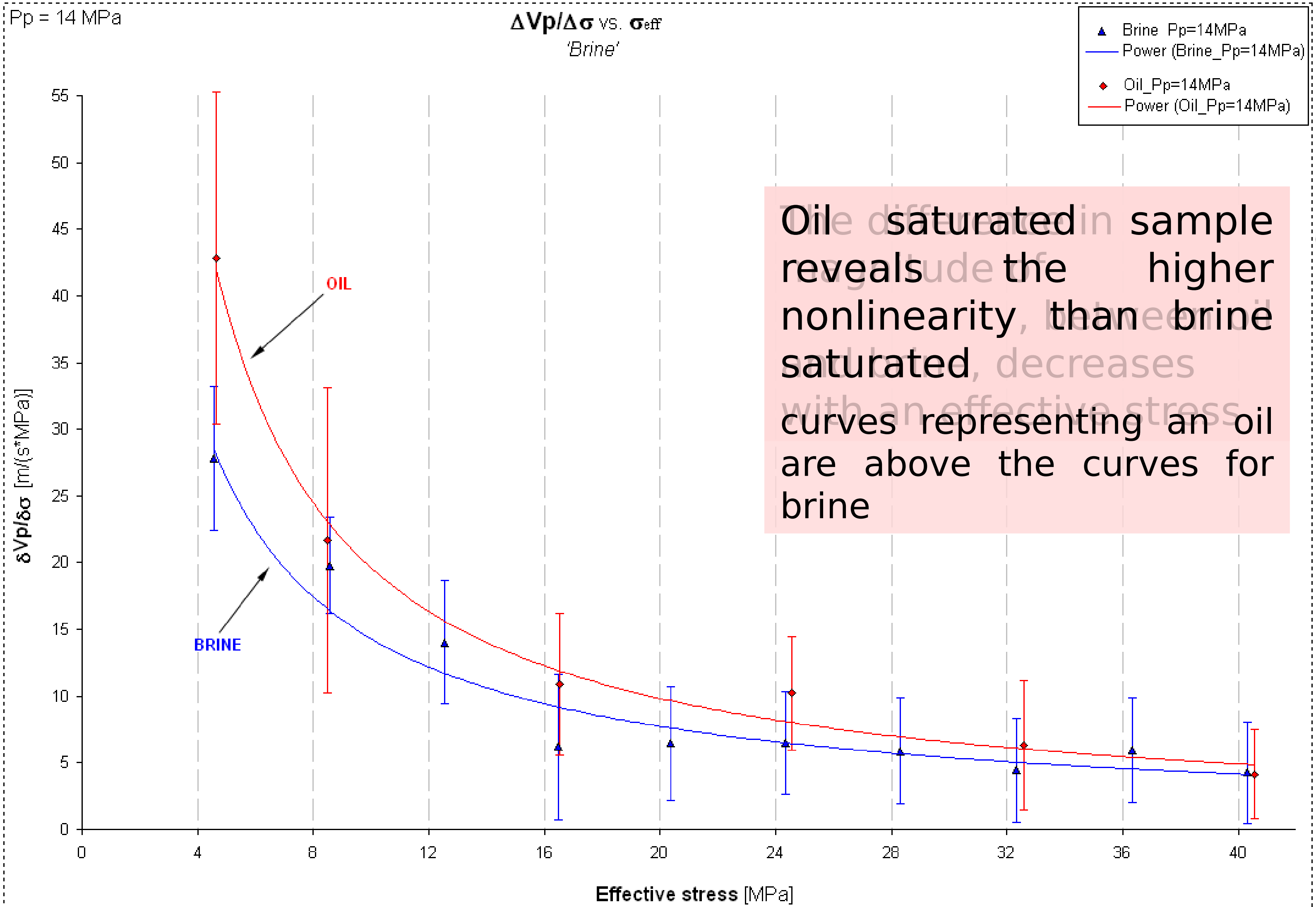
The nonlinear parameter = $$\frac{\partial V_p}{\partial \sigma_p}$$ = derivative of the wave velocity with respect to stress



Nonlinearity decreases with increasing net stress

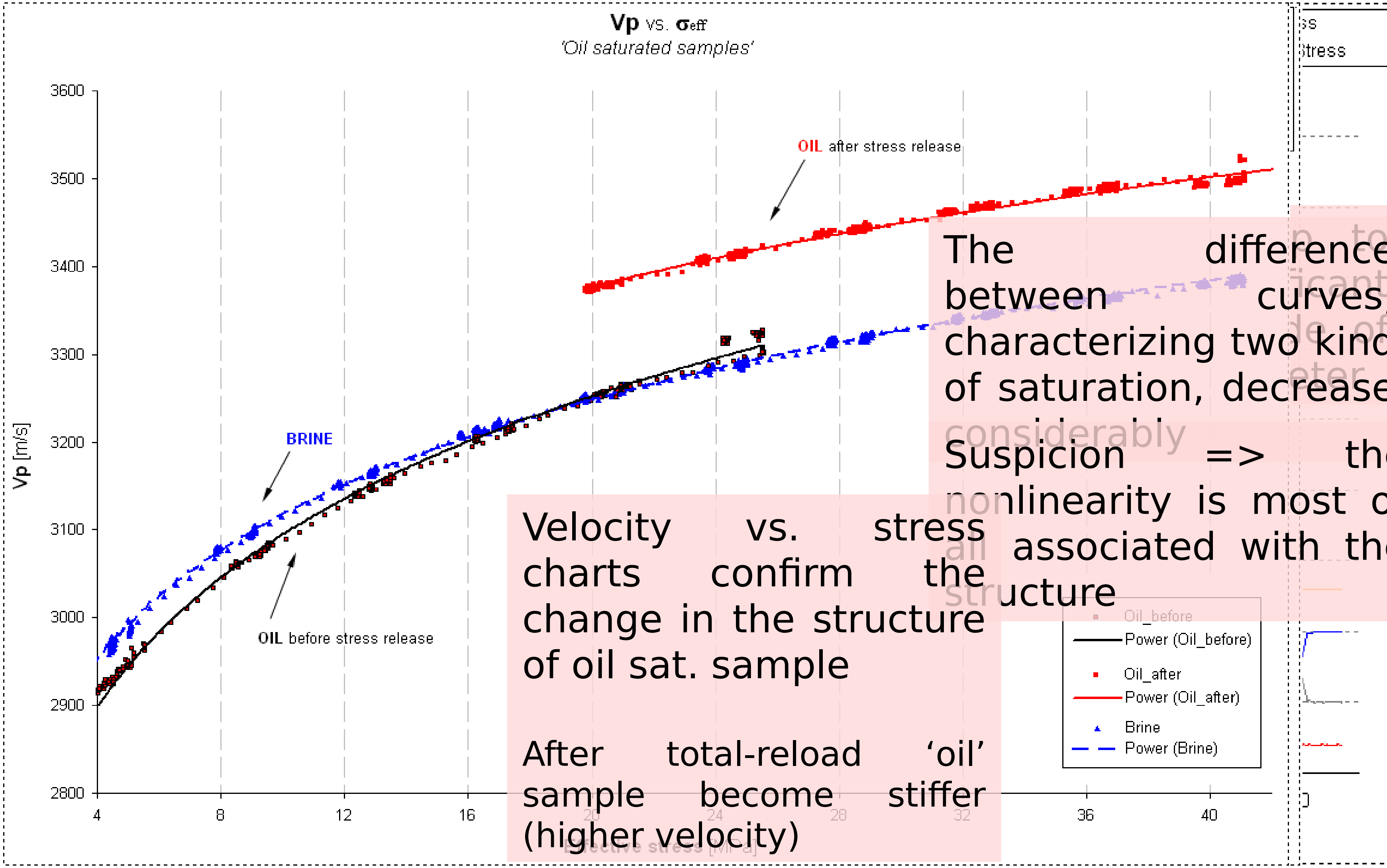
No statements can be made about the relation between pore pressure and nonlinearity

Brine and Oil saturation – results comparison



Oil saturated sample reveals the higher nonlinearity than brine saturated curves representing an oil are above the curves for brine

Oil saturation – results comparison



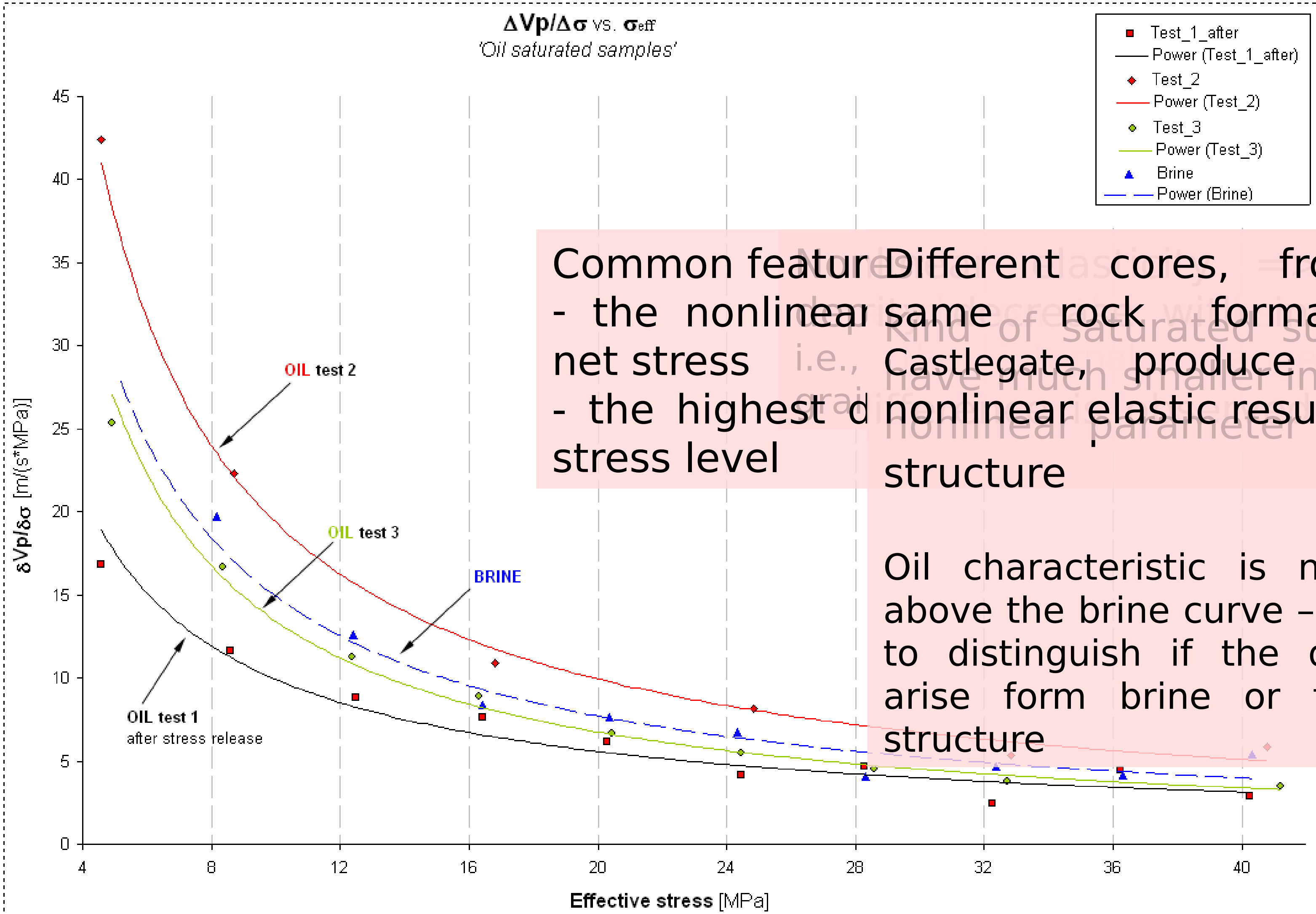
The difference between curves, characterizing two kind of saturation, decrease considerably

Suspicion => the nonlinearity is most of all associated with the structure

Velocity vs. stress charts confirm the change in the structure of oil sat. sample

After total-reload 'oil' sample become stiffer (higher velocity)

Oil saturation – results comparison



Common featur
- the nonlinea
net stress
- the highest d
stress level

Different cores, from the same rock formation - Castlegate, produce various nonlinear elastic results

structure

Oil characteristic is no longer above the brine curve – it is hard to distinguish if the difference arise form brine or from the structure

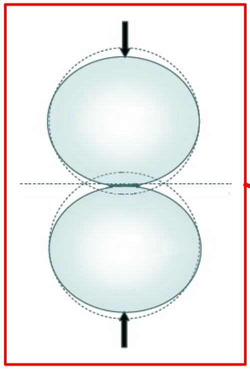
Theory - assumptions

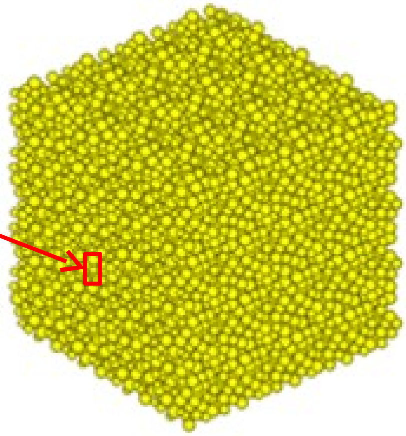
Theory - assumptions

Model => Hertz-Mindlin rock model

Rock structure => grain pack model (identical spherical grains)

Grains => rigid quartz bodies (deformable parts framework and fluid)





Describe => Bulk K_{fr} and shear G_{fr} frame moduli

Conditions => Hydrostatic sterss σ_p and undrained conditions

Saturation => 100% , single substances: **Brine (3.5%)** and **Oil (45 deg. API)**

Biot-Gassmann equation => Effective bulk K_{eff} and shear G_{eff} moduli

Batzle & Wang, 1992 => Fluid parameters K_f and ρ_f vs. Pp

Biot's theory of elastic wave propagation => P-wave velocity Vp

Calculations

Nonlinear parameters

Determination of the nonlinear parameter

$$\frac{\partial V_{p\,total}}{\partial \sigma_p} \Rightarrow V_p^{'}(\sigma_p) = V_p^{'}\left(\frac{\partial K_{fr}}{\partial \sigma_p}, \frac{\partial G_{fr}}{\partial \sigma_p}, \frac{\partial \Phi}{\partial \sigma_p}, \frac{\partial K_f}{\partial \sigma_p}, \frac{\partial \rho_f}{\partial \sigma_p}\right)$$

The stress-dependent parameters

The nonlinear parameter for the solid part (framework)

$$\frac{\partial K_f}{\partial \sigma_p}, \frac{\partial \rho_f}{\partial \sigma_p} = 0$$

⇩

$$V_p^{'}(\sigma_p)_{solid} = V_p^{'}\left(\frac{\partial K_{fr}}{\partial \sigma_p}, \frac{\partial G_{fr}}{\partial \sigma_p}, \frac{\partial \Phi}{\partial \sigma_p}\right)$$

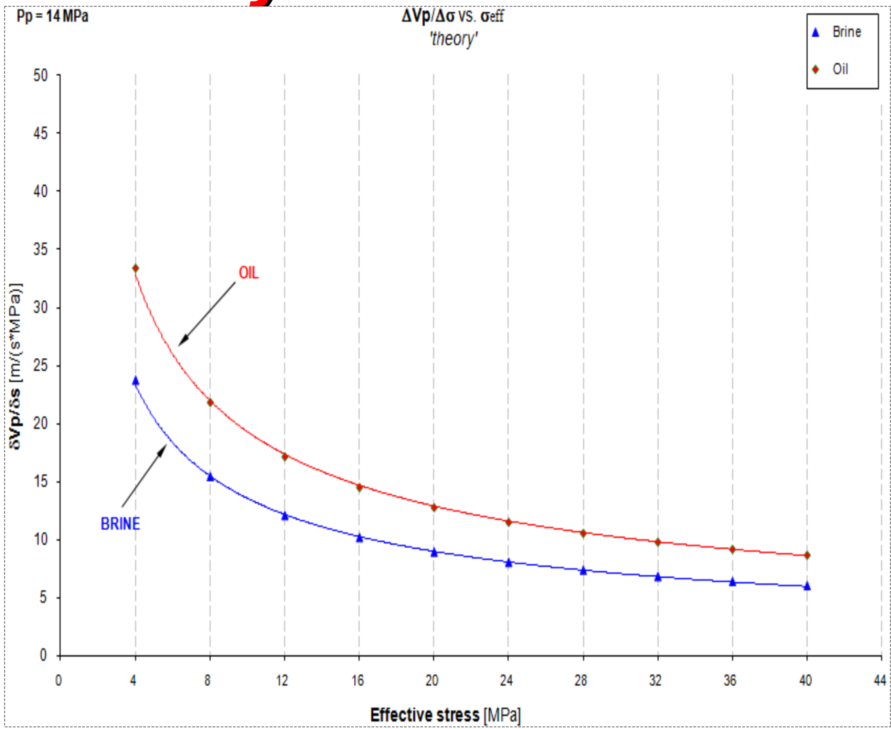
The nonlinear parameter for the fluid part

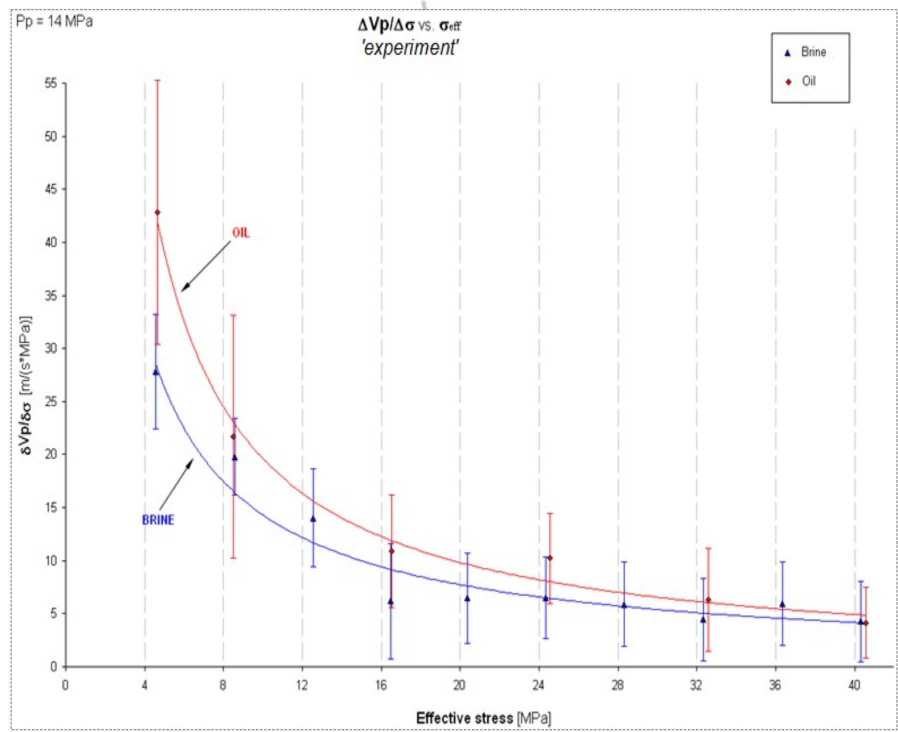
$$\frac{\partial K_{fr}}{\partial \sigma_p}, \frac{\partial G_{fr}}{\partial \sigma_p} = 0$$

⇩

$$V_p^{'}(\sigma_p)_{fluid} = V_p^{'}\left(\frac{\partial K_f}{\partial \sigma_p}, \frac{\partial \rho_f}{\partial \sigma_p}, \frac{\partial \Phi}{\partial \sigma_p}\right)$$

Brine and Oil saturation – research vs. theory

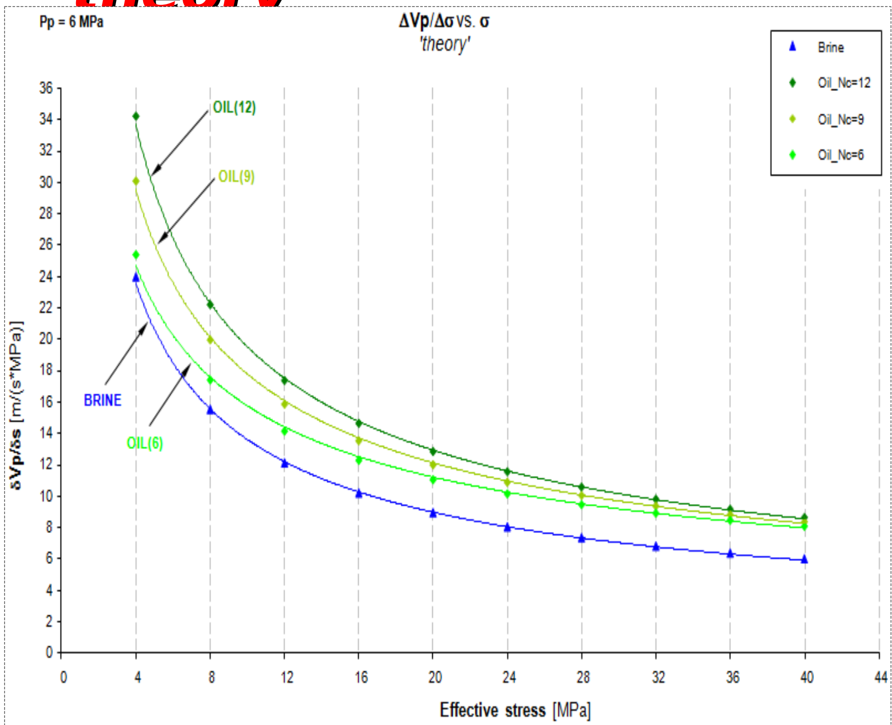


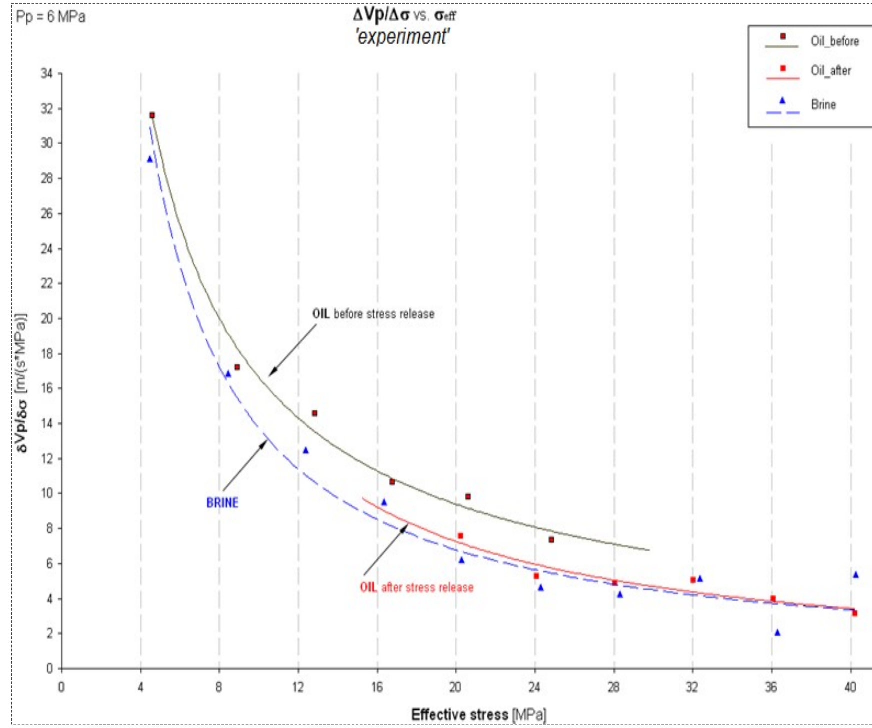


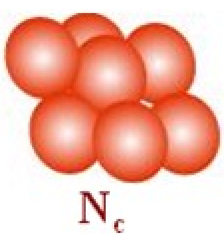
Similar trend of characteristics:

- decrease of nonlinearity with increasing stress
- decrease of nonlinear separation between brine and oil for higher stresses

Brine and Oil saturation – research vs. theory







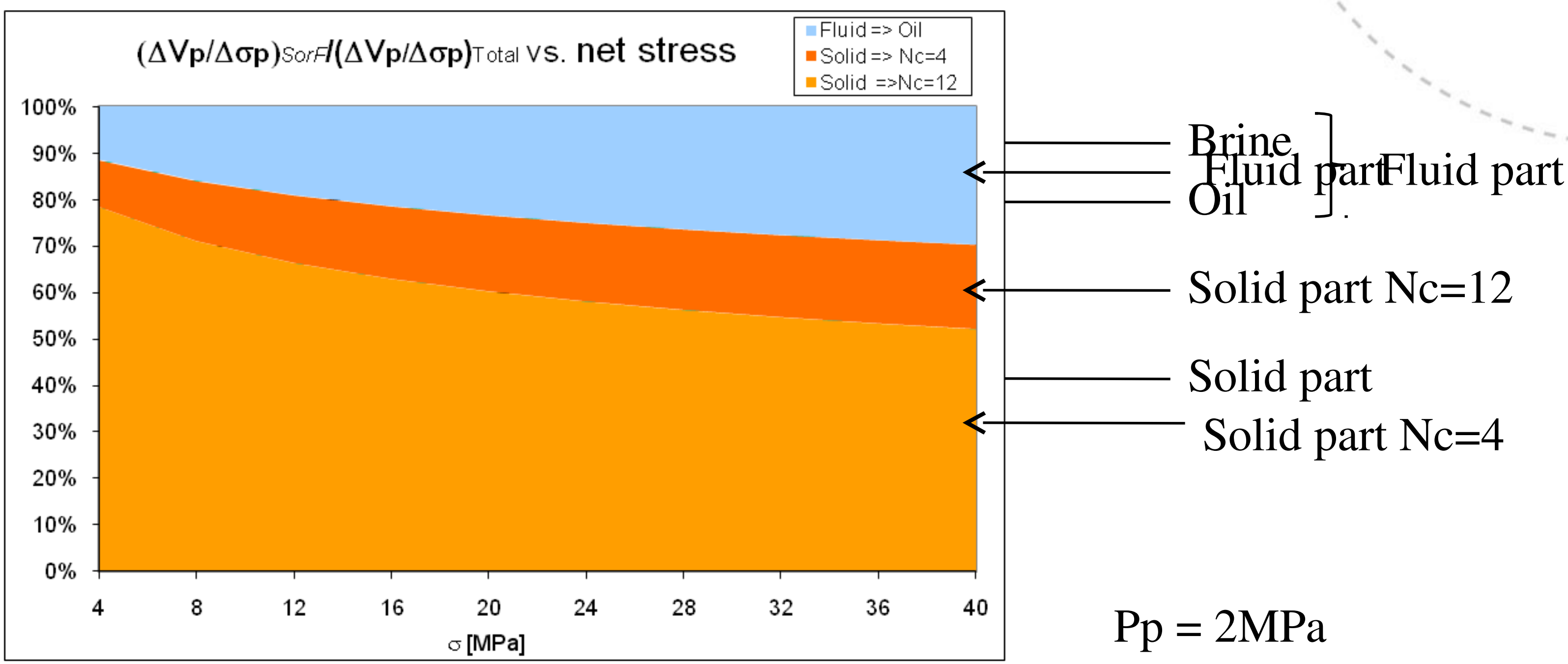
N_c - coordination number
(the average number of contacts per sphere)

Rock structure is characterized by the grain contact number Nc (in the theoretical studies)

Change in the grain arrangemnet (consequently the number of micro-cracks) affects the change of nonlinear parameter

Theory – contribution of fluid and soild part on nonlinearity

Theoretical study allows to estimate what is the impact of fluid and solid part on nonlinear parameter



- The contribution of soild part is higher than fluid (especially for lower stress)
- The difference in the rock structure has high impact on the nonlinearity
- The difference between Brine and Oil saturated sample is insignificant

Conclusions

1. The nonlinear elasticity is not sufficiently sensitive parameter to kind of saturating substance => most likely, it can not be effectively used to fluid distinction

Based on literature (*Van Dan Abeele et al., 2002*) - nonlinearity could give better results in study degrees of saturation

2. The parameter seems to be sensitive to the structure – grains arrangement inside the rock – number of discontinuities (fractures)

3. Theoretical consideration reveals that:

a. The nonlinearity is strongly dependend on the rocks structure

b. Both solid and fluid part has an impact on the nonlinear parameter

c. The kind of saturated substance has an impact on the nonlinearity however, the difference is insignificant

d. The contribution of solid part, framework, is much higher than fluid (especially at low net stress)

Summary

Plans for future work

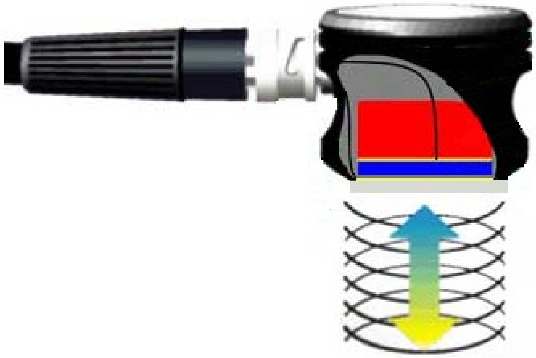
Summary

- **Tests on the artificially fractured sample**
  (the method of fracture detection)

  Verification of crack influence on the nonlinear elastic properties of rock

- **Rock attenuation measurements**

- **Design of the prototype of dual-band array transducer capable to transmit the low- and high-frequency pulses simultaneously**



- **Tests with the SURF method**

Acknowledgments

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