Hydromechanical Behaviour of the Aquifer and Caprock under High Pressure Injection

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INTRODUCTION

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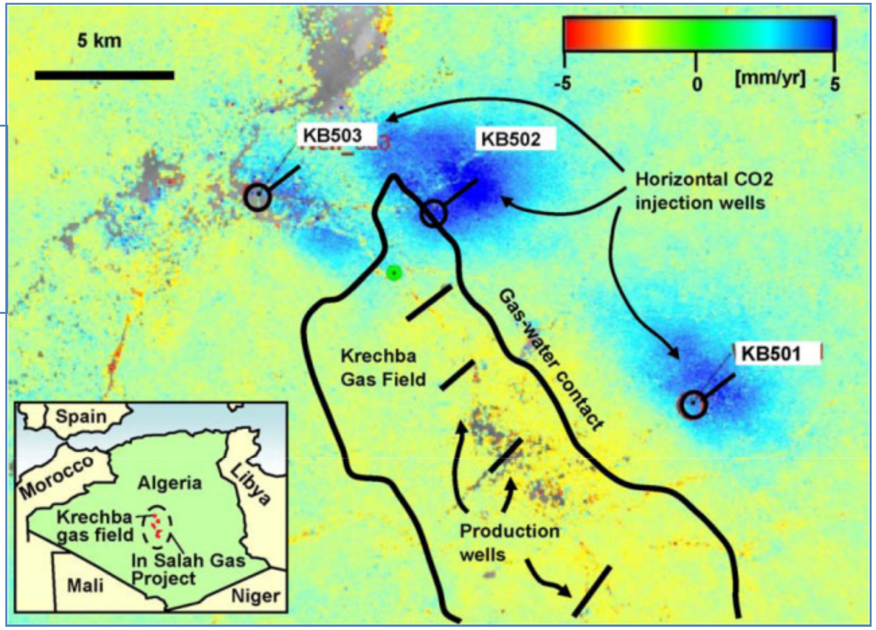
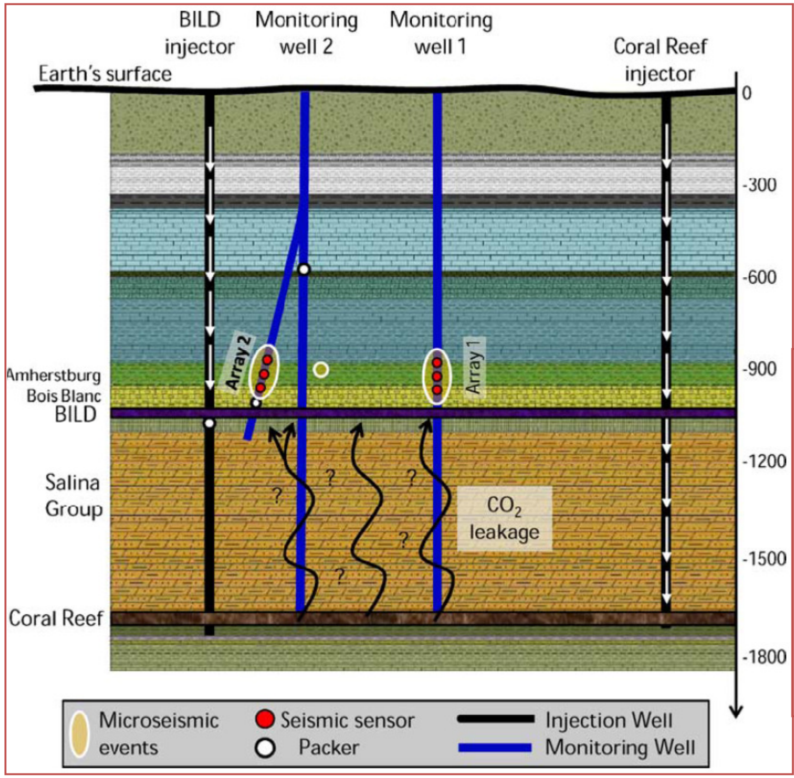
HYDROMECHANICAL EFFECTS

Uplift of 5 mm/yr in In Salah
(Rutqvist *et al*., 2010, IJGGC)



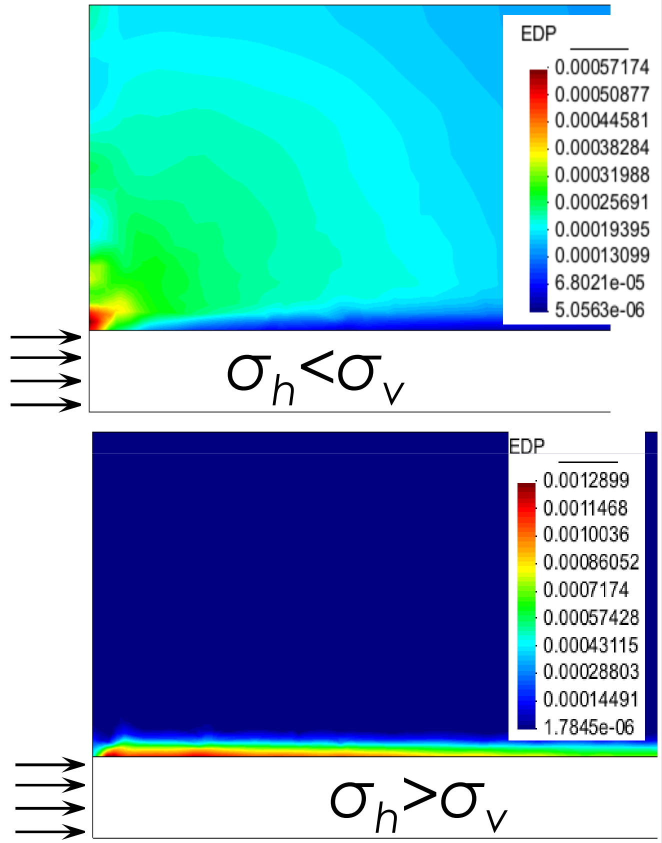


Microseismicity due to CO_2 leakage around wells at Otsego County, Michigan Basin, USA
(Bohnhoff *et al*., 2010, IJGGC)

INTRODUCTION

HYDROMECHANICAL EFFECTS

Plastic strain in the caprock as a result of CO_2 injection
(Vilarrasa *et al.*, 2011, Energy Procedia)



Trees killed by CO_2 leakage from a natural source in Mammoth Mountains, USA
(Farrar *et al.*, 1995, Nature)

MOTIVATION

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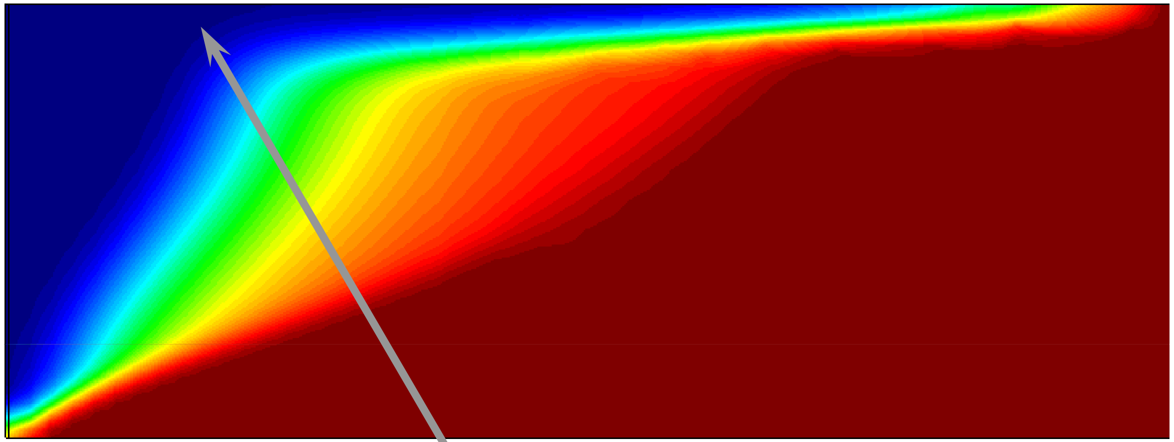
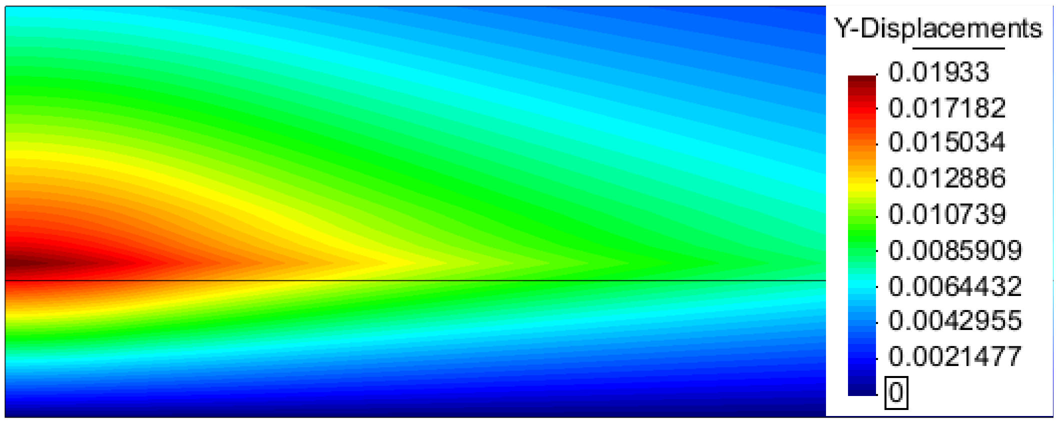
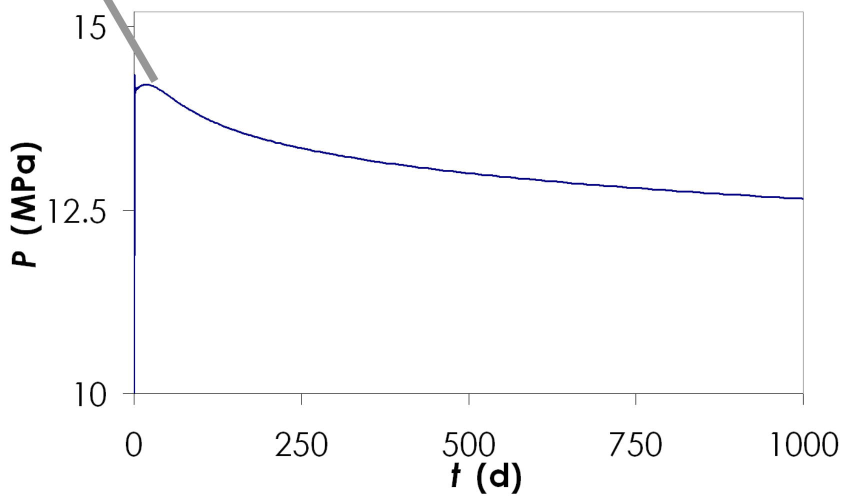
Fluid pressure builds up during injection

$$\uparrow P \Rightarrow \downarrow \sigma' \Rightarrow \varepsilon$$

Caprock stability may be compromised



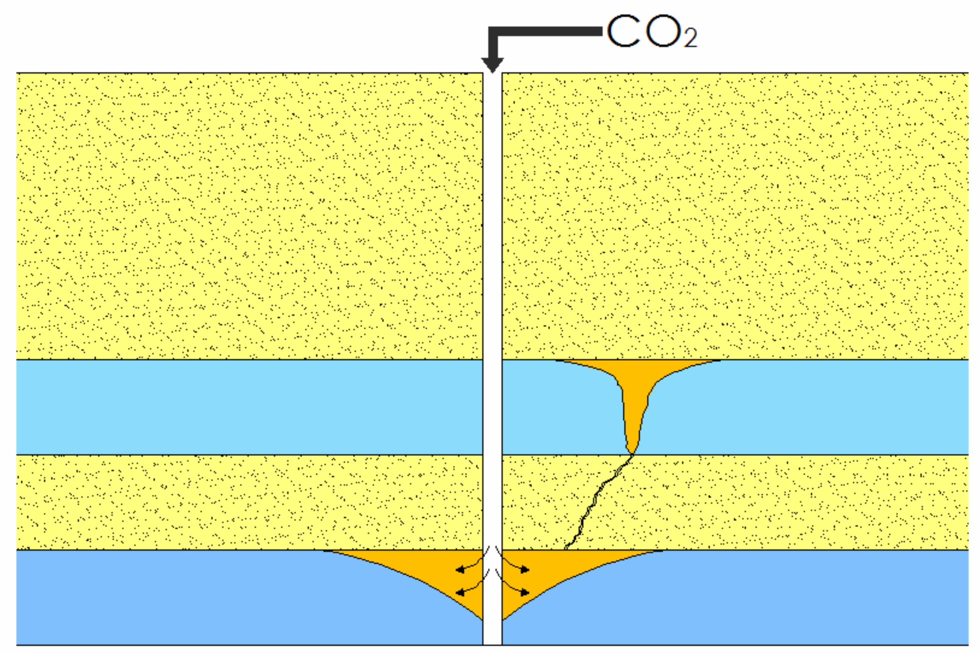




(Vilarrasa *et al.*, 2010, IJGGC)

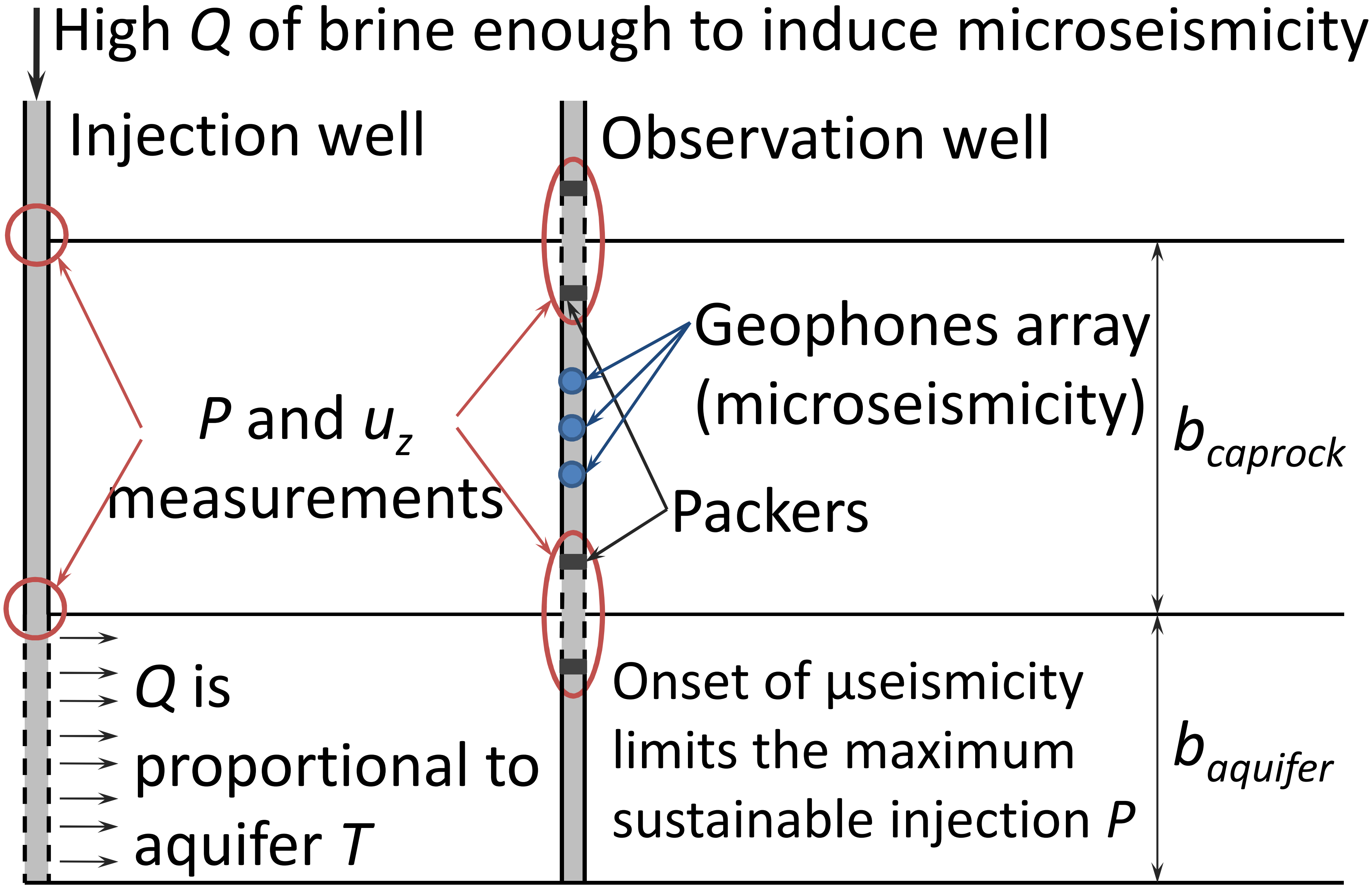
OBJECTIVE

Hydromechanical (HM) coupled effects need a better understanding. The development of a HM characterization technique is required to ensure a safe CO_2 injection at industrial scale



A HM test will be performed in the Hontomin pilot test site (Spain)

TEST DESCRIPTION



METHODOLOGY

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GOVERNING EQUATIONS

Mass conservation equation

$$\phi\beta\frac{\partial p_f}{\partial t}+\frac{\mathrm{d}}{\mathrm{d}t}(\nabla\cdot\mathbf{u})+\nabla\cdot\mathbf{q}=0$$

Darcy's law

$$\mathbf{q}=-\frac{k}{\mu}\left(\nabla p_f+\rho g\nabla z\right)$$

Momentum balance

$$\nabla\cdot\boldsymbol{\sigma}+\mathbf{b}=\mathbf{0}$$

Effective stress

$$\boldsymbol{\sigma}'=\boldsymbol{\sigma}+p_f\mathbf{I}$$

Hooke's law (linear elasticity)

$$\boldsymbol{\sigma}'=K\varepsilon_v\mathbf{I}+2G\left(\boldsymbol{\varepsilon}-\frac{\varepsilon_v}{3}\mathbf{I}\right)$$

Compatibility

$$\boldsymbol{\varepsilon}=\frac{1}{2}\left(\nabla\mathbf{u}+(\nabla\mathbf{u})^T\right)$$

Hydromechanical equation

$$G\frac{\partial}{\partial t}\nabla^2\mathbf{u}+\left(\frac{3K}{2(1+\nu)}+\frac{1}{\phi\beta}\right)\frac{\partial}{\partial t}\nabla(\nabla\cdot\mathbf{u})-\frac{1}{\phi\beta}\nabla\left(\nabla\cdot(\kappa\nabla h)\right)=\mathbf{0}$$

Shear term — Volumetric term — Flow term

METHODOLOGY

DIMENSIONAL ANALYSIS

Dimensionaless variables

$$t_D = \frac{t}{t_c}, h_D = \frac{h}{h_c}, \mathbf{u}_D = \frac{\mathbf{u}}{u_c}, r_D = \frac{r}{L}, \kappa_D = \frac{\kappa}{\kappa_c}, \phi_D = \frac{\phi}{\phi_c}, K_D = \frac{K(1+\nu_c)}{K_c(1+\nu)}, G_D = \frac{G}{G_c}$$

Characteristic variables

$$t_c = \frac{L^2 S_s}{\kappa_c}, h_c = \frac{Q}{2\pi b_{aq}\kappa_c}, u_c = h_c S_s b_{aq}, \kappa_c = \kappa_{aq}, \phi_c = \phi_{aq}, K_c = K_{aq}, G_c = G_{aq}$$

Dimensionless hydromechanical equation

$$N_m N_g G_D \frac{\partial}{\partial t_D} \nabla_D{}^2 \mathbf{u}_D + \left(N_M N_m N_g K_D + \frac{N_g}{\phi_D} \right) \frac{\partial}{\partial t_D} \nabla_D (\nabla_D \cdot \mathbf{u}_D) - \frac{1}{\phi_D} \nabla_D (\nabla_D \cdot (\kappa_D \nabla_D h_D)) = \mathbf{0}$$

Dimensionless numbers

$$N_m = G_c \phi_c \beta, \qquad N_M = \frac{3K_c}{2G_c(1+\nu_c)} = \frac{1}{1-2\nu_c}, \qquad N_g = \frac{b_{aq}}{L} = 1$$

HYDROMECHANICAL BEHAVIOUR

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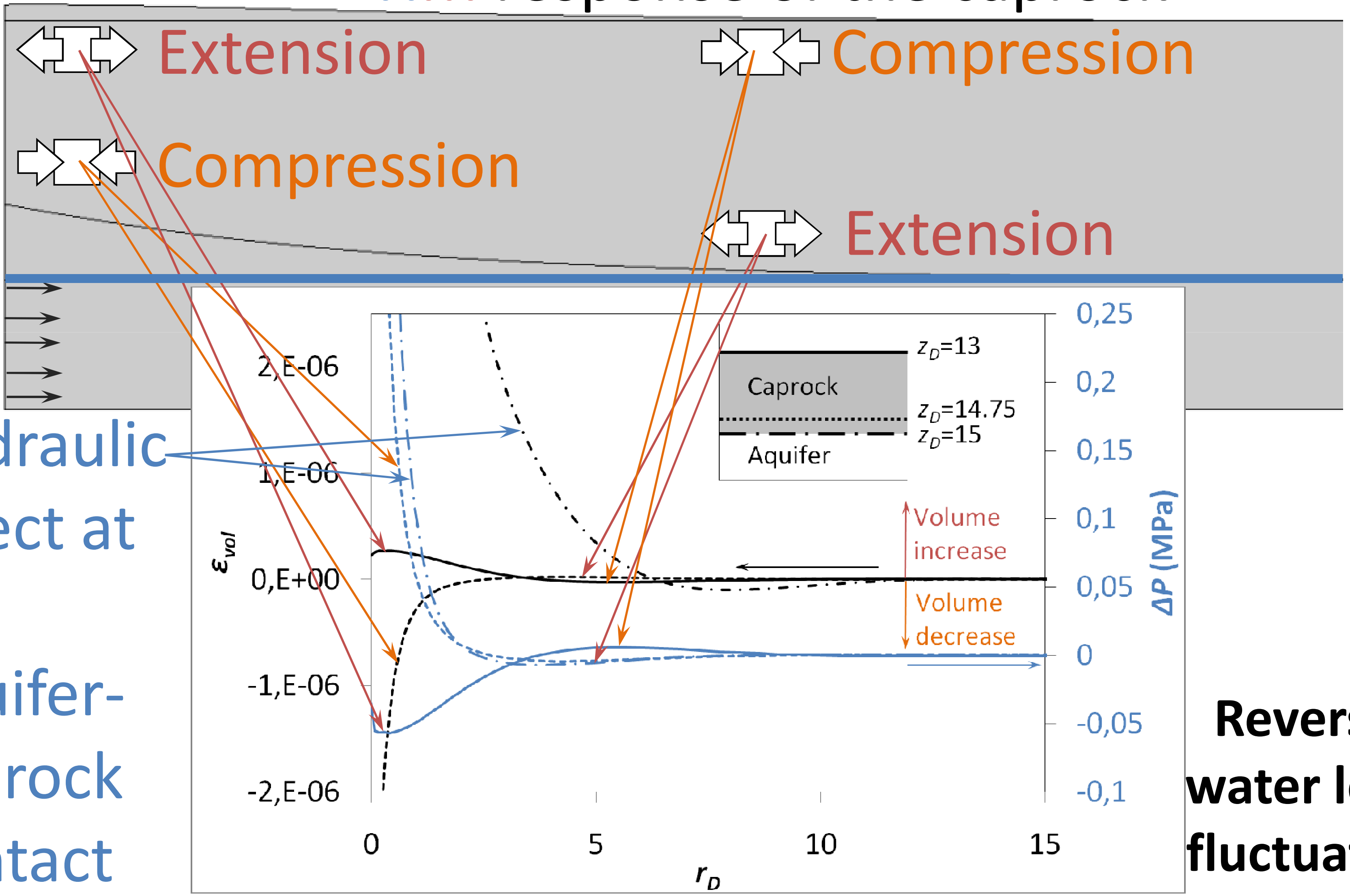
HM response of the caprock

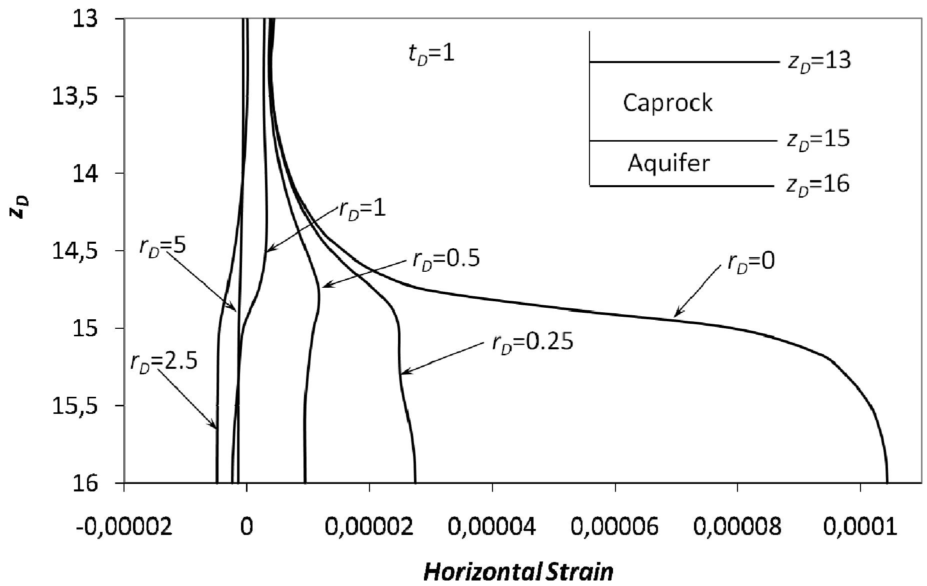


Hydraulic effect at the aquifer-caprock contact

Reverse-water level fluctuation

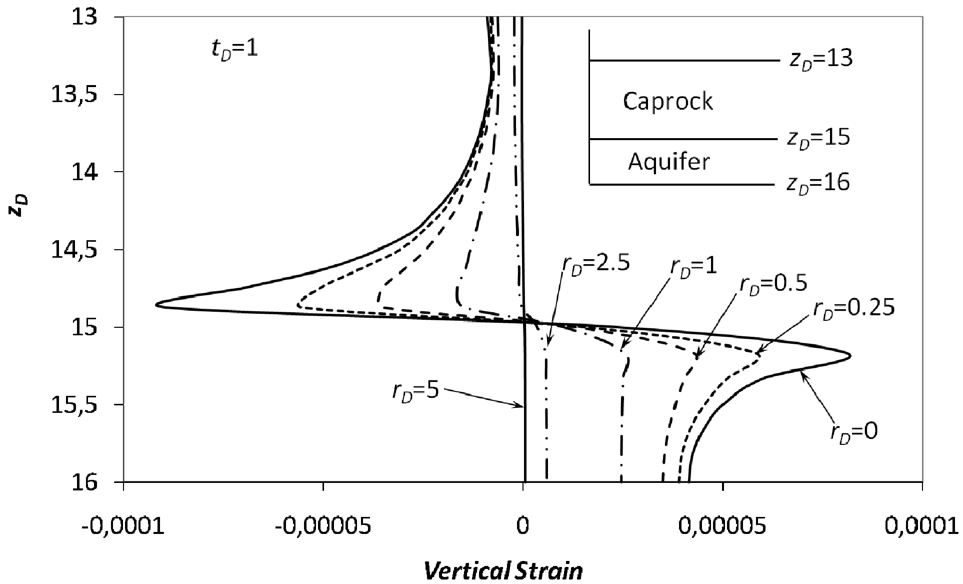
HYDROMECHANICAL BEHAVIOUR

STRAINS



Relative displacements on the aquifer-caprock contact may occur in the presence of a rich-clay layer with low friction angle.

The injected water expands the pore volume, lifting the aquifer. The caprock, which is pushed upwards, mitigates the uplift.

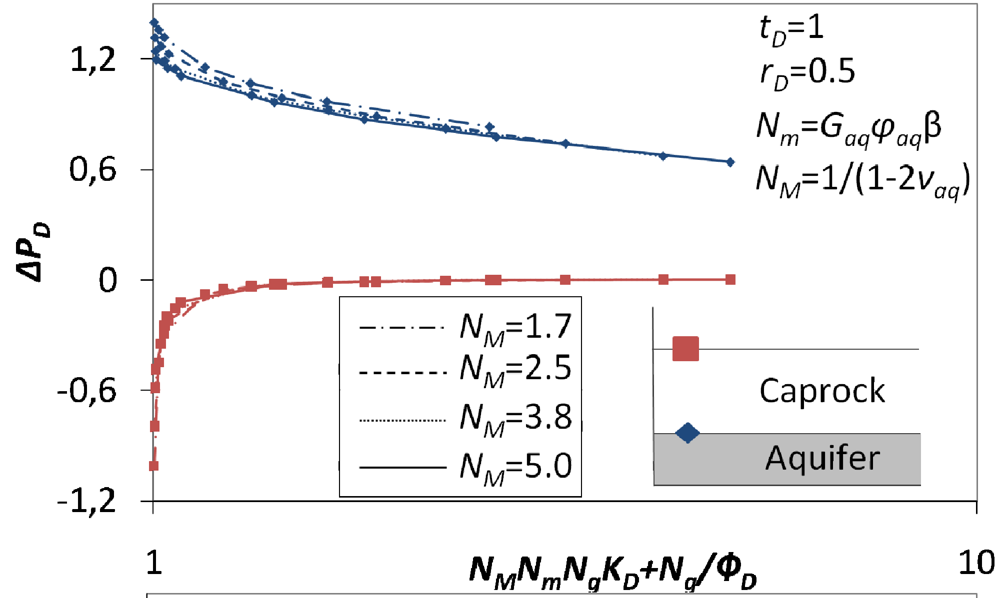


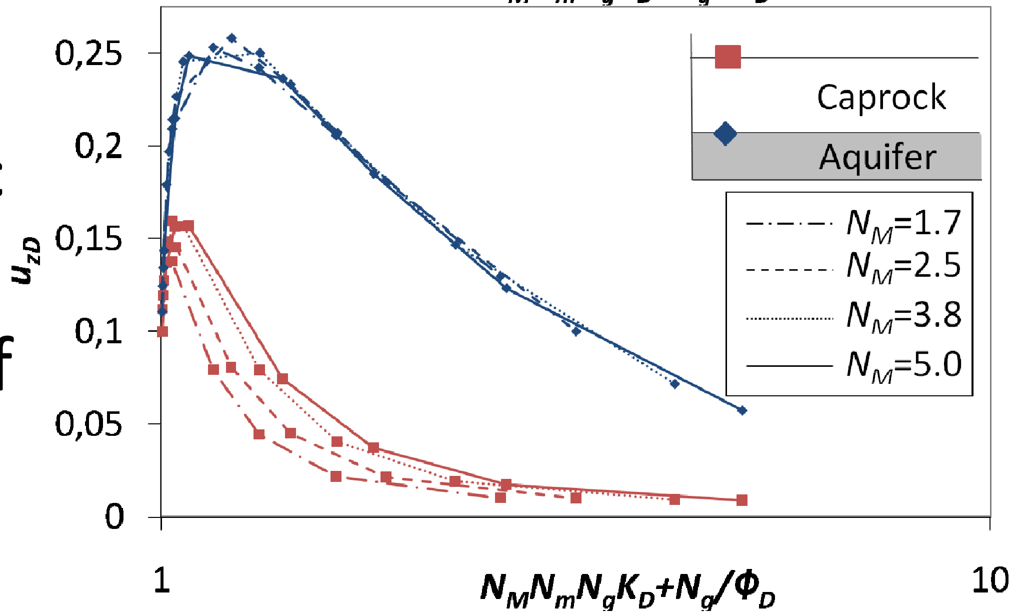
SENSITIVITY ANALYSIS

AQUIFER PROPERTIES

The greater the aquifer rigidity, the lower the overpressure in the aquifer.

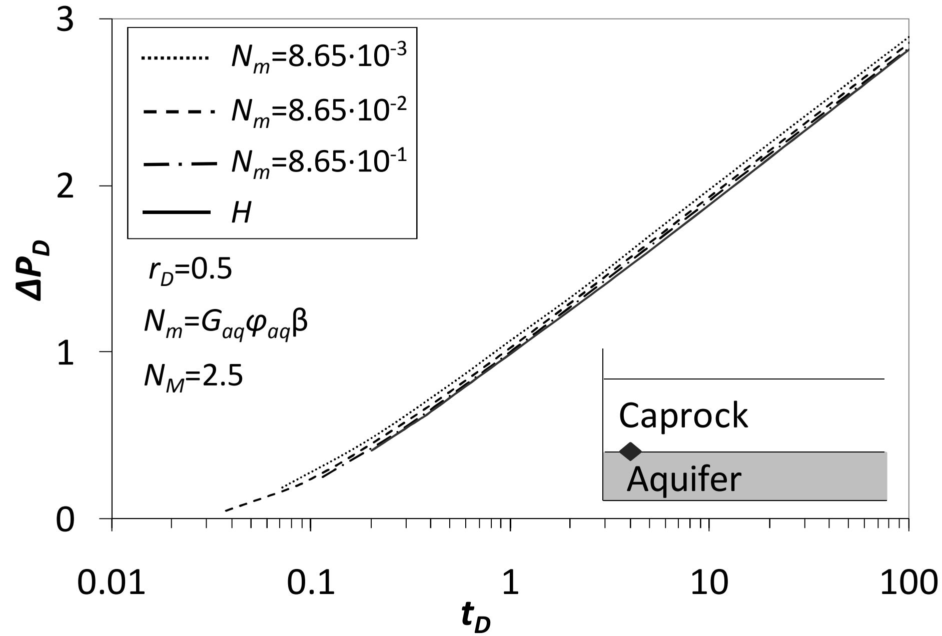
Overpressure and vertical displacement are a function of the volumetric term (vertical displacement at the top of the caprock also depends on Poisson ratio).

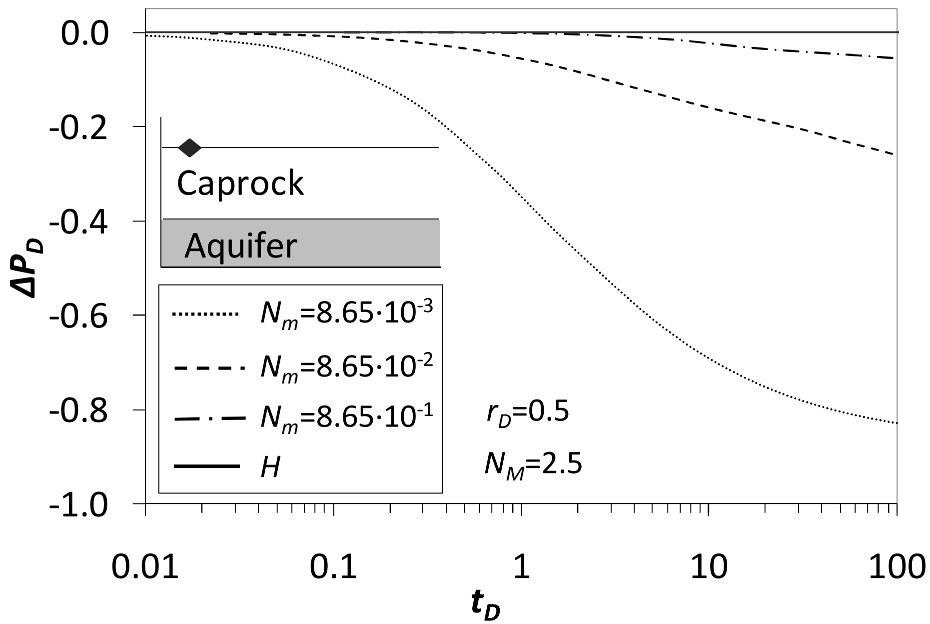




SENSITIVITY ANALYSIS

PRESSURE EVOLUTION





Aquifer *T* and *S* can be determined from the injection test using Jacob’s method

The softer the aquifer, the greater the pressure drop at the top of the caprock

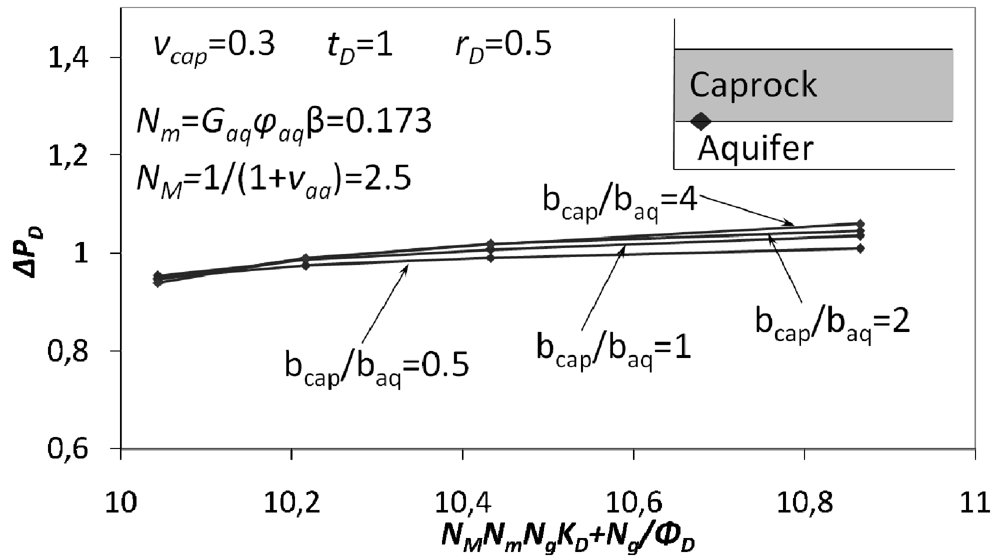
SENSITIVITY ANALYSIS

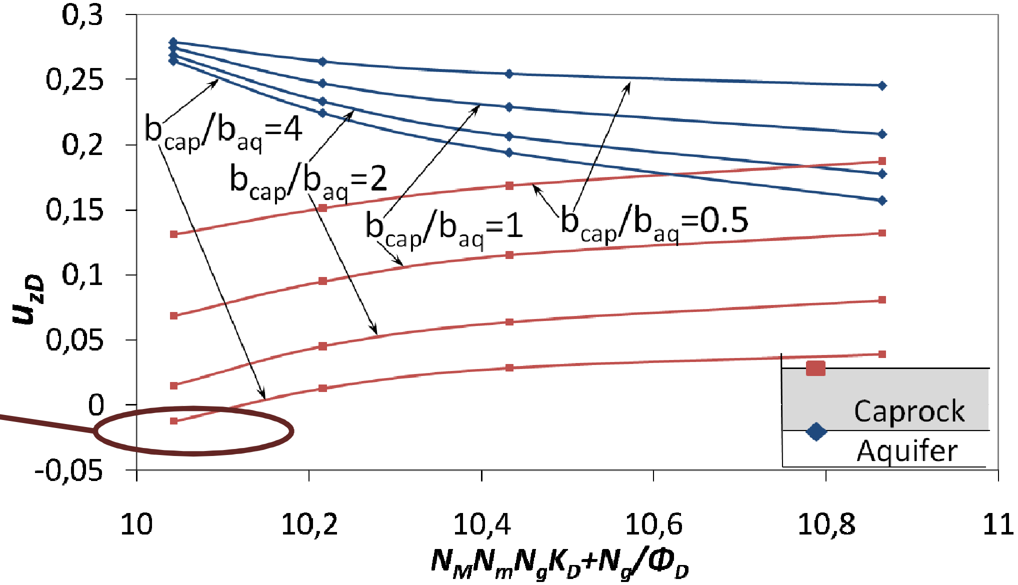
CAPROCK PROPERTIES

Changes in the caprock properties and thickness have little effect on overpressure.

The effect on vertical displacement is greater.

Soft thick caprocks can yield subsidence





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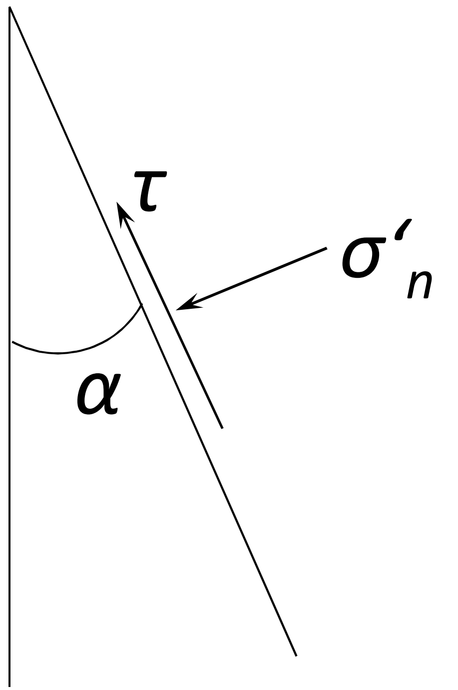
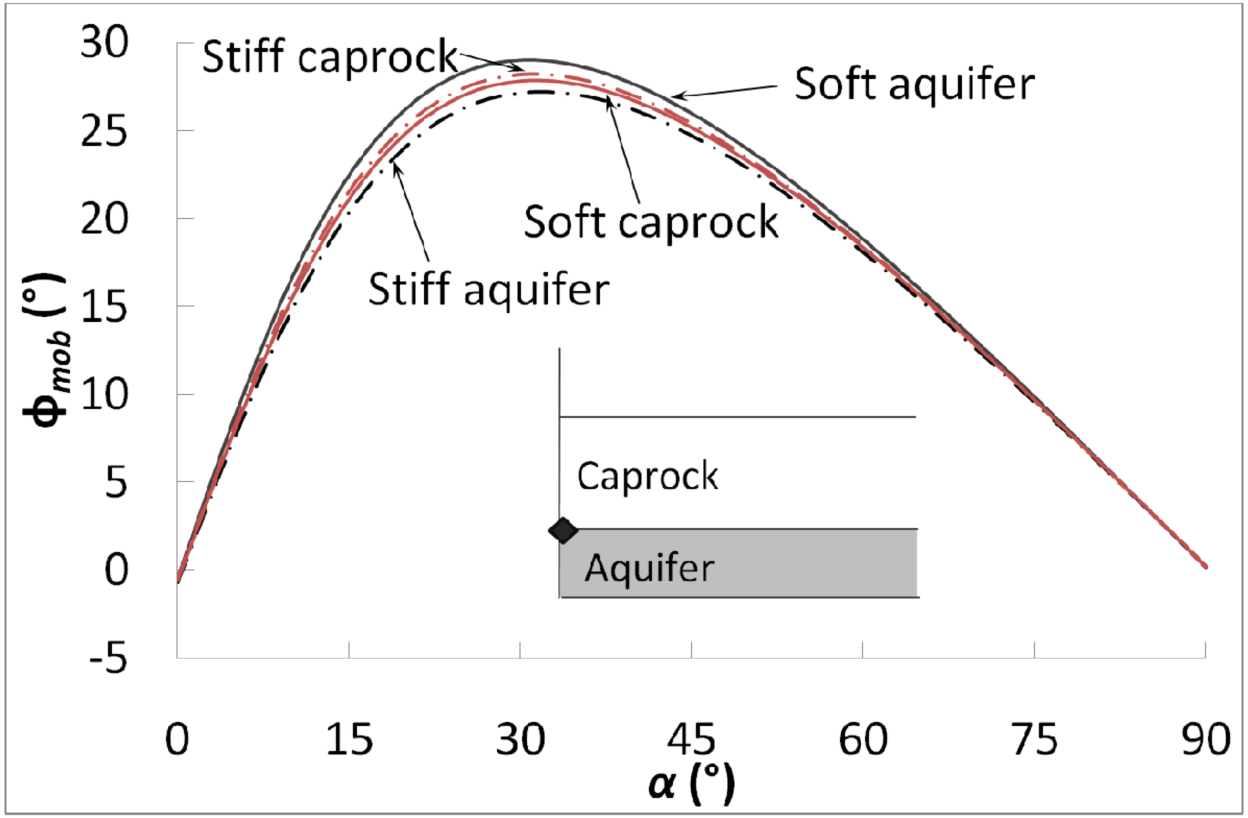
MOBILIZED FRICTION ANGLE IN THE AQUIFER



$$\tan \phi_{mob} = \frac{\tau}{\sigma'_n}$$

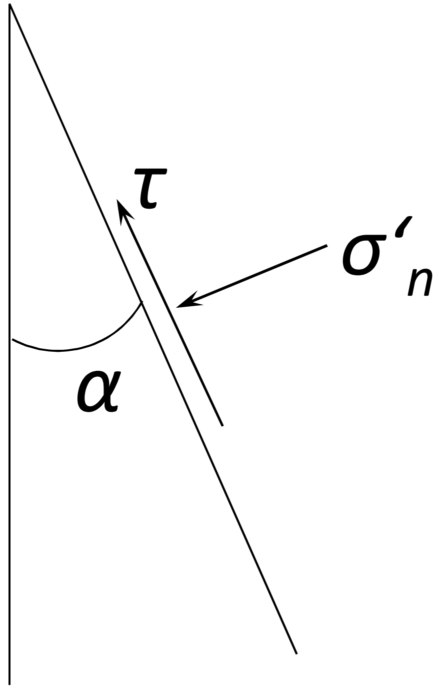
$$\alpha = \pi/4 - \phi'_{mob}/2$$



The most unfavorable fractures are those with an angle of 30°

INDUCED MICROSEISMICITY

MOBILIZED FRICTION ANGLE IN THE CAPROCK



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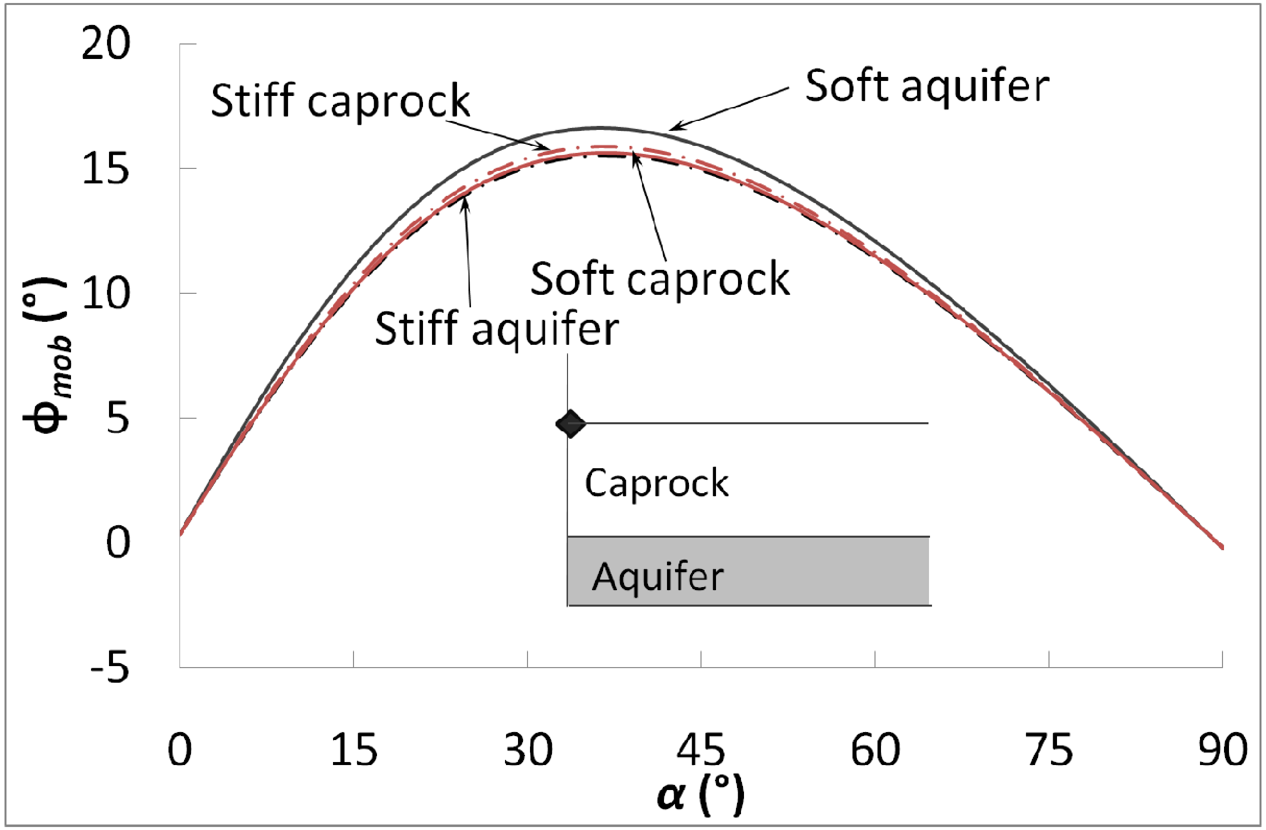

The most unfavorable fractures are those with an angle of 35°

CONCLUSIONS

- We have developed **dimensionless curves for charactering rock properties**, which can be used for long term CO_2 storage simulations.
- Measuring **pressure changes in the caprock** gives valuable information on HM processes.
- **Mechanical properties** of aquifer have more effect on **overpressure and displacements** than those of the caprock.
- Thick soft caprocks can yield **subsidence**.
- The **onset of microseismicity** in the caprock limits the maximum sustainable injection pressure.

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MUSTANG

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