EAGE

EUROPEAN ASSOCIATION OF GEOSCIENTISTS & ENGINEERS

Second EAGE Workshop on Geomechanics and Energy

The ground as energy source and storage

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Celle, Germany

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Geomechanics and Energy

Efficiency of shaft sealing for CO_2 sequestration in coal mines

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University of Liège

October 2015

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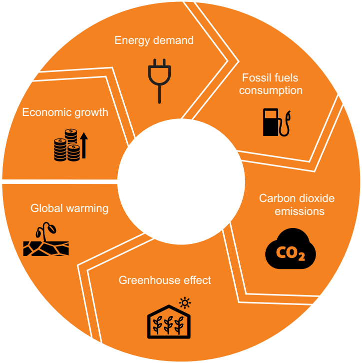
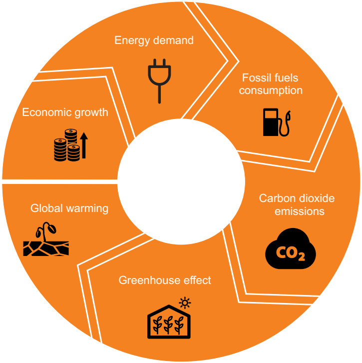
Introduction



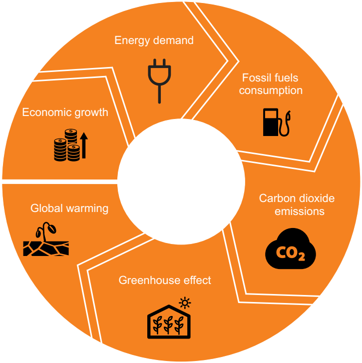
Introduction



Different approaches
to mitigate climate change:

- Improve energy efficiency;
- Increase use of renewable energy or nuclear power;
- Reforestation;
- CO_2 **capture and storage**.

Introduction



Different approaches
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- Improve energy efficiency;
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Geological sequestration,
e.g. deep unmineable **coal** seams.

Anderlues coal mine

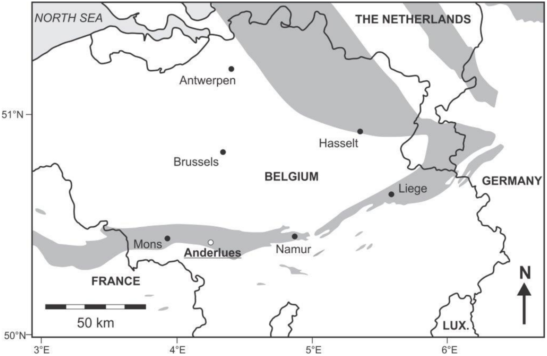

Figure: Map of the outcropping or shallow subsurface coal basins (shaded area) in and around Belgium. Modified after [Piessens and Dusar, 2006].

Host rocks

= Westphalian formations

(313-304 Ma)

= 60% **shale** + 37% sandstone

+ 3% **coal**

1857-1969 : Coal exploitation, **only 3.5**% of the total **coal** volume **extracted**

1978-2000 : Former coal mine used as a reservoir for **storage of natural gas**

Shaft sealing system

→ **Gas sequestrated** in the deep geological formation **through the shafts**.

↓

Sealing system required
Efficiency?

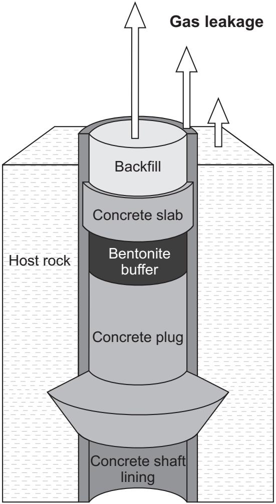

Figure: Layout of the sealing system used for the shaft n°6 of Anderlues coal mine.

Shaft sealing system

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Sealing system required

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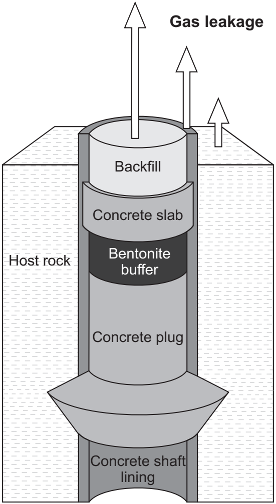
Numerical modelling with the FE code Lagamine



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Two-dimensional axisymmetric analysis:

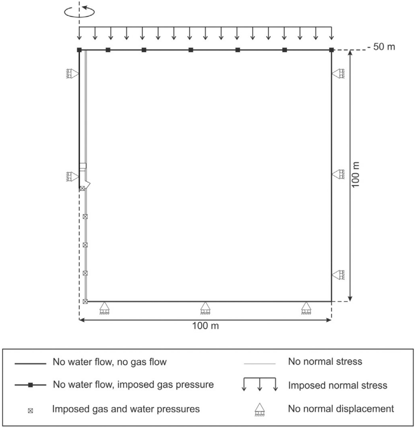

Figure: Geometry and boundary conditions used for the hydromechanical analysis.

Materials considered in the first model:
host **rock**, **concrete**, **bentonite** and **backfill**.

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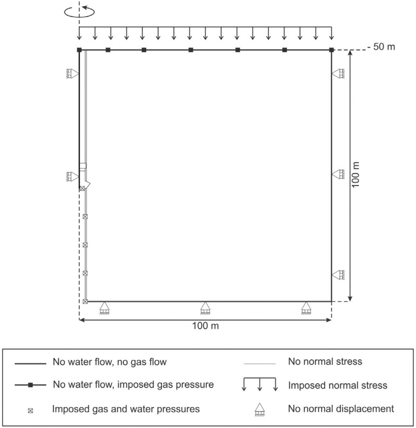

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4 different stages:

1. Shaft **excavation** (50 days)
2. **Set-up** of the **concrete** shaft lining and ventilation of the mine (50 years)
3. Set-up of the **sealing system** (50 days)
4. **Injection** of CO_2 into the mine (500 years)

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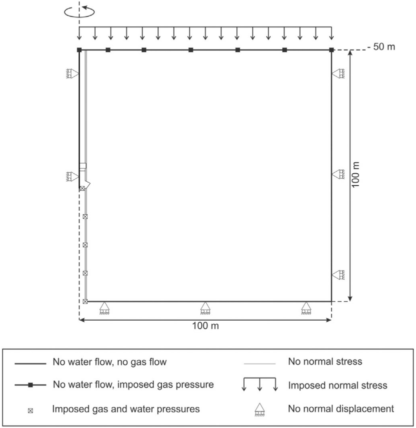

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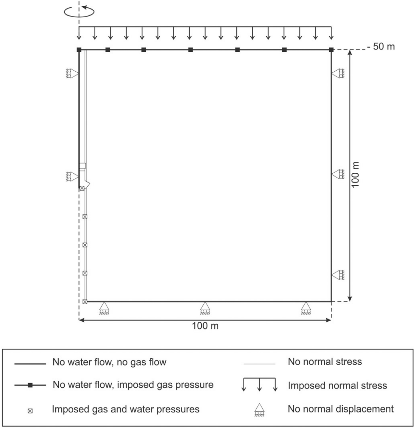

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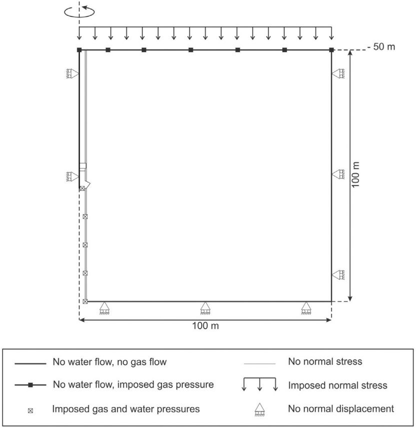

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First 3 steps = **establishment of the hydro-mechanical conditions** before *CO_2* injection.

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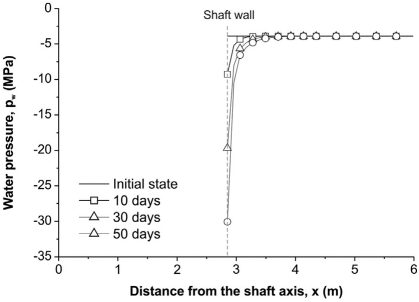

Figure: Evolution of pore water pressure profiles in the shale during the shaft excavation.

Modelling

- **3 balance equations**:
  - **stress equilibrium** equation
  - mass balance equation for **water**
  - mass balance equation for $\mathbf{CO_2}$
- **2 phases flow model**
- **2 transport processes**
  - **advection** of each phase (Darcy's law)
  - **diffusion** of the components within each phase (Fick's law)

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Modelling

without coal

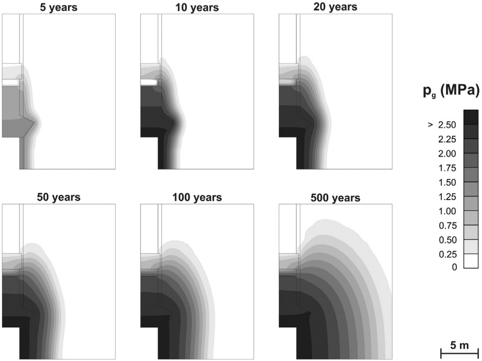

Figure: Evolution of gas pressures in the different materials during CO_2 storage in the coal mine.

➡ **Increase** in gas **pressure** essentially localized in the **concrete elements**.

Time	Backfill	Concrete	Shale
1 year	9 kg	0.02 kg	0.20 kg
5 years	4761 kg	0.52 kg	0.96 kg
10 years	3.49E04 kg	3.34 kg	1.42 kg
50 years	4.15E05 kg	31.67 kg	2.63 kg
100 years	8.52E05 kg	53.42 kg	3.72 kg
250 years	2.09E06 kg	93.13 kg	6.96 kg
500 years	4.11E06 kg	140.80 kg	11.96 kg

Table: Contribution of the different materials to the total mass of CO_2 rejected to the atmosphere, determined at 50m depth.

Reference case:

$$S_{r,w} = 90\% \; ; \quad K_{int,shale} = 2 \cdot 10^{-19} m^2 \; ; \quad K_{int,concrete} = 1 \cdot 10^{-16} m^2 .$$

↓

Because of its high permeability,

the **backfill drains almost all** CO_2 fluxes.

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without coal

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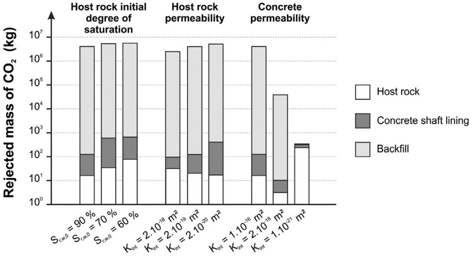
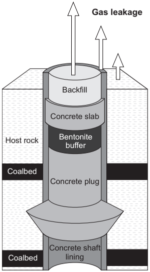


Figure: Parameters analysis, mass rejected after 500 years.



Mass balance equation for CO_2

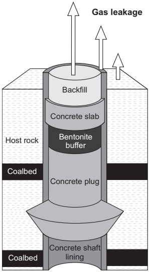
$$\underbrace{div(f_{CO_2}) + \frac{\partial}{\partial t}(\rho_{CO_2}\phi(1-S_{r,w}))}_{\text{Dry } CO_2 \text{ in gas phase}} + \underbrace{div(f_{CO_2-d}) + \frac{\partial}{\partial t}(\rho_{CO_2-d}\,\phi S_{r,w})}_{\text{Dissolved } CO_2 \text{ in water}} = Q_{CO_2}$$

where f is the total mass flow, ρ is the bulk density, ϕ is the porosity, $S_{r,w}$ is the water degree of saturation,

Q is the volume source

Modelling

considering coal



Mass balance equation for CO_2 taking into account **adsorption**:

$$\underbrace{div(f_{CO_2}) + \frac{\partial}{\partial t}(\rho_{CO_2}\phi(1-S_{r,w}))}_{\text{Dry } CO_2 \text{ in gas phase}} + \underbrace{div(f_{CO_2-d}) + \frac{\partial}{\partial t}(\rho_{CO_2-d}\,\phi S_{r,w})}_{\text{Dissolved } CO_2 \text{ in water}} + \boxed{\underbrace{\frac{\partial}{\partial t}((1-\phi)\rho_{stdCO_2}\,\rho_{coal}\,V_{ad})}_{\text{Adsorbed } CO_2 \text{ on coal}}} = Q_{CO_2}$$

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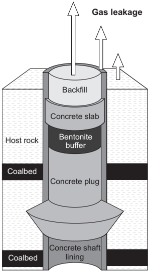

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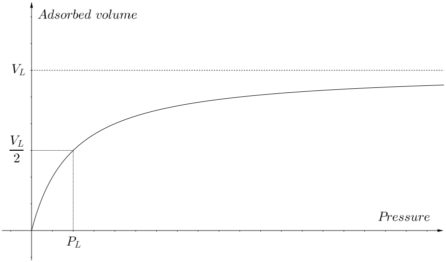
V_{ad} determined by a **Langmuir Isotherm**:

$$V_{ad} = \frac{V_L \cdot P}{P_L + P}$$

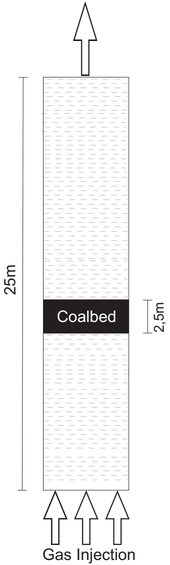
where P is the gas pressure and V_L and P_L are two parameters.

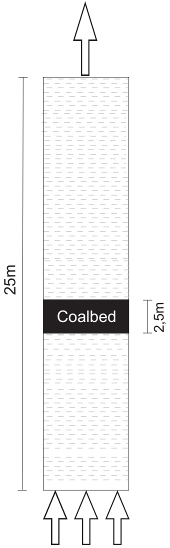
[Wu et al., 2011] : $V_L = 0.0477 m^3/kg$; $P_L = 1.38 MPa$



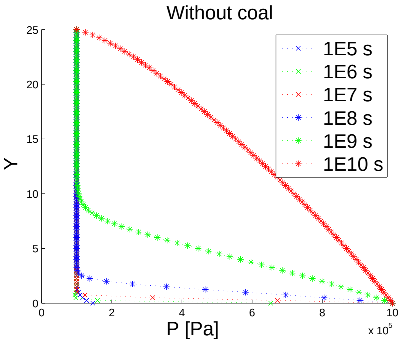
Modelling

considering coal - 1D

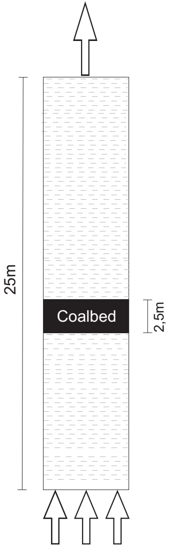




25m
Coalbed
2,5m
Gas Injection



Without coal
Y
P [Pa]
x 10^5
1E5 s
1E6 s
1E7 s
1E8 s
1E9 s
1E10 s
0
5
10
15
20
25
0
2
4
6
8
10



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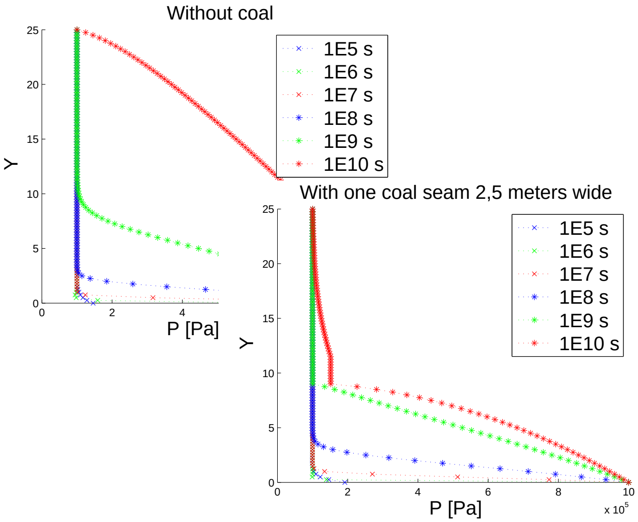
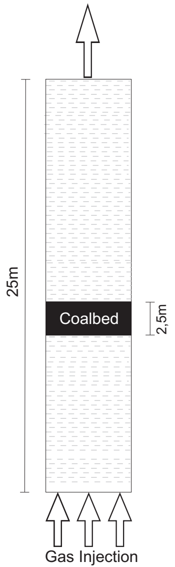
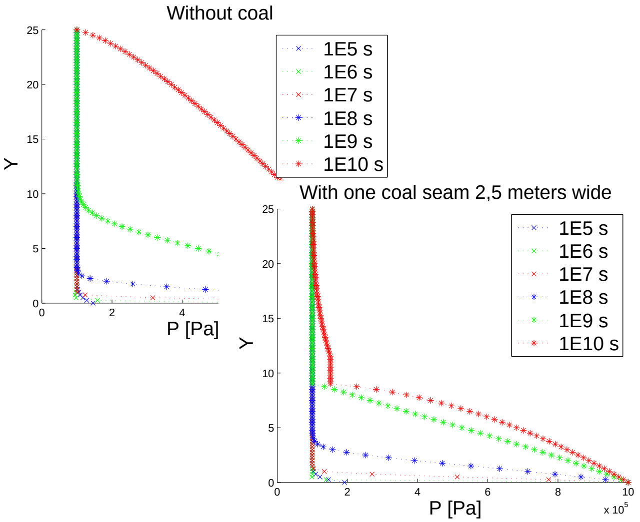


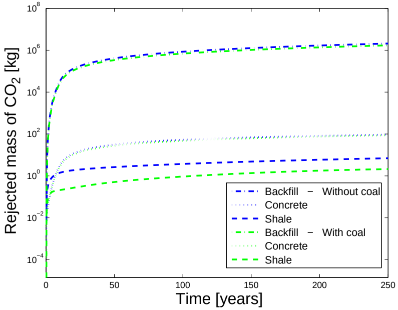
Without coal
Y
P [Pa]
1E5 s
1E6 s
1E7 s
1E8 s
1E9 s
1E10 s
With one coal seam 2,5 meters wide
x 10^5





CO_2 rejected (300 years): 6% without coal → 0.03% with the coal.

Back to the shaft sealing **considering a coal seam** $0,25m$ wide **above the injection zone.**



-20% rejected after 250 years

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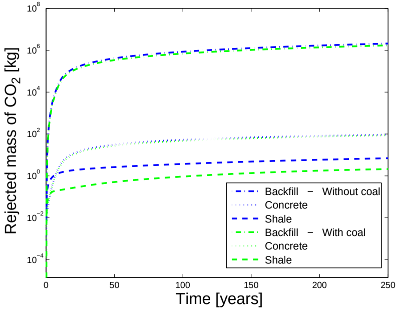
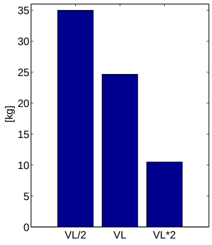
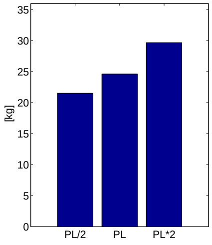


-20% rejected after 250 years

Rejected mass of CO_2 through the shale (after 500 years)





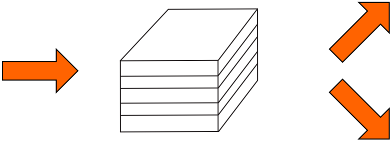
$V_L \nearrow$ $V_{ad} \nearrow$ Rejected mass $\searrow$ $P_L \nearrow$ $V_{ad} \searrow$ Rejected mass $\nearrow$

Modelling

considering coal + shale anisotropy

Modelling

considering coal + shale anisotropy



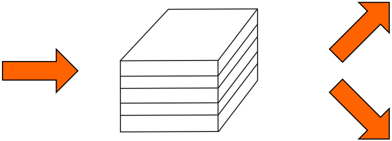
Mechanical anisotropy

Hydraulic anisotropy

$k_{\perp}$; $k_{/\!/}$

Modelling

considering coal + shale anisotropy



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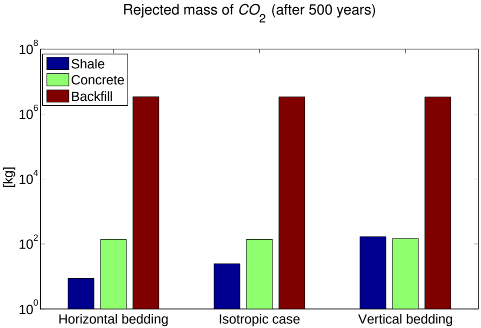

Anisotropic cases:

$$10 \cdot k_{\perp} = k_{/\!/}$$

Conclusions

➡ **Better understanding** of the CO_2 transfer mechanisms through and around a shaft and its sealing system (Anderlues).

Realistic values for the parameters + sensitivity analysis + HM conditions reproduced

- Concrete permeability > Host rock permeability

  ➡ CO_2 **preferentially** flows **through** the **concrete then** the **backfill**.

- **Bentonite buffer** has shown **limited efficiency** as CO_2 by-passes it to flow through the concrete support. ➡ Design?

- Due to **adsorption**, coal has a **favourable impact** on gas leakage.

- Depending on bedding plan orientation, **shale anisotropy** can also have a favourable impact on gas leakage.

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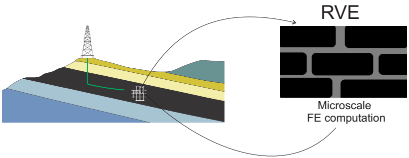
Conclusions

- Future works

CO_2 injection = **stimulation** for coalbed **methane recovery**

$$\Delta S_{r,w} \Rightarrow \text{Shrinkage/Swelling} \Rightarrow \Delta k$$

➡ Take into account **couplings at the micro-scale** via a multi-scale finite element method.



Thank you for your attention!

References

Piessens, K. and Dusar, M. (2006).
Feasibility of CO_2 sequestration in abandoned coal mines in belgium.
Geologica Belgica.

Wu, Y., Liu, J., Elsworth, D., Siriwardane, H., and Miao, X. (2011).
Evolution of coal permeability: Contribution of heterogeneous swelling processes.
International Journal of Coal Geology, 88(2):152–162.

- **Stress equilibrium** equation

$$div(\sigma) + b = 0$$

- Mass balance equation for **water**

$$\underbrace{div(f_w) + \frac{\partial}{\partial t}(\rho_w \phi S_{r,w})}_{\text{Liquid water}} + \underbrace{div(f_v) + \frac{\partial}{\partial t}(\rho_v\, \phi(1 - S_{r,w}))}_{\text{Water vapour}} = Q_w$$

- Mass balance equation for $\mathbf{CO_2}$

$$\underbrace{div(f_{CO_2}) + \frac{\partial}{\partial t}(\rho_{CO_2} \phi(1 - S_{r,w}))}_{\text{Dry } CO_2 \text{ in gas phase}} + \underbrace{div(f_{CO_2-d}) + \frac{\partial}{\partial t}(\rho_{CO_2-d}\, \phi S_{r,w})}_{\text{Dissolved } CO_2 \text{ in water}} + \boxed{\underbrace{\frac{\partial}{\partial t}((1-\phi)\rho_{stdCO_2}\rho_{coal} V_{ad})}_{\text{Adsorbed } CO_2 \text{ on coal}}} = Q_{CO_2}$$

- Mass flows : advection + diffusion

$$\underline{f}_w = \rho_w \underline{q}_l$$
$$\underline{f}_v = \rho_v \underline{q}_g + \underline{i}_v$$
$$\underline{f}_{CO_2} = \rho_{CO_2} \underline{q}_g + \underline{i}_{CO_2}$$
$$\underline{f}_{CO_2-d} = \rho_{CO_2-d} \underline{q}_g + \underline{i}_{CO_2-d}$$

- Advection: Darcy's law

$$\underline{q}_l = -\frac{K_{int} \cdot k_{rw}}{\mu_w} \left(\underline{grad}(p_w) + g\, \rho_w \underline{grad}(y) \right)$$
$$\underline{q}_g = -\frac{K_{int} \cdot k_{rg}}{\mu_g} \left(\underline{grad}(p_g) + g\, \rho_g \underline{grad}(y) \right)$$

- Diffusion: Fick's law

$$\underline{i}_v = -\phi(1 - S_{r,w})\, \tau\, D_{v/CO_2}\, \rho_g\, \underline{grad}\left(\frac{\rho_v}{\rho_g} \right) = -\underline{i}_{CO_2}$$
$$\underline{i}_{CO_2-d} = -\phi S_{r,w}\, \tau\, D_{CO_2-d/w}\, \rho_w\, \underline{grad}\left(\frac{\rho_{CO_2-d}}{\rho_w} \right)$$

		Coal	Shale	Concrete	Bentonite	Backfill
Young's modulus (MPa)	E	2710	3000	33	150	38.5
Poisson's ration	ν	0.34	0.3	0.16	0.3	0.2
Cohesion (MPa)	c	-	2.66	-	-	-
Friction angle (°)	ϕ	-	22.7	-	-	
Biot coefficient	b	1	0.4	0.8	1	1

Table: Mechanical properties

Additional Information

Hydraulic properties

Van Genuchten model to relate suction with degree of saturation:

$$S_{r,w} = \left[1 + \left(\frac{s}{P_r}\right)^n\right]^{-m}$$

Van Genuchten water relative permeability model:

$$k_{rw} = \sqrt{S_{r,w}}\left(1 - \left(1 - S_{r,w}^{-m}\right)^m\right)^2$$

Gas relative permeability model:

$$k_{rg} = (1 - S_{r,w})^3$$

		Shale	Concrete	Bentonite	Backfill
Intrinsic permeability (m^2)	K_{int}	2E-19	1E-16	8E-21	1E-15
Porosity	ϕ	0.054	0.15	0.37	0.33
Tortuosity	τ	0.25	0.25	0.0494	1
Van Genuchten parameter (*MPa*)	P_r	9.2	2	16	0.12
Van Genuchten parameter	n	1.49	1.54	1.61	1.4203
Van Genuchten parameter	m	0.33	0.35	0.38	0.30

Table: Hydraulic parameters

Additional Information

Hydraulic properties

For coal:

$$S_{r,w} = \frac{1}{100}\left(CSR1 \cdot \log\left(\frac{s}{10^6}\right) + CSR2\right)$$

$$k_{rw} = \frac{(S_{r,w} - S_{res})^{CKW1}}{(1 - S_{res})^{CKW2}}$$

$$k_{rg} = CKA3 \cdot (1 - S_e)^{CKA1} \cdot (1 - S_e^{CKA2}) \quad \text{with } S_e = \frac{S_{r,w} - S_{res}}{1 - S_{res}}$$

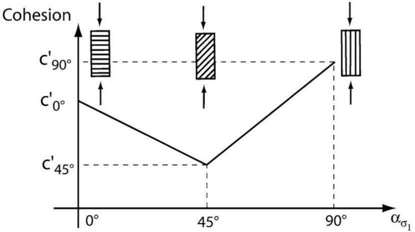
$CSR1$	-7.5
$CSR1$	1
$CKW1$	30.2
$CKW2$	30.2
$CKA1$	0.5
$CKA2$	10.2
$CKA3$	0.65

		Coal
Intrinsic permeability (m^2)	K_{int}	1E-16
Porosity	ϕ	0.01
Tortuosity	τ	0.25

Table: Hydraulic parameters for coal

Mechanical shale anisotropy:

- Elasticity (Orthotropy) : $E_{/\!/}, E_{\perp}, \nu_{/\!/,/\!/}, \nu_{/\!/,\perp}, G_{/\!/,\perp}$
- Plasticity : anisotropy through the cohesion



[François *et al*, 2014]

Hydraulic anisotropy:

$$k_{\perp} \quad ; \quad k_{/\!/}$$

Coalbeds = **dual porosity** systems

Micropores + Macropores $\Longleftrightarrow$ Matrix + Cleats

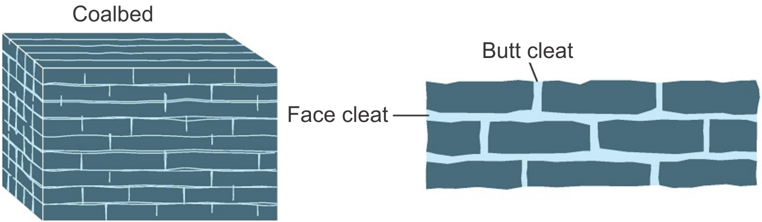
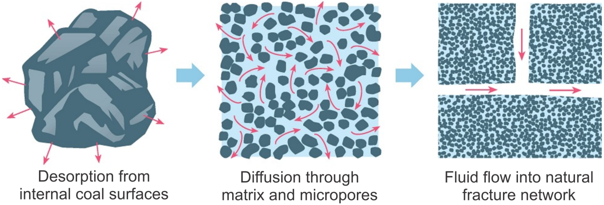


Figure: [Schlumberger, 2015]

Coalbeds = **dual permeability** systems

Matrix permeability $<<$ Permeability of the **cleat** system

Fick's law of diffusion in the coal **matrix** $><$ **Darcy's law** in the **fracture** system

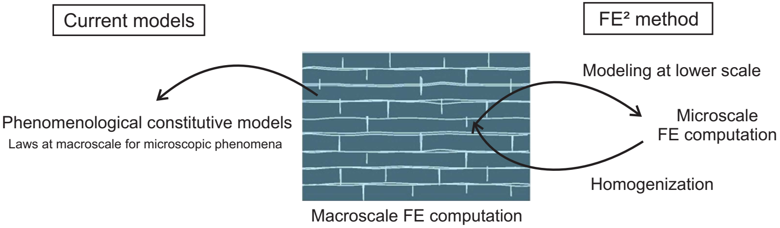


Cleat **permeability** is directly dependent on the **width of the cleats**.

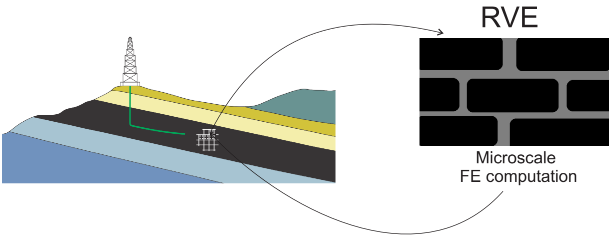
Figure: [Schlumberger, 2015]

Additional Information

Future works : FE^2



Apply a **multi-scale method** taking advantage of the **periodical structure of coal**.



Constitutive equations (flow law, storage law) are applied only on the **microscopic scale**.

Homogenization equations are employed **to compute the macroscopic flows** knowing the pore pressure state at microscopic scale.