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UNIVERSIDAD NACIONAL DE SAN JUAN

Laboratorio de Geotecnia
UNIVERSIDAD NACIONAL DE CÓRDOBA

Geotécnia e Ingeniería Sísmica aplicadas a la Minería

San Juan, Argentina, 16 de Octubre de 2007

CÁMARA MINERA DE SAN JUAN

AGENCIA ESPAÑOLA DE COOPERACIÓN INTERNACIONAL

SECRETARIA DE ESTADO DE MINERIA

FORMULATION FOR THERMO HYDRO MECHANICAL PROBLEMS IN POROUS MEDIA

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Jornada Geotecnia e Ingeniería Sísmica,
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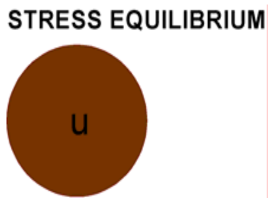
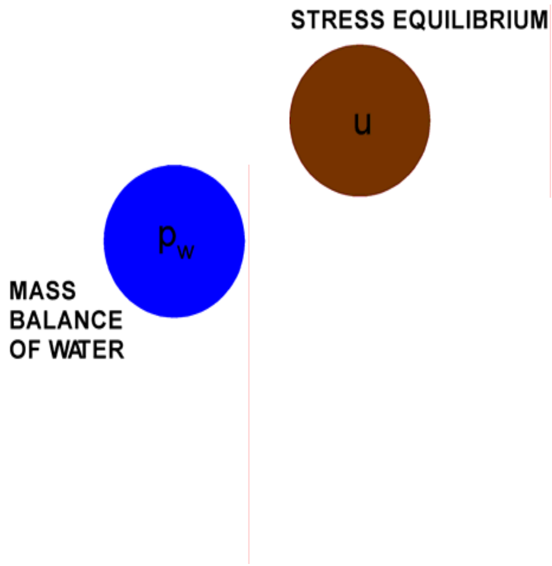
PROBLEMAS ACOPLADOS



Mechanical problems
in soils and rocks

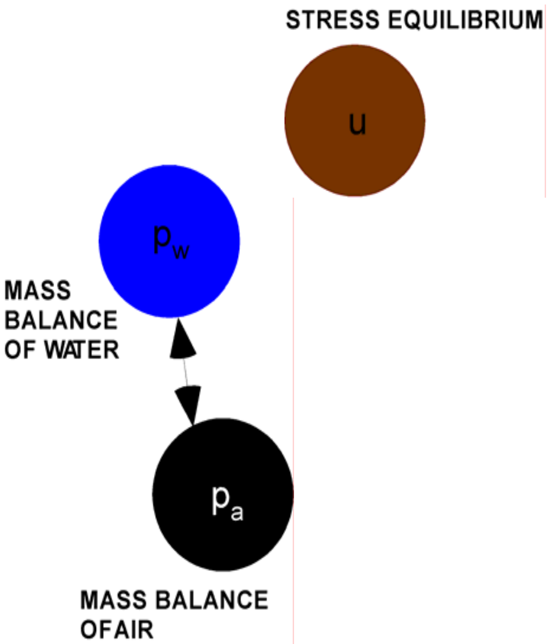
PROBLEMAS ACOPLADOS



Mechanical problems
in soils and rocks

One phase flow

PROBLEMAS ACOPLADOS



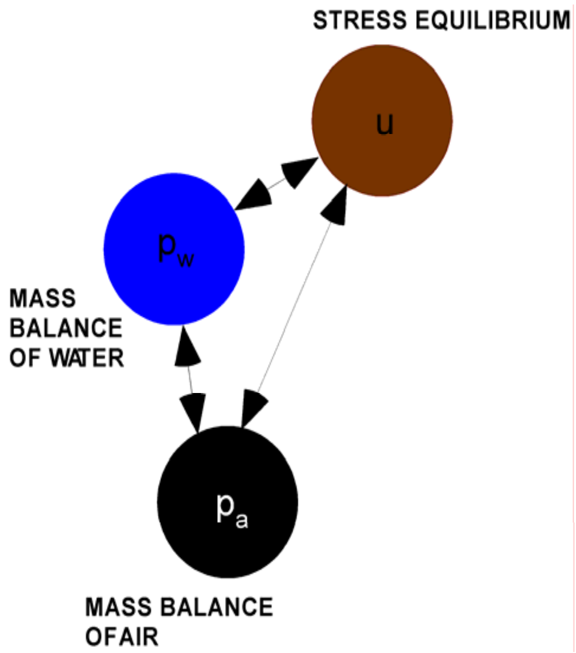
Mechanical problems

in soils and rocks

One phase flow

Two phase flow

PROBLEMAS ACOPLADOS



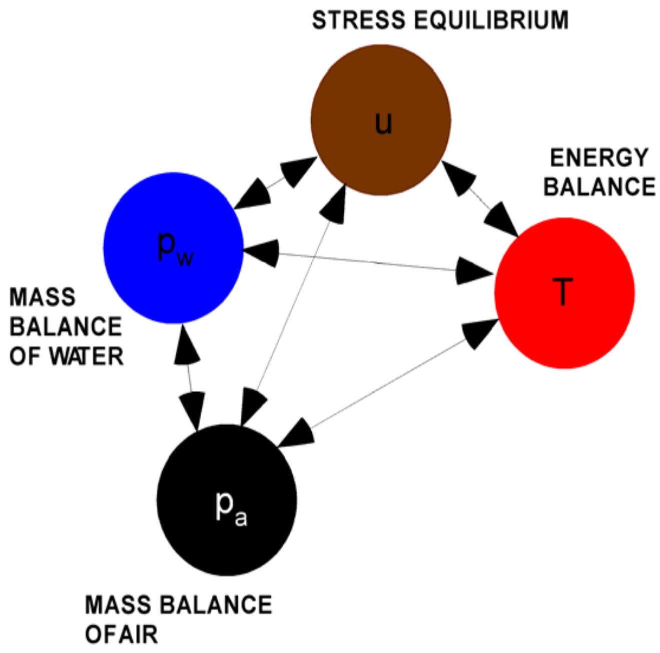
Mechanical problems in soils and rocks

One phase flow

Two phase flow

Saturated consolidation / unsaturated consolidation

PROBLEMAS ACOPLADOS



Mechanical problems

in soils and rocks

One phase flow

Two phase flow

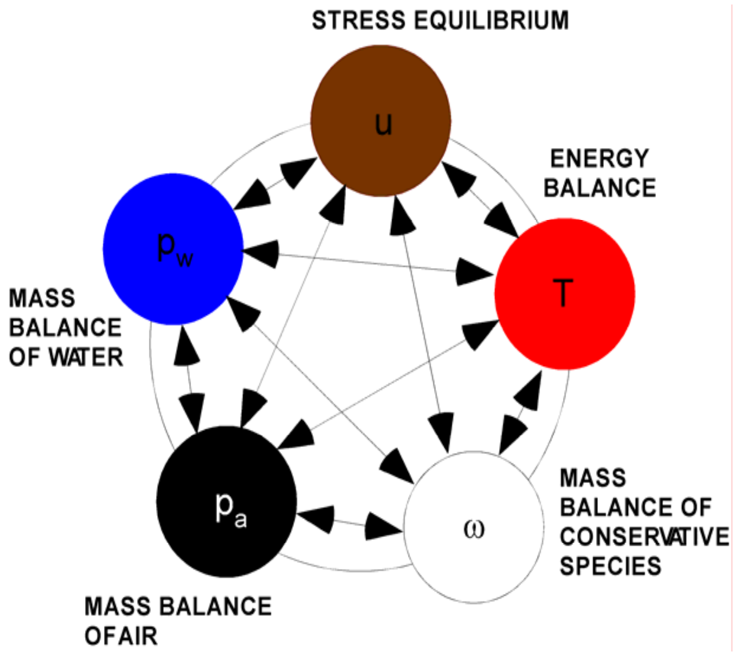
Saturated consolidation / unsaturated consolidation

Evaporation / evapotranspiration

Waste disposals

Geothermal fluid extraction

PROBLEMAS ACOPLADOS



Mechanical problems

in soils and rocks

One phase flow

Two phase flow

Saturated consolidation / unsaturated consolidation

Evaporation / evapotranspiration

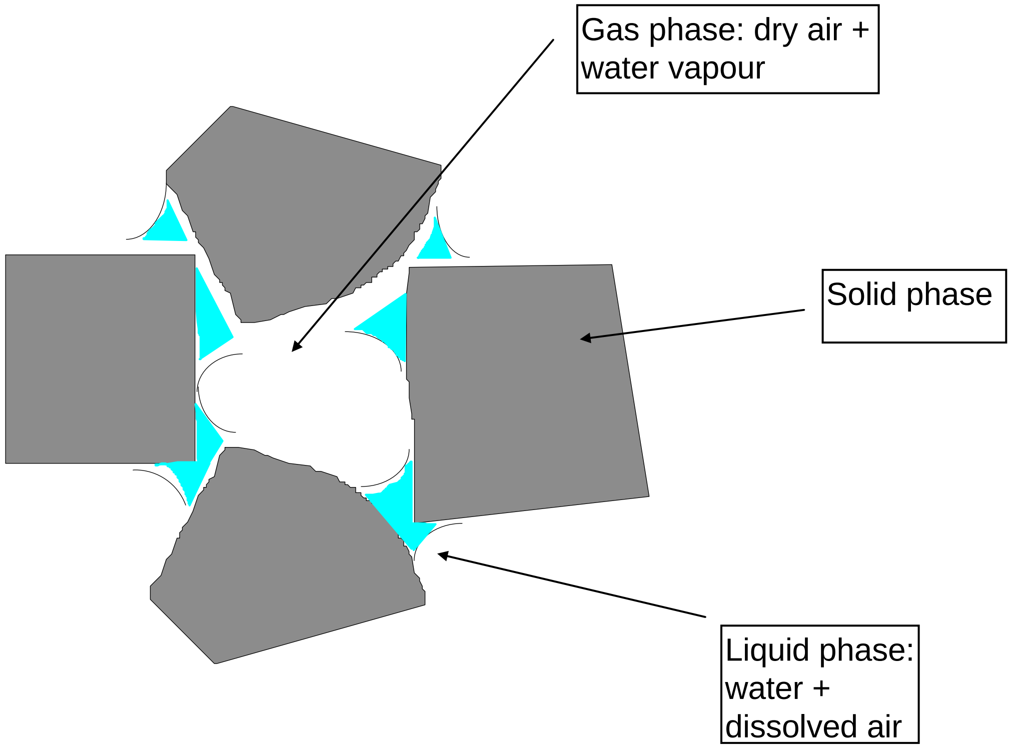
Waste disposals

Geothermal fluid extraction

Solute transport problems

CODE_BRIGHT

2. BASIC FORMULATION



The three phases are:

- solid phase (*s*) :mineral
- liquid phase (*l*) :water + air dissolved
- gas phase (*g*) :mixture of dry air and water vapour

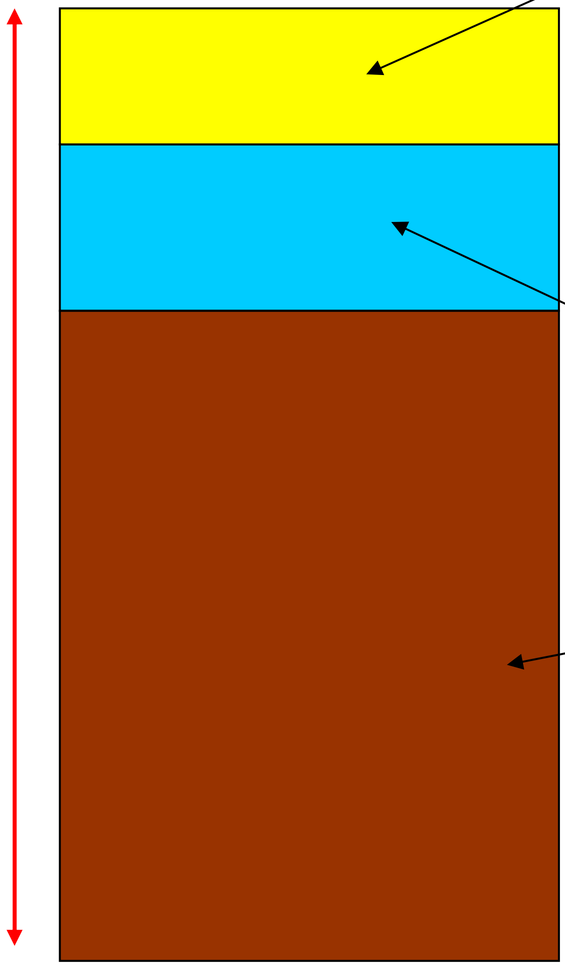
The three species are:

- Solid (-): the mineral is coincident with solid phase
- Water (*w*):as liquid or evaporated in the gas phase
- Air (*a*) :dry air, as gas or dissolved in the liquid phase

Unsaturated soil: Porosity and degree of Saturation

Gas phase

$$V_g / V = V_g / V_h \times V_h / V = S_g \times \phi$$



Liquid phase

$$V_l / V = V_l / V_h \times V_h / V = S_l \times \phi$$

Total volume

$$V = V_s + V_l + V_g = V_s + V_h$$

Solid phase

$$V_s / V = 1 - \phi$$

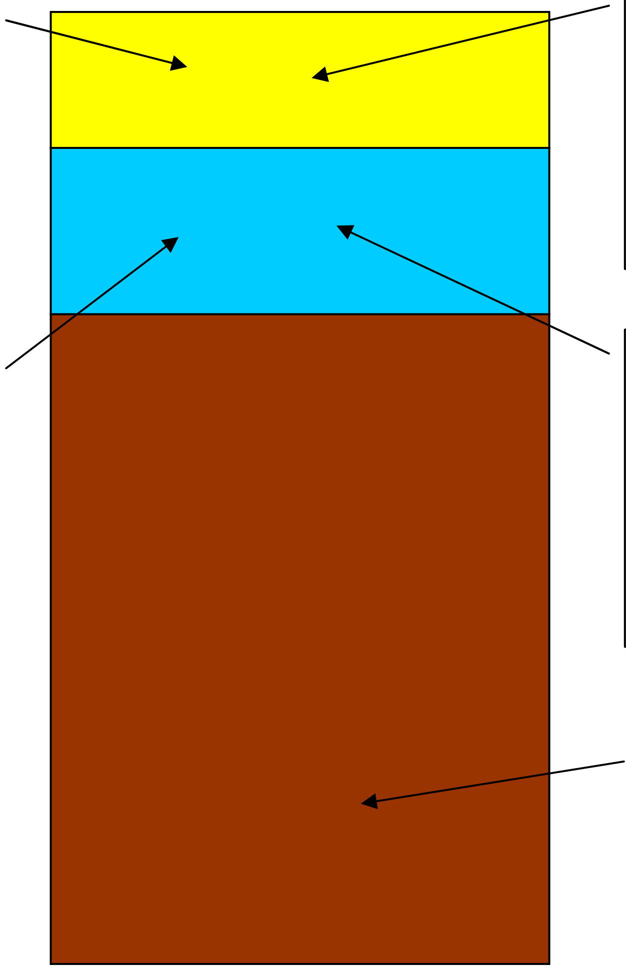
Unsaturated soil: Mass in phases

Mass of air in the gas phase

$$\omega_g^a \rho_g$$

Mass of water in the liquid phase

$$\omega_l^a \rho_l$$



Mass of water in the gas phase

$$\omega_g^w \rho_g$$

Mass of water in the liquid phase

$$\omega_l^w \rho_l$$

Mass of Solid in the Solid phase

$$\rho_s$$

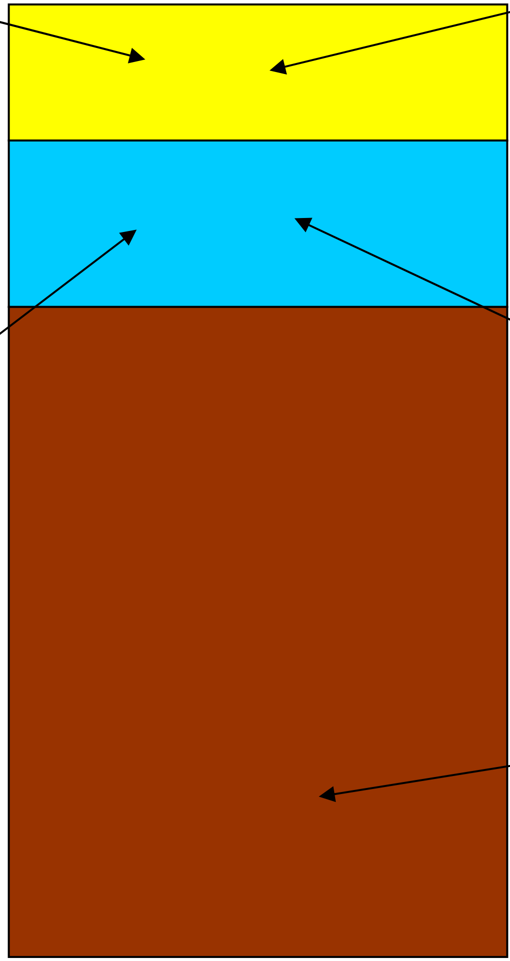
Unsaturated soil: Mass in porous medium

Mass of air in the gas phase

$$\omega_g^a \rho_g S_g \phi$$

Mass of water in the liquid phase

$$\omega_l^a \rho_l S_l \phi$$



Mass of water in the gas phase

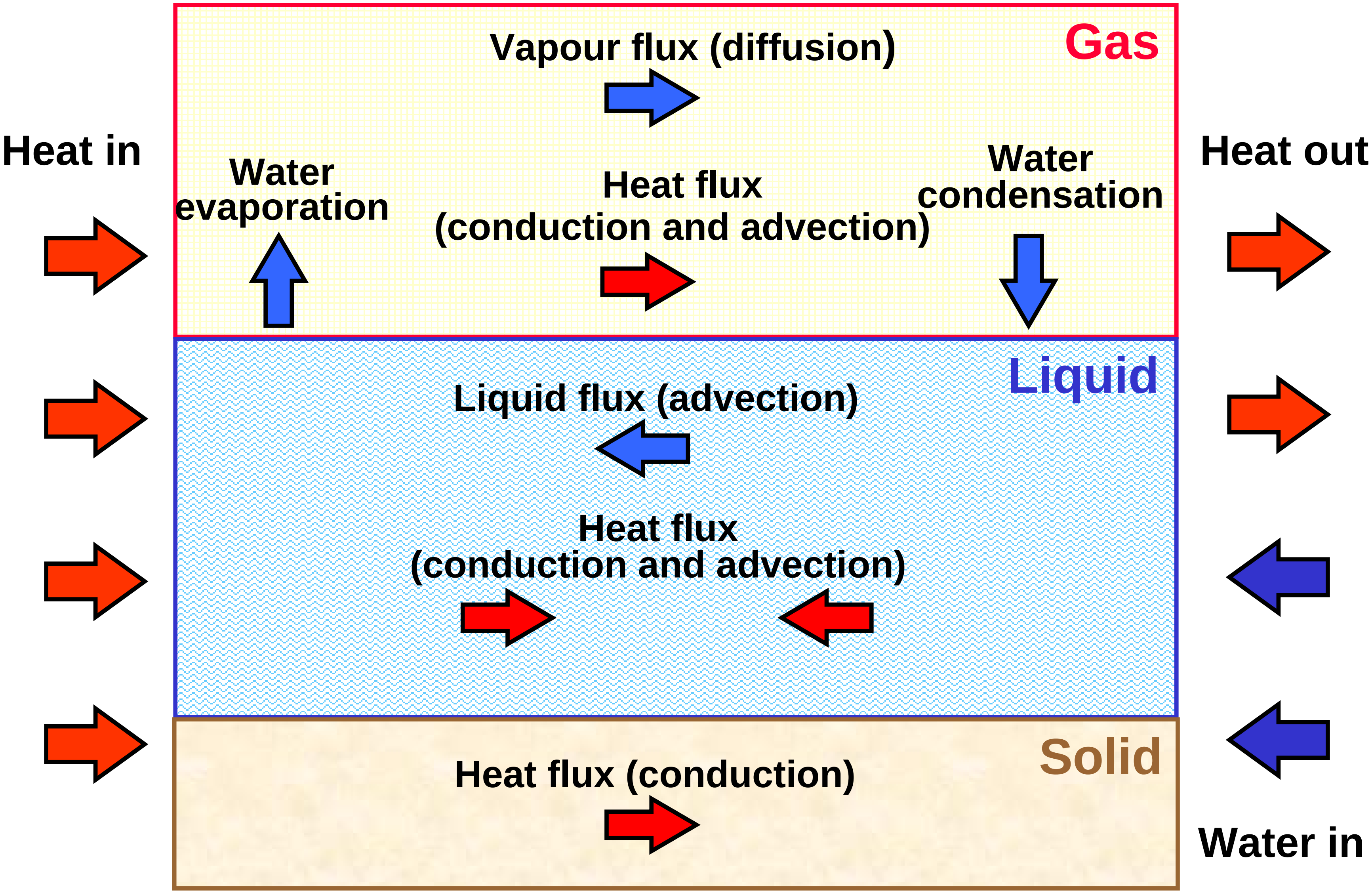
$$\omega_g^w \rho_g S_g \phi$$

Mass of water in the liquid phase

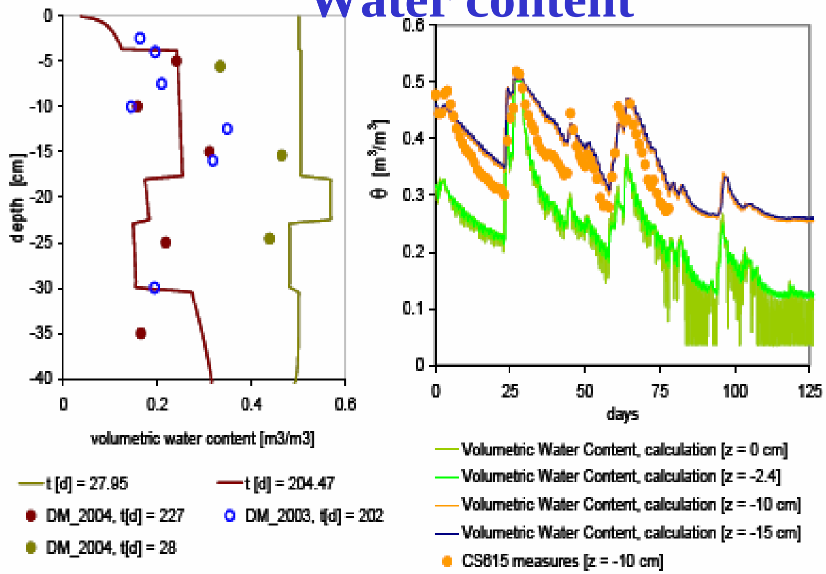
$$\omega_l^w \rho_l S_g \phi$$

Mass of Solid in the Solid phase

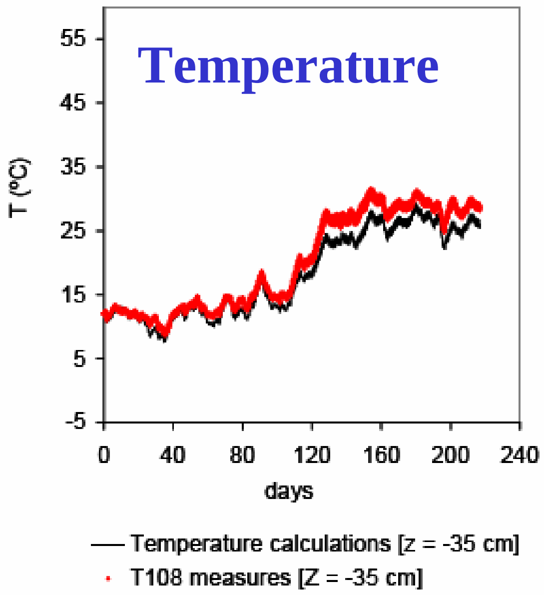
$$\rho_s \left(1-\phi\right)$$

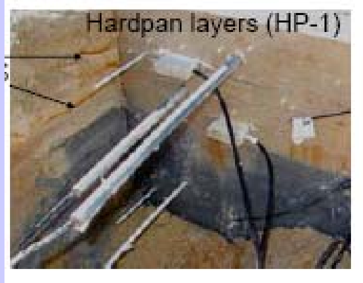

Gas
Vapour flux (diffusion)
Heat in
Water
evaporation
Heat flux
(conduction and advection)
Water
condensation
Heat out
Liquid
Liquid flux (advection)
Heat flux
(conduction and advection)
Solid
Heat flux (conduction)
Water in

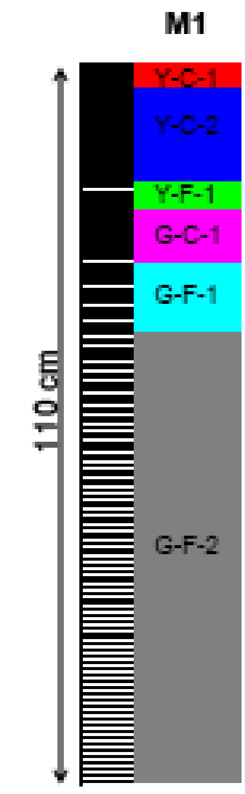
Water content

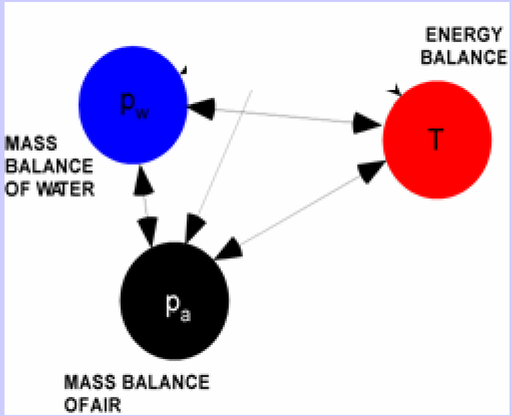


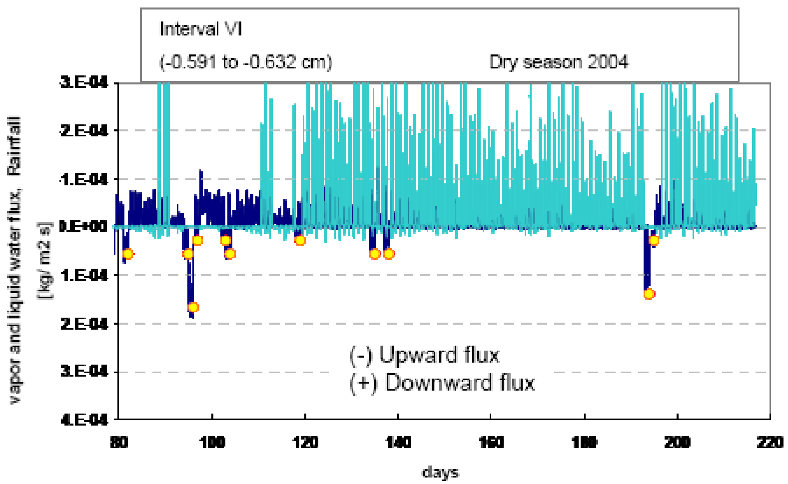
Temperature











Water fluxes

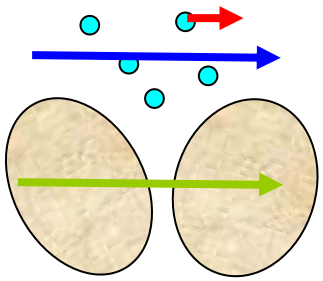
- Rainfall
- Liquid water
- Vapor

Formulación para problemas THM

THE TOTAL MASS FLUX OF A SPECIES IN A PHASE (E.G. FLUX OF AIR PRESENT IN GAS PHASE j_G^W IS, IN GENERAL, THE SUM OF THREE TERMS

the nonadvective flux: $\mathbf{i}_g^w$, i.e. diffusive/ dispersive,	$\mathbf{i}_g^w$
the advective flux caused by fluid motion: $\omega_g^w \rho_g \mathbf{q}_g$, where $\mathbf{q}_g$ is the Darcy's flux,	$\omega_g^w \rho_g \mathbf{q}_g$
the advective flux caused by solid motion: $\phi S_g \omega_g^w \rho_g \, d\mathbf{u}/dt$ where $d\mathbf{u}/dt$ is the vector of solid velocities, S_g is the volumetric fraction of pores occupied by the gas phase and ϕ is porosity.	$\phi S_g \omega_g^w \rho_g \, d\mathbf{u}/dt$

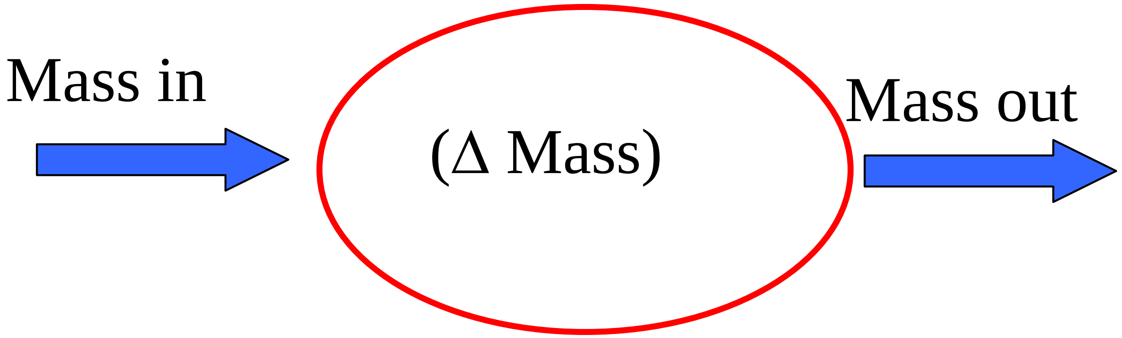
$\phi S_g \omega_g^w \rho_g \, d\mathbf{u}/dt$ $\quad$ $\omega_g^w \rho_g \mathbf{q}_g$ $\quad$ $\mathbf{i}_g^w$



The following balance equation will be applied

$$\frac{\partial}{\partial t}\begin{pmatrix}\text{mass or energy per}\\ \text{unit volume of porous media}\end{pmatrix}+\nabla\bullet\begin{pmatrix}\text{fluxes of mass}\\ \text{or energy}\end{pmatrix}=$$

$$=\begin{pmatrix}\text{sources or sinks of}\\ \text{mass and energy}\end{pmatrix}$$



MASS BALANCE OF SOLID

Mass balance of solid:

$$\frac{\partial}{\partial t}\left(\rho_s\left(1-\phi\right)\right)+\nabla\cdot\left(\mathbf{j}_s\right)=0$$

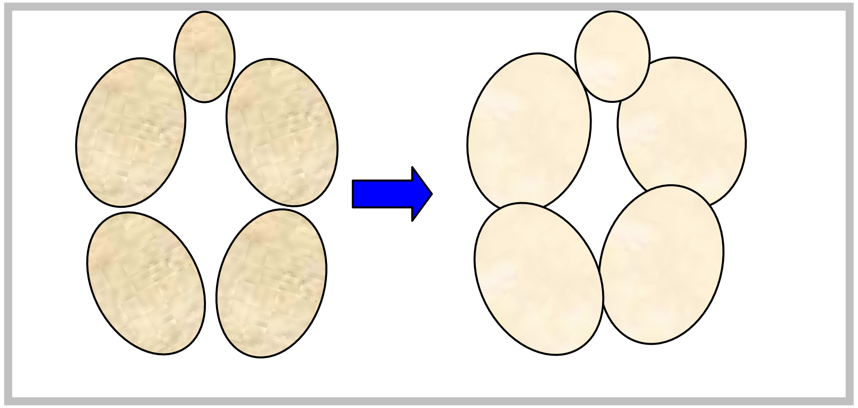
ρ_s solid density and $\mathbf{j}_s$ is the flux of solid.

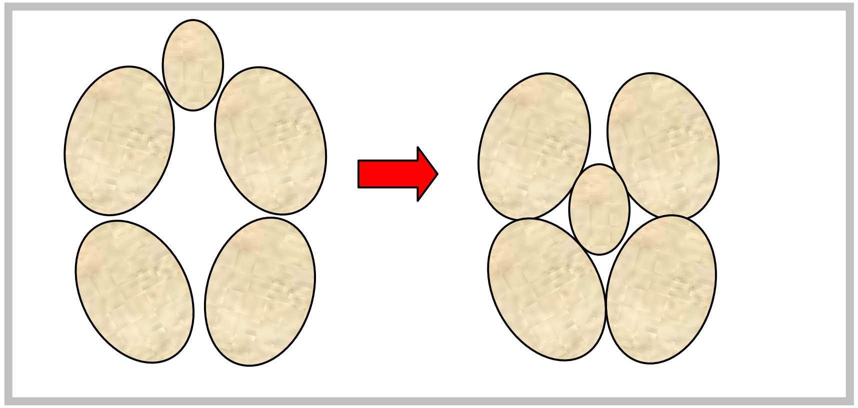
$$\frac{\partial}{\partial t}\left(\rho_s\left(1-\phi\right)\right)+\nabla\cdot\left(\rho_s\left(1-\phi\right)\frac{d\mathbf{u}}{dt}\right)=0$$

Porosity variation:

$$\frac{D_s\phi}{Dt}=\frac{1}{\rho_s}\left[\left(1-\phi\right)\frac{D_s\rho_s}{Dt}\right]+\left(1-\phi\right)\nabla\cdot\frac{d\mathbf{u}}{dt}$$

$$\frac{D_s\phi}{Dt} = \frac{1}{\rho_s}\left[(1-\phi)\frac{D_s\rho_s}{Dt}\right] + (1-\phi)\nabla\cdot\frac{d\mathbf{u}}{dt}$$



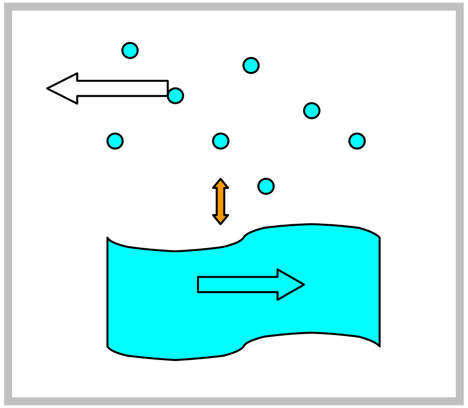


Volumetric strain:

$$\nabla\cdot\frac{d\mathbf{u}}{dt} = \frac{d\varepsilon_x}{dt} + \frac{d\varepsilon_y}{dt} + \frac{d\varepsilon_y}{dt}$$

MASS BALANCE OF WATER

Water is present in liquid an gas phases. The mass balance of water in the liquid and in the gas phase is expressed as:



$$\frac{\partial}{\partial t}\left(\omega_g^w \rho_g S_g \phi\right) + \nabla \cdot \left(\mathbf{j}_g^w\right) = f^{\,evaporation} + f^{\,w}$$

$$\frac{\partial}{\partial t}\left(\omega_l^w \rho_l S_l \phi\right) + \nabla \cdot \left(\mathbf{j}_l^w\right) = f^{\,condensation} + f^{\,w}$$

$f^{\,w}$ is an external supply of water and:

$$f^{\,condensation} + f^{\,evaporation} = 0$$

Adding the two mass balance equations leads to:

$$\frac{\partial}{\partial t}\left(\omega_l^w \rho_l S_l \phi + \omega_g^w \rho_g S_g \phi\right) + \nabla \cdot \left(\mathbf{j}_l^w + \mathbf{j}_g^w\right) = f^{\,w}$$

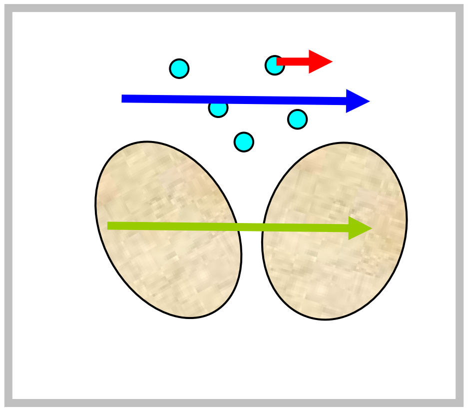
$$\frac{\partial}{\partial t}\left(\omega_l^w \rho_l S_l \phi + \omega_g^w \rho_g S_g \phi\right) + \nabla \cdot \left(\mathbf{j}_l^w + \mathbf{j}_g^w\right) = f^w$$

Flux referred to a fixed framework:

$\mathbf{j}_g^{w} = \mathbf{i}_g^{w} + \omega_g^{w} \rho_g \, \mathbf{q}_g + \phi S_g \omega_g^{w} \rho_g \, d\boldsymbol{u}/dt = \mathbf{j'}_g^{w} + \phi S_g \omega_g^{w} \rho_g \, d\boldsymbol{u}/dt$

Flux referred to the solid skeleton:

$\mathbf{j'}_g^{w} = \mathbf{i}_g^{w} + \omega_g^{w} \rho_g \, \mathbf{q}_g$



The use of the material derivative leads to:

$$\phi \frac{D_s\left(\omega_l^w \rho_l S_l + \omega_g^w \rho_g S_g\right)}{Dt} + \left(\omega_l^w \rho_l S_l + \omega_g^w \rho_g S_g\right)\frac{D_s \phi}{Dt} +$$

$$+\left(\left(\omega_l^w \rho_l S_l + \omega_g^w \rho_g S_g\right)\phi\right)\nabla \cdot \frac{d\mathbf{u}}{dt} + \nabla \cdot \left(\mathbf{j}'^w_l + \mathbf{j}'^w_g\right) = f^w$$

Porosity appears in this equation as:

- **a coefficient in storage terms**
- **in a term involving its variation caused by different processes**
- **hidden in variables that depend on porosity (e.g. intrinsic permeability).**

Porosity from solid balance leads to:

$$\phi \frac{D_s\left(\omega_l^w \rho_l S_l + \omega_g^w \rho_g S_g\right)}{Dt} + \left(\omega_l^w \rho_l S_l + \omega_g^w \rho_g S_g\right)\frac{1-\phi}{\rho_s}\frac{D_s \rho_s}{Dt} +$$

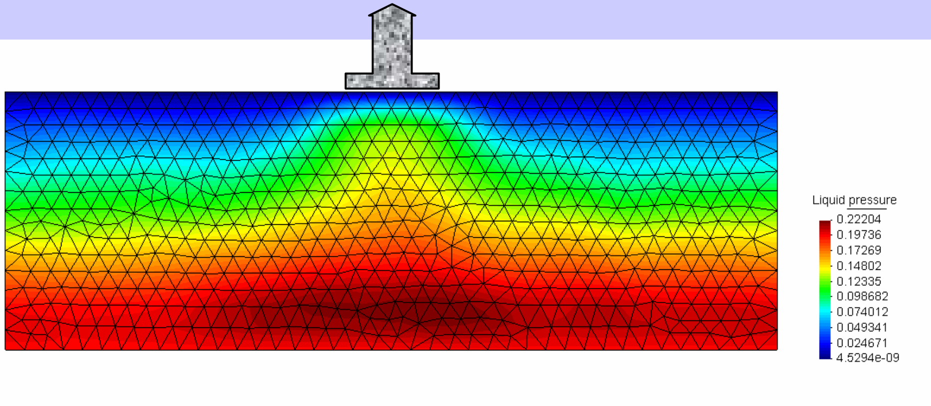
$$+\left(\left(\omega_l^w \rho_l S_l + \omega_g^w \rho_g S_g\right)\right)\nabla \cdot \frac{d\mathbf{u}}{dt} + \nabla \cdot \left(\mathbf{j}'^w_l + \mathbf{j}'^w_g\right) = f^w$$

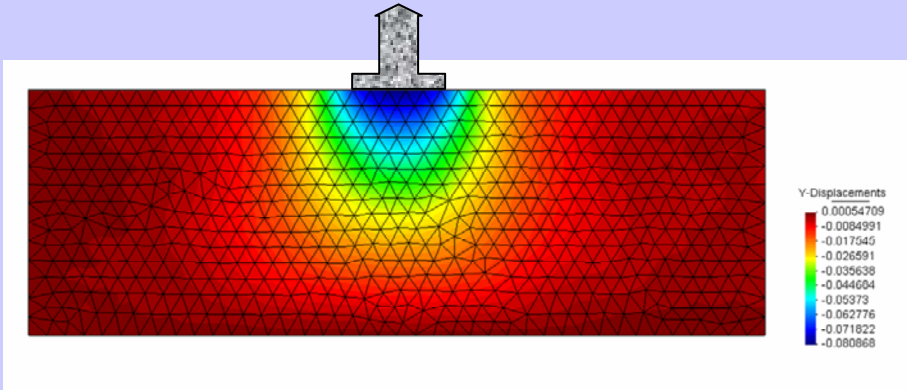
For incompressible solid:

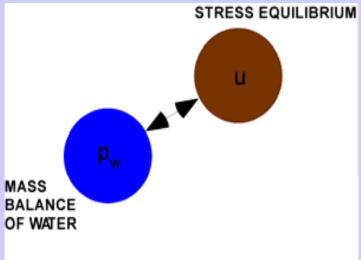
$$\phi \frac{D_s\left(\omega_l^w \rho_l S_l + \omega_g^w \rho_g S_g\right)}{Dt} + \nabla \cdot \left(\mathbf{j}'^w_l + \mathbf{j}'^w_g\right) =$$

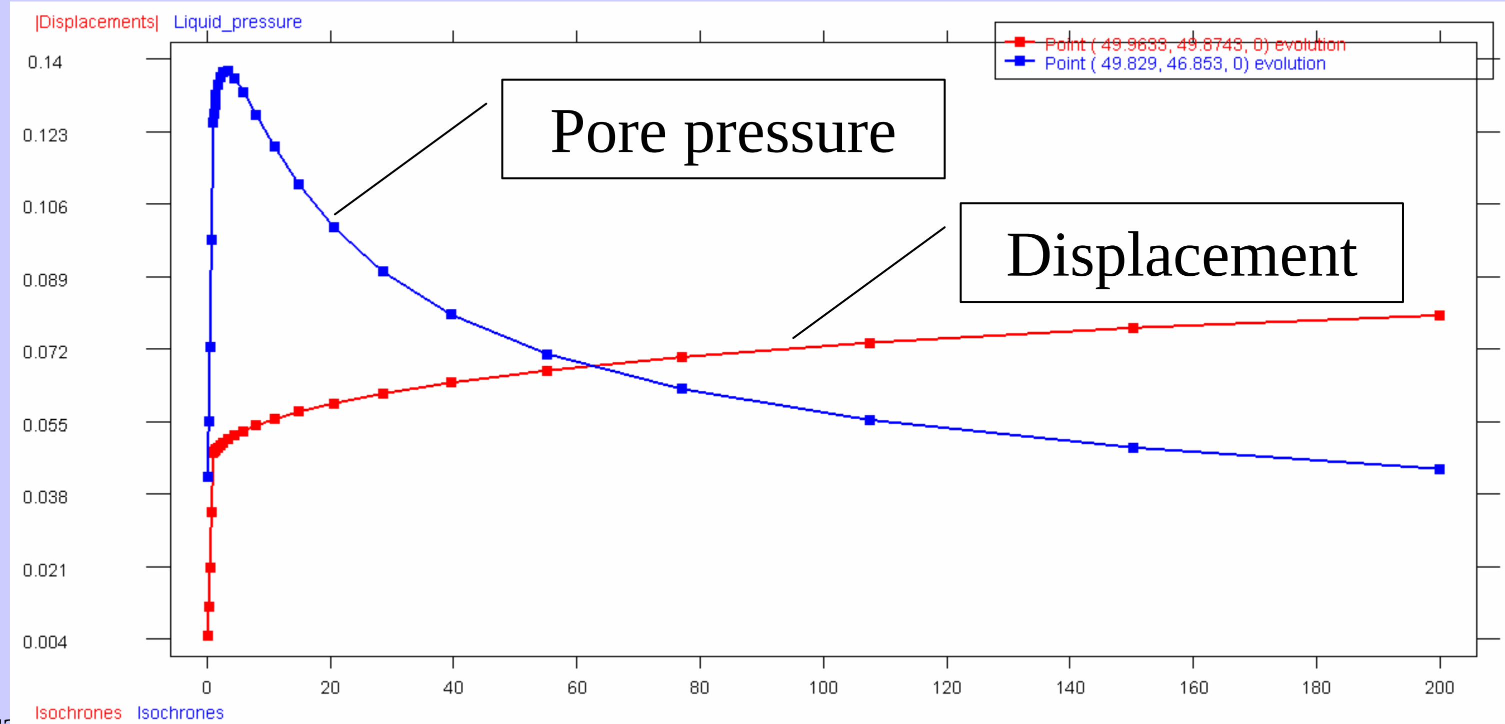
$$= -\left(\left(\omega_l^w \rho_l S_l + \omega_g^w \rho_g S_g\right)\right)\nabla \cdot \frac{d\mathbf{u}}{dt} + f^w$$

Foundation in a saturated soil

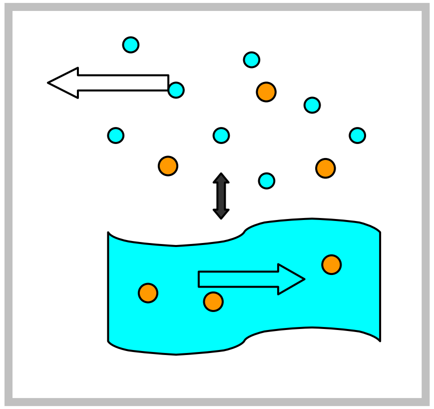








MASS BALANCE OF AIR



$$\frac{\partial}{\partial t}\left(\omega_g^a \rho_g S_g \phi\right) + \nabla \cdot \left(\mathbf{j}_g^a\right) = f^{\,liberation} + f^{\,a}$$

$$\frac{\partial}{\partial t}\left(\omega_l^a \rho_l S_l \phi\right) + \nabla \cdot \left(\mathbf{j}_l^a\right) = f^{\,dissolution} + f^{\,a}$$

where $f^{\,a}$ is an external supply of air and the internal source terms that represent phase change are:

$$f^{\,dissolution} + f^{\,liberation} = 0$$

Adding the two equations leads to:

$$\frac{\partial}{\partial t}\left(\omega_l^a \rho_l S_l \phi + \omega_g^a \rho_g S_g \phi\right) + \nabla \cdot \left(\mathbf{j}_l^a + \mathbf{j}_g^a\right) = f^{\,a}$$

An internal production term is not present because the total mass balance inside the medium is considered in this equation.

MOMENTUM BALANCE FOR THE MEDIUM

Momentum balance = equilibrium of stresses
(inertial terms neglected)

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

where $\boldsymbol{\sigma}$ is the stress tensor and $\mathbf{b}$ is the vector of body forces.

INTERNAL ENERGY BALANCE FOR THE MEDIUM

Internal energy balance for the porous medium (e_s, e_l, e_g):

$$\frac{\partial}{\partial t}\left(e_s\rho_s(1-\phi)+e_l\rho_l S_l\phi+e_g\rho_g S_g\phi\right)+\nabla\cdot(\mathbf{i}_c+\mathbf{j}_{es}+\mathbf{j}_{el}+\mathbf{j}_{eg})=f^Q$$

- $\mathbf{i}_c$ is energy flux: conduction through the porous medium
- ($\mathbf{j}_{es}$, $\mathbf{j}_{el}$, $\mathbf{j}_{eg}$) are advective fluxes of energy caused by mass motions
- f^Q is an internal/external energy supply.

Advective heat fluxes due to mass movement

The internal energy in each phase can be calculated as a function of internal energy of each component.

$$e_g \rho_g = e_g^w \omega_g^w \rho_g + e_g^a \omega_g^a \rho_g = \left(e_g^w \omega_g^w + e_g^a \omega_g^a \right) \rho_g$$

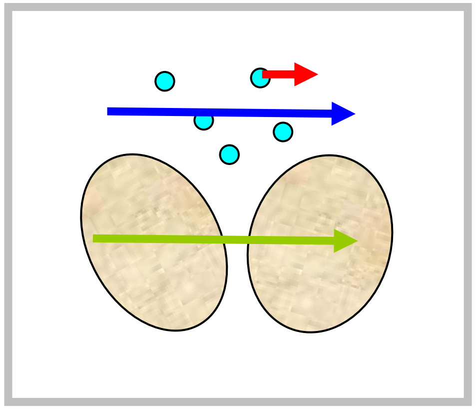
$$e_g = e_g^w \omega_g^w + e_g^a \omega_g^a$$

Following this decomposition, the advective fluxes of energy in each phase are calculated as:

$$\dot{\mathbf{j}}_g = e_g^w \dot{\mathbf{j}}_g^w + e_g^a \dot{\mathbf{j}}_g^a$$

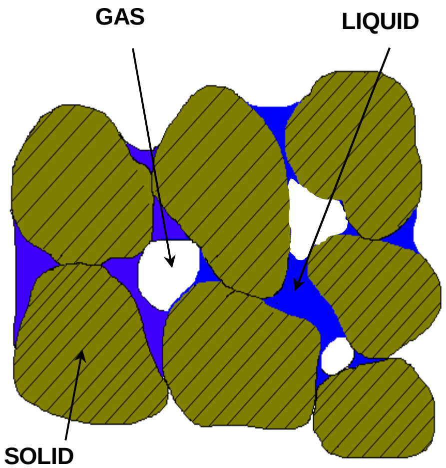
$$e_g^w \dot{\mathbf{j}}_g^w = e_g^w \left(\dot{\mathbf{i}}_g^w + \omega_g^w \rho_g \mathbf{q}_g + \omega_g^w \rho_g S_g \phi \frac{d\mathbf{u}}{dt} \right)$$

$$e_g^a \dot{\mathbf{j}}_g^a = e_g^a \left(\dot{\mathbf{i}}_g^a + \omega_g^a \rho_g \mathbf{q}_g + \omega_g^a \rho_g S_g \phi \frac{d\mathbf{u}}{dt} \right)$$



$$\dot{\mathbf{j}}_g = e_g^w \dot{\mathbf{j}}_g^w + e_g^a \dot{\mathbf{j}}_g^a = e_g^w \dot{\mathbf{i}}_g^w + e_g^a \dot{\mathbf{i}}_g^a + e_g \rho_g \left(\mathbf{q}_g + S_g \phi \frac{d\mathbf{u}}{dt} \right)$$

FINAL SET OF BALANCE EQUATIONS



MASS BALANCE OF WATER. Unknown: P_l

$$\frac{\partial}{\partial t}\left(\omega_l^w \rho_l S_l \phi + \omega_g^w \rho_g S_g \phi\right) + \nabla \cdot \left(\mathbf{j}_l^w + \mathbf{j}_g^w\right) = f^w$$

MASS BALANCE OF AIR. Unknown: P_g

$$\frac{\partial}{\partial t}\left(\omega_l^a \rho_l S_l \phi + \omega_g^a \rho_g S_g \phi\right) + \nabla \cdot \left(\mathbf{j}_l^a + \mathbf{j}_g^a\right) = f^a$$

INTERNAL ENERGY BALANCE FOR THE MEDIUM. Unknown: T

$$\frac{\partial}{\partial t}\left(E_s \rho_s (1-\phi) + E_l \rho_l S_l \phi + E_g \rho_g S_g \phi\right) + \nabla \cdot (\mathbf{i}_c + \mathbf{j}_{Es} + \mathbf{j}_{El} + \mathbf{j}_{Eg}) = f^Q$$

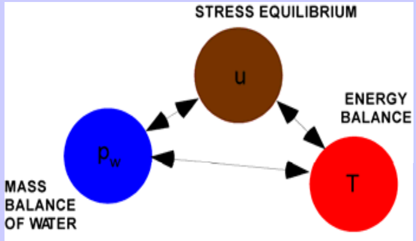
MOMENTUM BALANCE FOR THE MEDIUM. Unknown: u

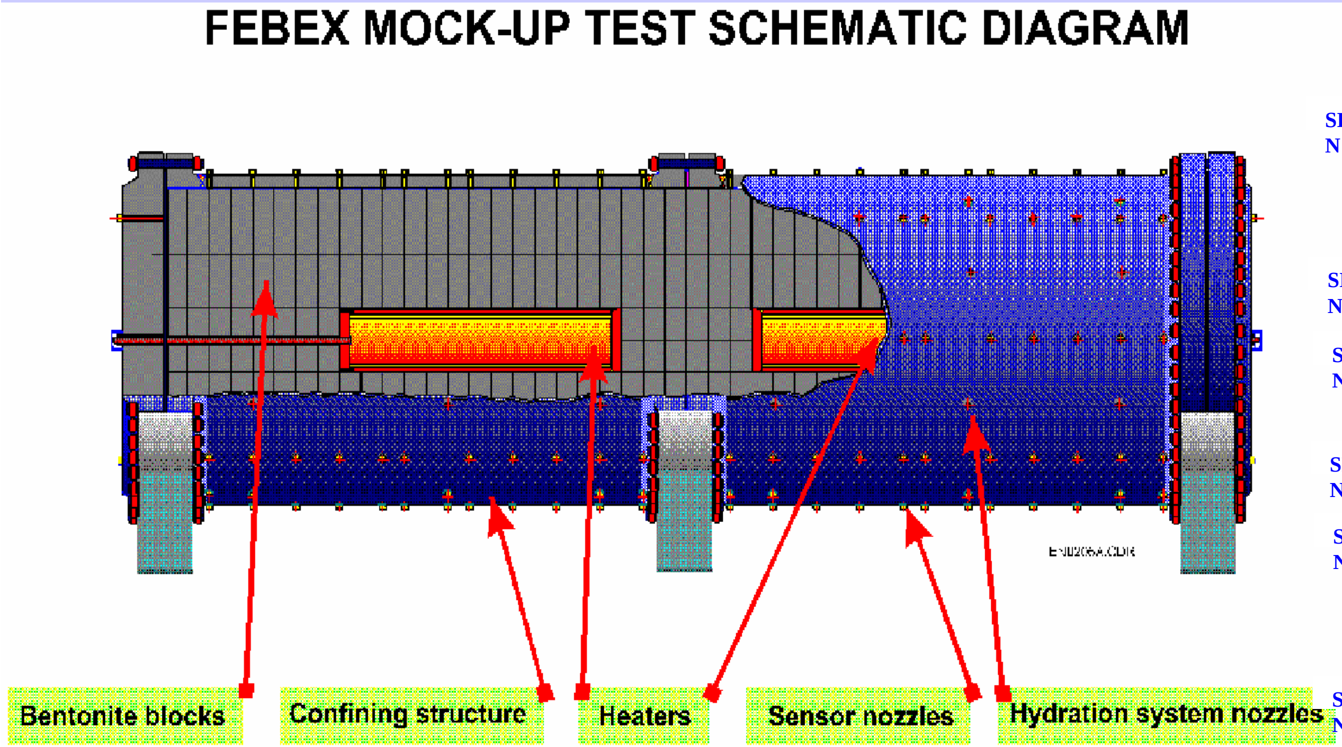
$$\nabla \cdot \boldsymbol{\sigma} + \mathbf{b} = \mathbf{0}$$

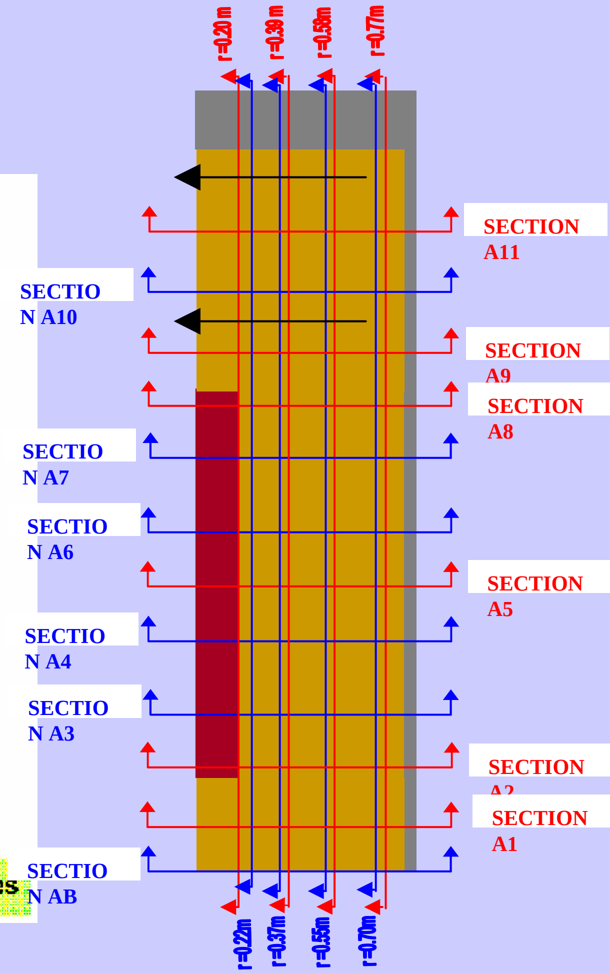
SPECIES MASS BALANCE (REACTIVE TRANSPORT). Unknown: c

$$\frac{\partial}{\partial t}(\phi S_l \rho_l c) + \nabla \cdot \mathbf{j} = R$$

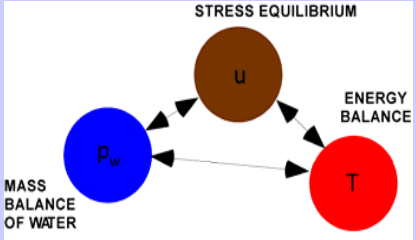
THM problem: Febex mock-up

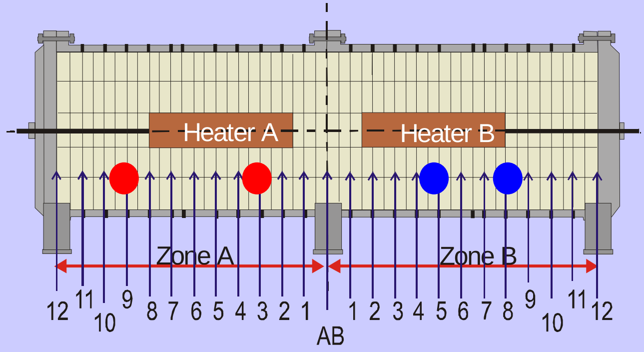


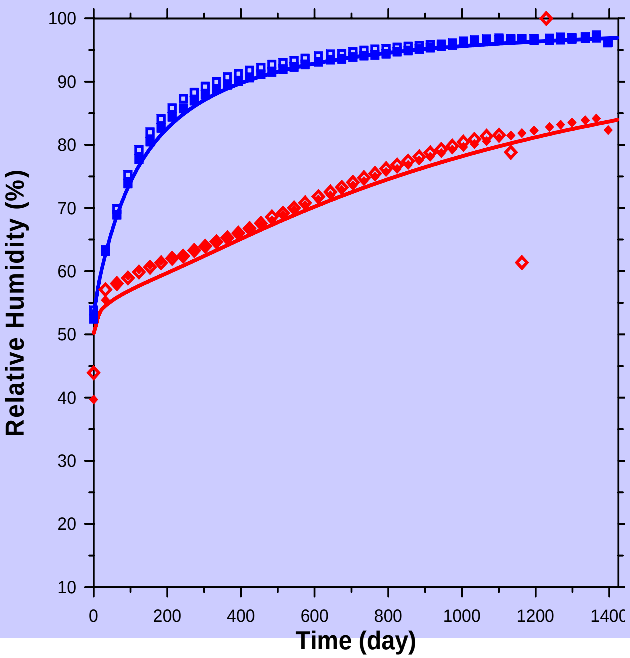


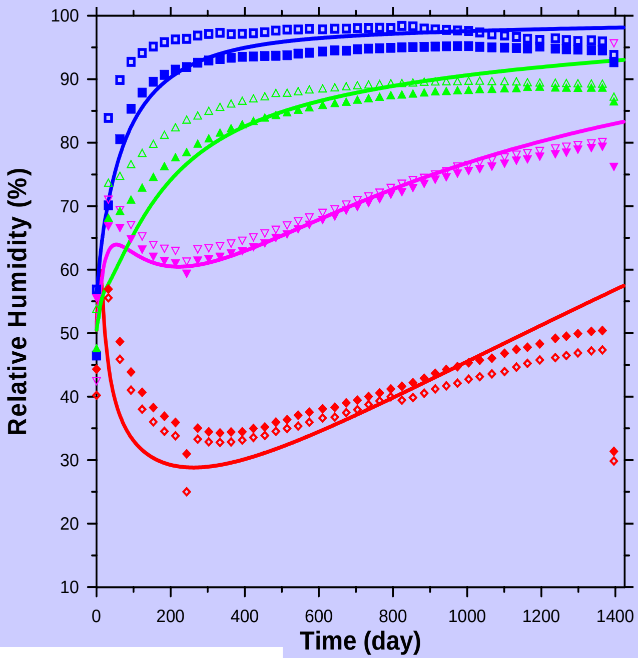


THM problem: Febex mock-up

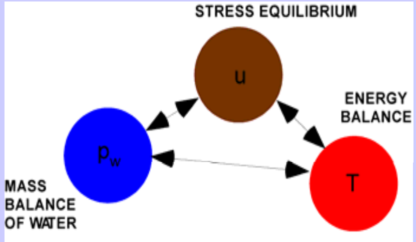


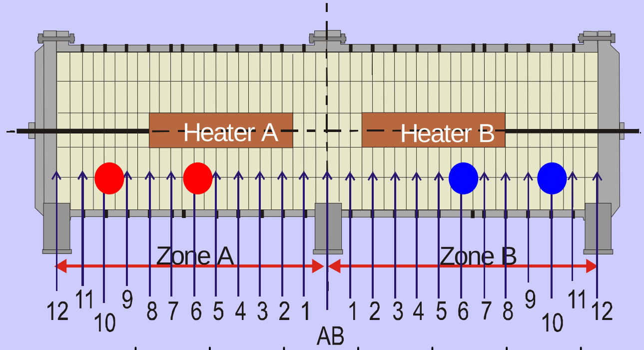


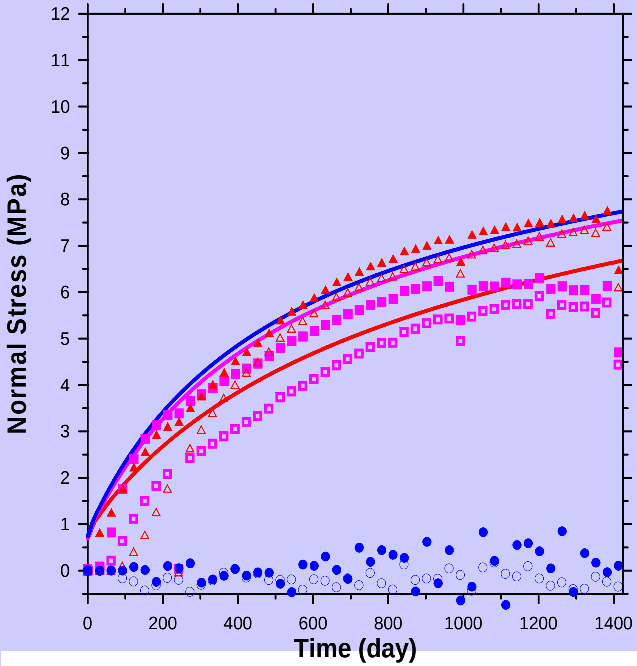


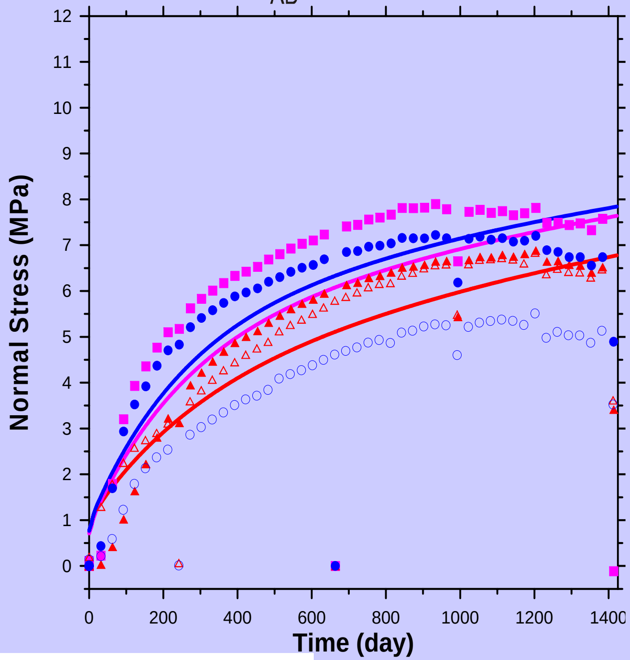


THM problem: Febex mock-up









Boundary conditions

$$j_g^w = \left(\omega_g^w\right)^0 j_g^0 + \left(\omega_g^w\right)^0 \gamma_g \left(P_g^0 - P_g\right) + \beta_g \left(\left(\rho_g \omega_g^w\right)^0 - \left(\rho_g \omega_g^w\right)\right)$$

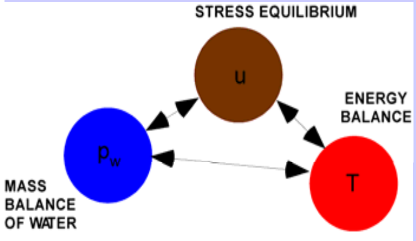
where the superscript $()^0$ stands for prescribed values.

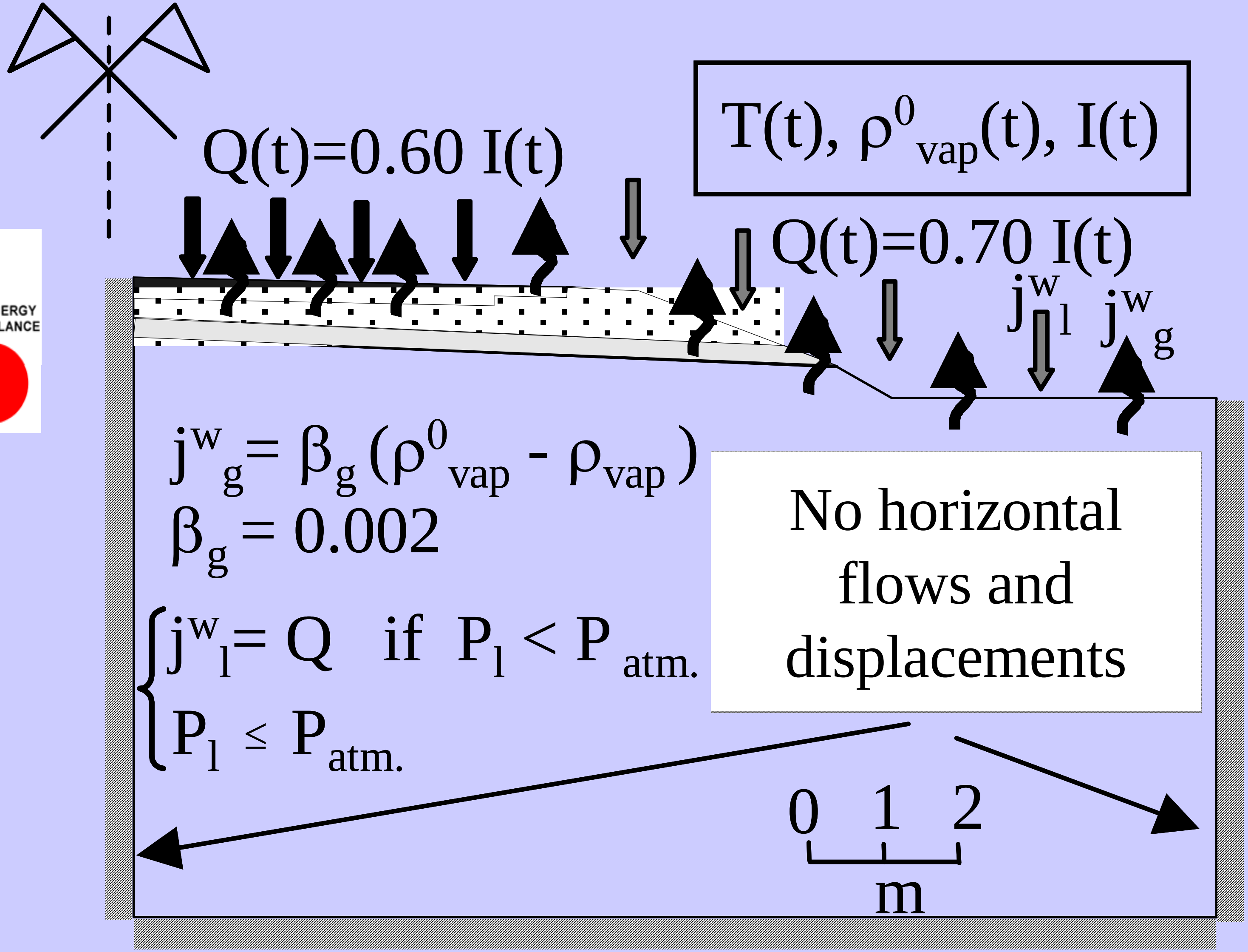
•The **first term** is the mass inflow or outflow that takes place when a flow rate of gas (j_g^0) is prescribed.

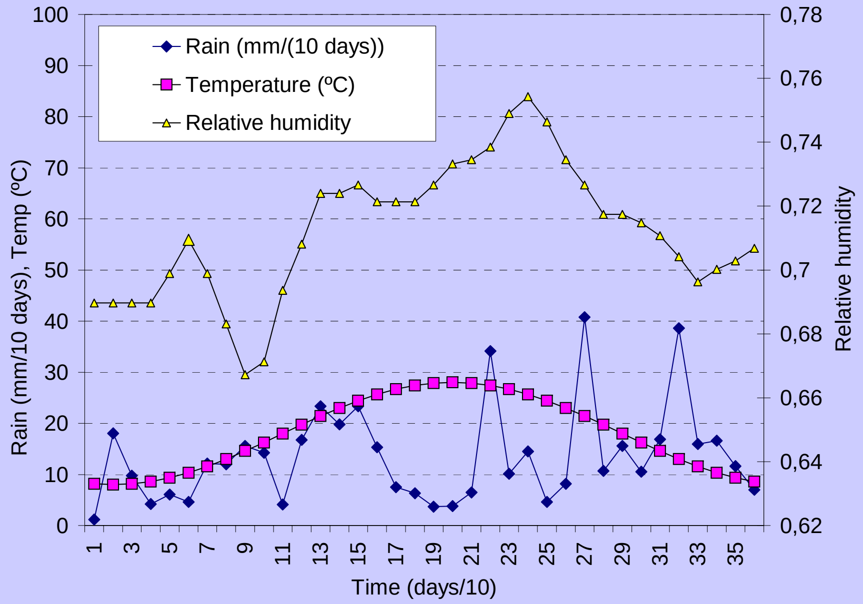
•The **second term** is the mass inflow or outflow that takes place when gas phase pressure (P_g^0) is prescribed at a node. The coefficient γ_g is a leakage coefficient, i.e., a parameter that allows a boundary condition of the Cauchy type.

•The **third term** is the mass inflow or outflow that takes place when vapour mass fraction is prescribed at the boundary. This term naturally comes from the nonadvective flux (Fick's law). Mass fraction and density prescribed values are only required when inflow takes place. For outflow the values in the medium are considered.

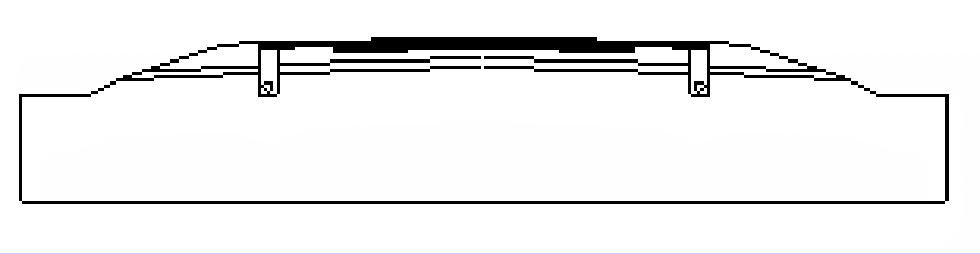
ROAD PAVEMENT PROBLEMS

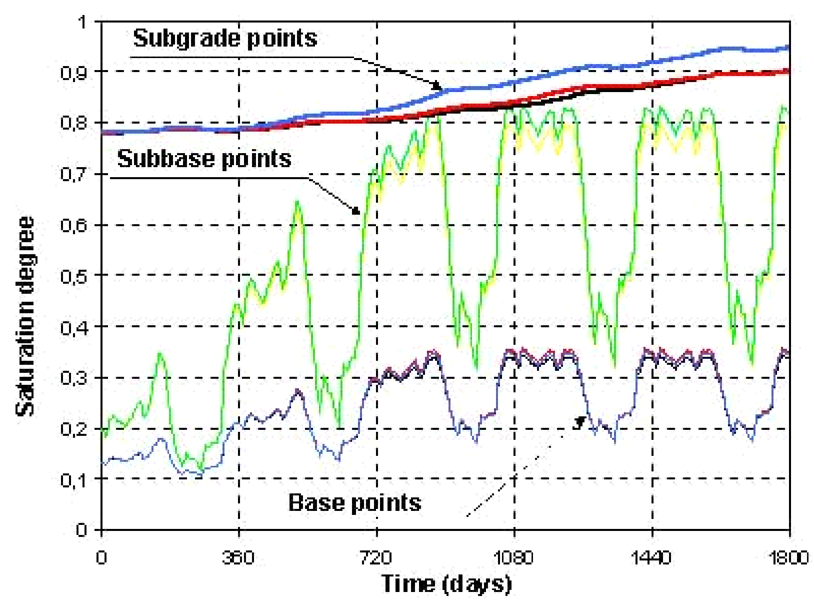




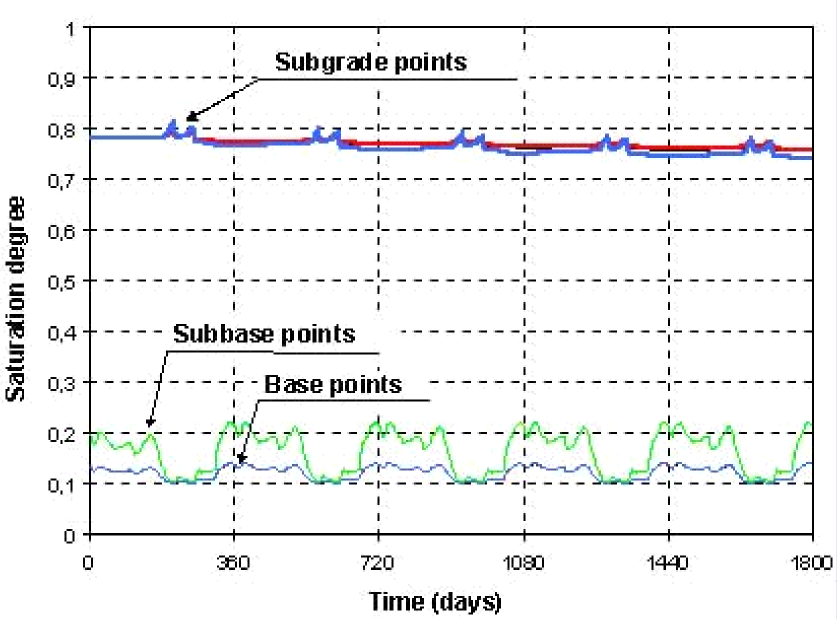


Rain (mm/(10 days))
Temperature (ºC)
Relative humidity
Rain (mm/10 days), Temp (ºC)
Relative humidity
Time (days/10)





Subgrade points
Subbase points
Base points
Saturation degree
Time (days)



Subgrade points
Subbase points
Base points
Saturation degree
Time (days)

Constitutive laws

Darcy ⇒ liquid and gas flow

Fick ⇒ vapor and air diffusion (dispersion)

Fourier ⇒ heat conduction

Retention curve ⇒ saturation versus suction

Water V-P-T ⇒ water density

Ideal gases law ⇒ gas density

Henry's law ⇒ dissolved air

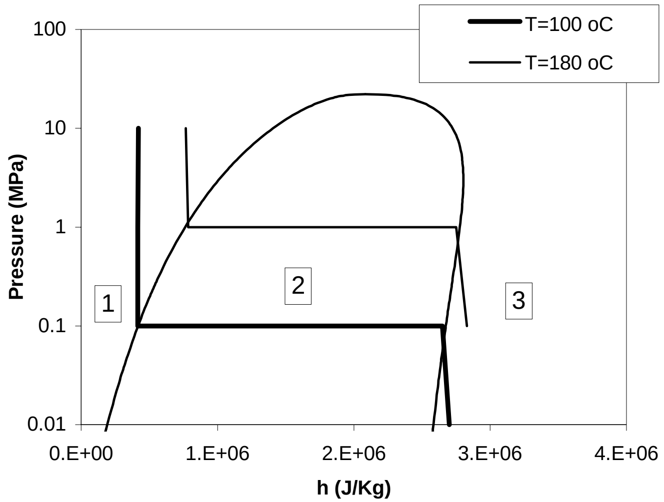
Psychrometric law ⇒ vapour concentration

Mechanical model ⇒ stress – strain response

Enthalpy of water

Depending on the pressure of water (*p*, MPa) and the enthalpy per unit mass (*h*, J/kg) three regions are distinguished.

From 100 °C to 180 °C, vapor pressure changes by one order of magnitude. While atmospheric pressure (0.1 MPa) is the vapor pressure at 100 °C, 1 MPa is the vapor pressure at 180 °C.



(1) Single phase region (liquid water)
(2) two phase region (liquid water+vapor)
(3) single phase region (heated vapor)

Pressure-enthalpy diagram for pure water. Isotherm lines for 100 °C and 180 °C are represented.

SOIL DESATURATION

•Liquid pressure decrease or air pressure increase: two phase flow with nearly immiscible fluids.

$P_g \approx P_a$ *(moderate T).*

•Vapour pressure increase: gas pressure is dominated by vapour pressure.

$P_g \approx P_v$ *(relatively high T).*

Thermal conductivity

Fourier's law to compute conductive heat flux, i.e.:

$$\mathbf{i}_c = -\lambda \nabla T$$

Where λ is thermal conductivity of the porous medium.

$$\lambda_{dry} = \lambda_{solid}^{(1-\phi)} \lambda_{gas}^{\phi} \qquad \lambda_{sat} = \lambda_{solid}^{(1-\phi)} \lambda_{liq}^{\phi}$$

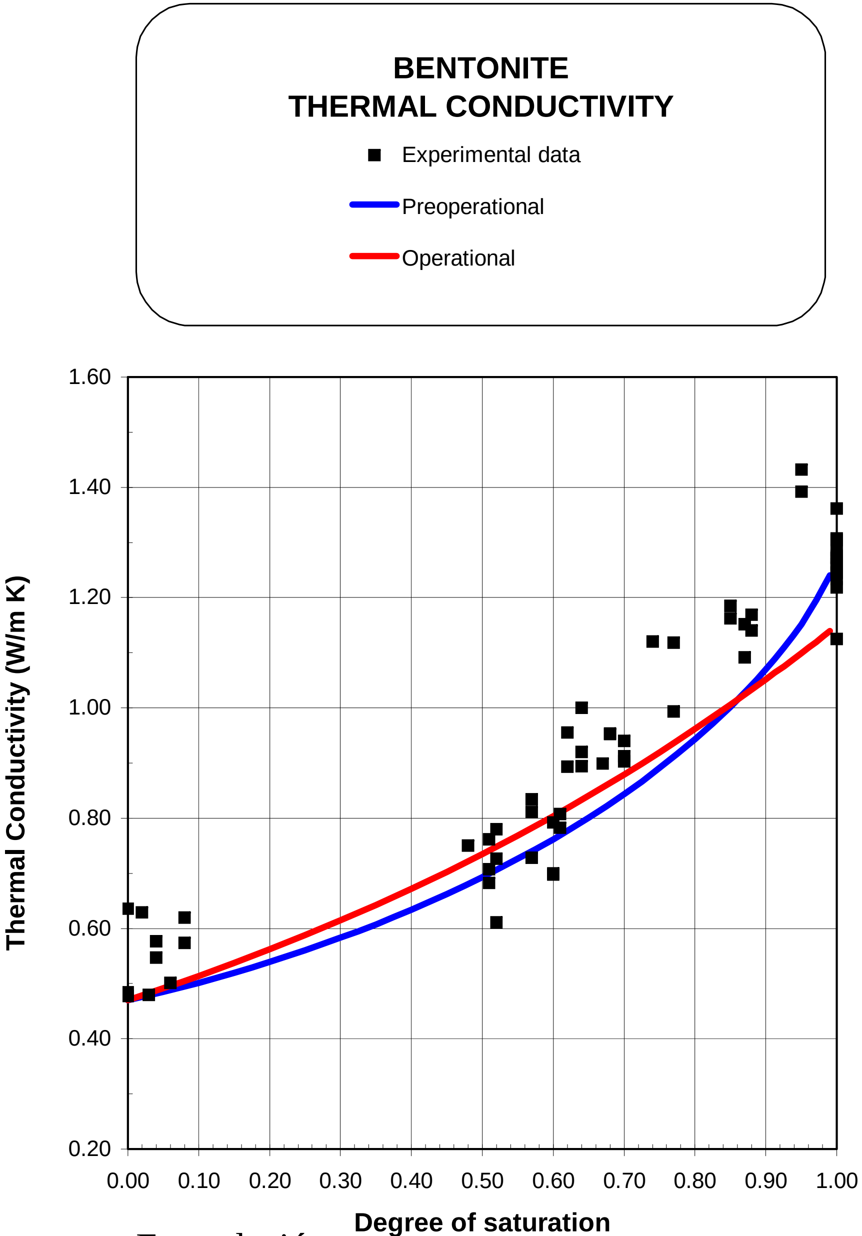
$$\lambda_{solid} = (\lambda_{solid})_o + a_1 T + a_2 T^2 + a_3 T^3$$

The definition of *dry* and *saturated* thermal conductivities permits to separate the dependence on porosity and the dependence on degree of saturation. Finally,

$$\lambda = \lambda_{sat}^{S_l} \lambda_{dry}^{(1-S_l)}$$

On the other hand, the *dry* and *saturated* thermal conductivities can be calculated as described above or directly determined experimentally.

Thermal conductivity



Thermal conductivity is used in Fourier's law to compute conductive heat flux, i.e.:

$$\mathbf{i}_c = -\lambda \nabla T$$

with

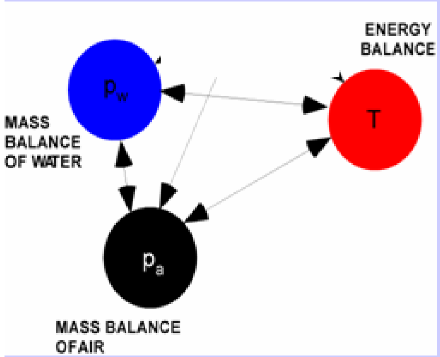
$$\lambda = \lambda_{sat}^{S_l} \lambda_{dry}^{(1-S_l)}$$

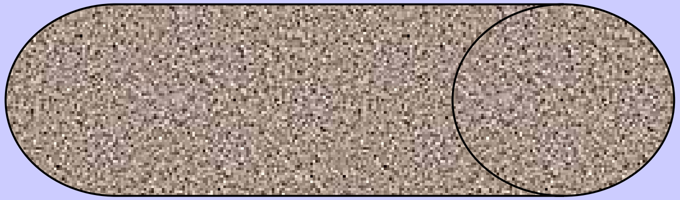
$$\lambda_{dry} = \lambda_{solid}^{(1-\phi)} \lambda_{gas}^{\phi}$$

$$\lambda_{sat} = \lambda_{solid}^{(1-\phi)} \lambda_{liq}^{\phi}$$

$$\lambda_{solid} = (\lambda_{solid})_o + a_1 T + a_2 T^2 + a_3 T^3$$

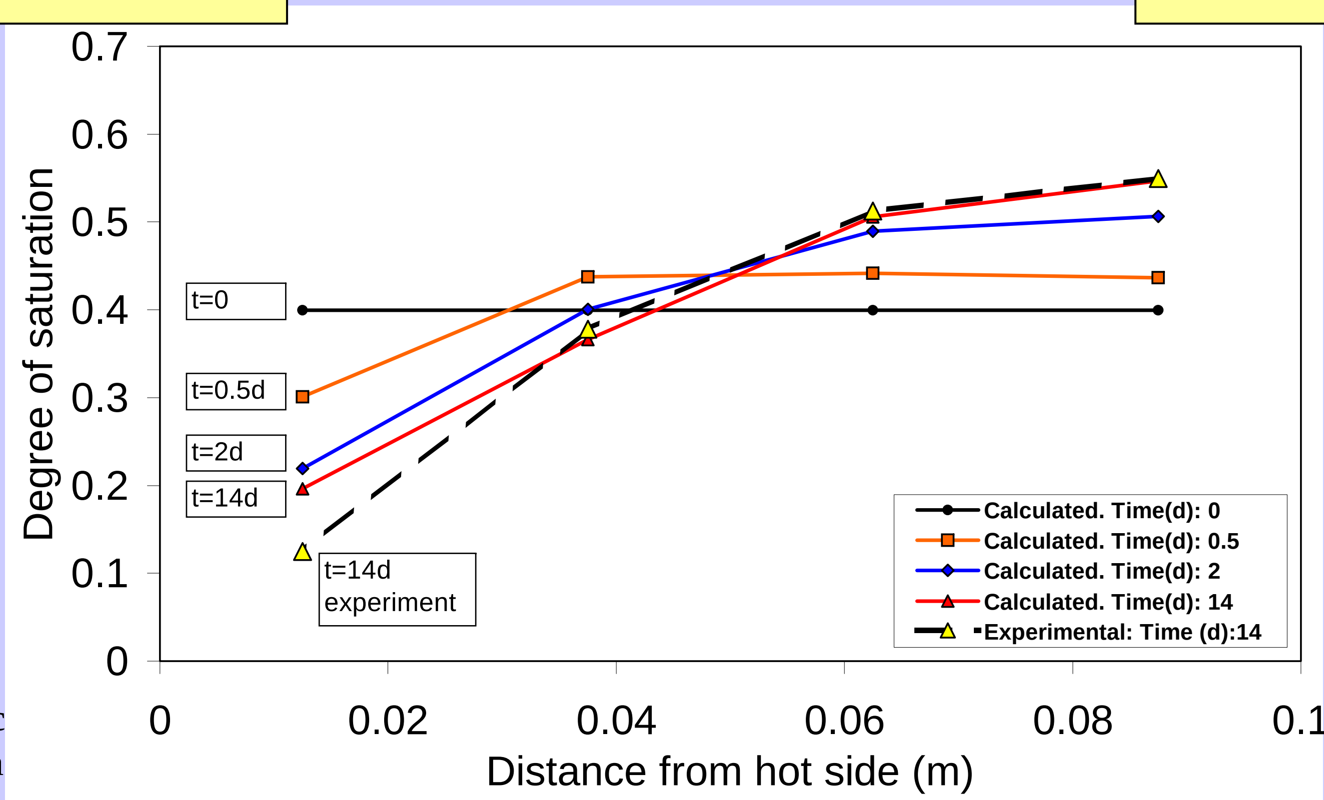
Numerical modelling of drying induced by temperature gradients





T=120 ºC

T=30 ºC



Formulac
problema

Liquid phase density

As a first approximation, the density of liquid phase can be calculated as:

$$\rho_l = \rho_{l0} \exp(\beta(P_l - P_{lo}) + \alpha T + \gamma c)$$

where a water compressibility (β) and a volumetric expansion coefficient (α) are defined. Reference values of 4.5 10^{-4} MPa^{-1} and -3.4 10^{-4} $^{o}C^{-1}$ can be used in this expression.

Gas phase density

Gas density is calculated as the sum of vapor and air density. This can be written as:

$$\rho_g = \rho_v + \rho_a$$

If ideal gases law is used to calculate vapor and air density, it follows that:

$$\rho_g = \rho_v + \rho_a = \frac{P_v M_v}{RT} + \frac{P_a M_a}{RT}$$

where the M_v = 0.018 kg/mol and M_a = 0.028 kg/mol are the molecular masses for vapor and dry-air. R is the ideal gas constant (8.3143 J/molK) and T is temperature. On the other hand, partial pressures principle is assumed to hold in the vapor-air mixture (P_g=P_v+P_a), which implies that:

$$M_g = \frac{P_v M_v + P_a M_a}{P_g}$$

i.e. the gas phase has variable molecular mass depending on its composition.
If P_g is given, air pressure can be calculated as $P_a = P_g - P_v$ where it is assumed that vapor pressure is also known.

Vapor partial pressure

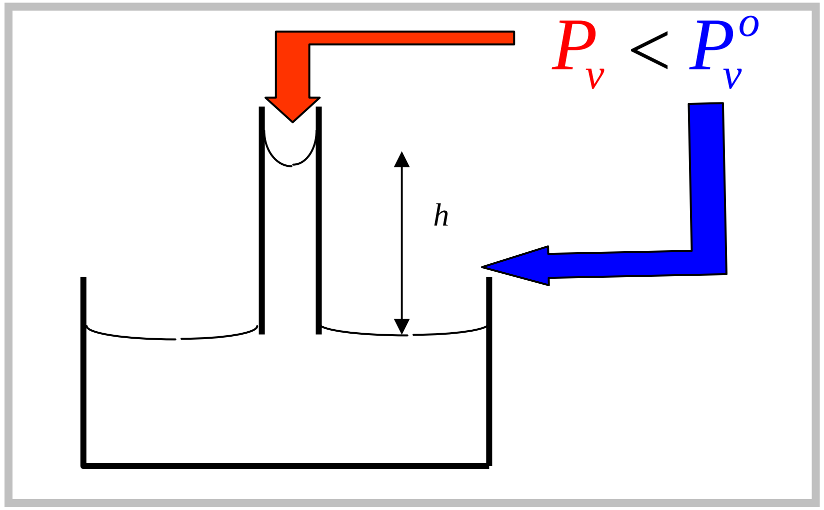
Vapor pressure depends on temperature and suction:

$$P_v(T,s) = P_v(T)\times F(s,T)$$

$$P_v(T) = 136075\exp\left(\frac{-5239.7}{273+T}\right)$$

$$F(P_c,T) = \exp\left(\frac{-sM_w}{R(273+T)\rho_l}\right)$$

$$s = P_g - P_l$$



In which $\boldsymbol{P_v(T)}$ is the boundary between (1) and (2) in the phase diagram for pure water and $\boldsymbol{F(s,T)}$ is a reduction term due to capillary effects (psychrometric law).

Relative humidity inside soil pores is assumed to be ***F***

Retention curve

This law relates capillary pressure and degree of saturation. One of the commonly used models is the van Genuchten model (van Genuchten, 1980) that can be written as:

$$S_e = \frac{S_l - S_{\min}}{S_{\max} - S_{\min}} = \left(1 + \left(\frac{P_g - P_l}{P} \right)^{1/(1-\lambda)} \right)^{-\lambda}$$

This equation contains the parameters λ and P. The first (λ) essentially controls the shape of the curve while the second (P) controls its height, so this latter can be interpreted as a measure of the capillary pressure required to start the desaturation of the soil. Since capillary pressure can be scaled with surface tension (Milly, 1982) it appears that *P* also does. This can be shown if Laplace's law is recalled:

$$P_g - P_l = \frac{2\sigma}{r} \qquad P_g - P_l = P\left(S_e^{-1/\lambda} - 1\right)^{(1-\lambda)} \qquad P = P_o \frac{\sigma(T)}{\sigma(T_o)}$$

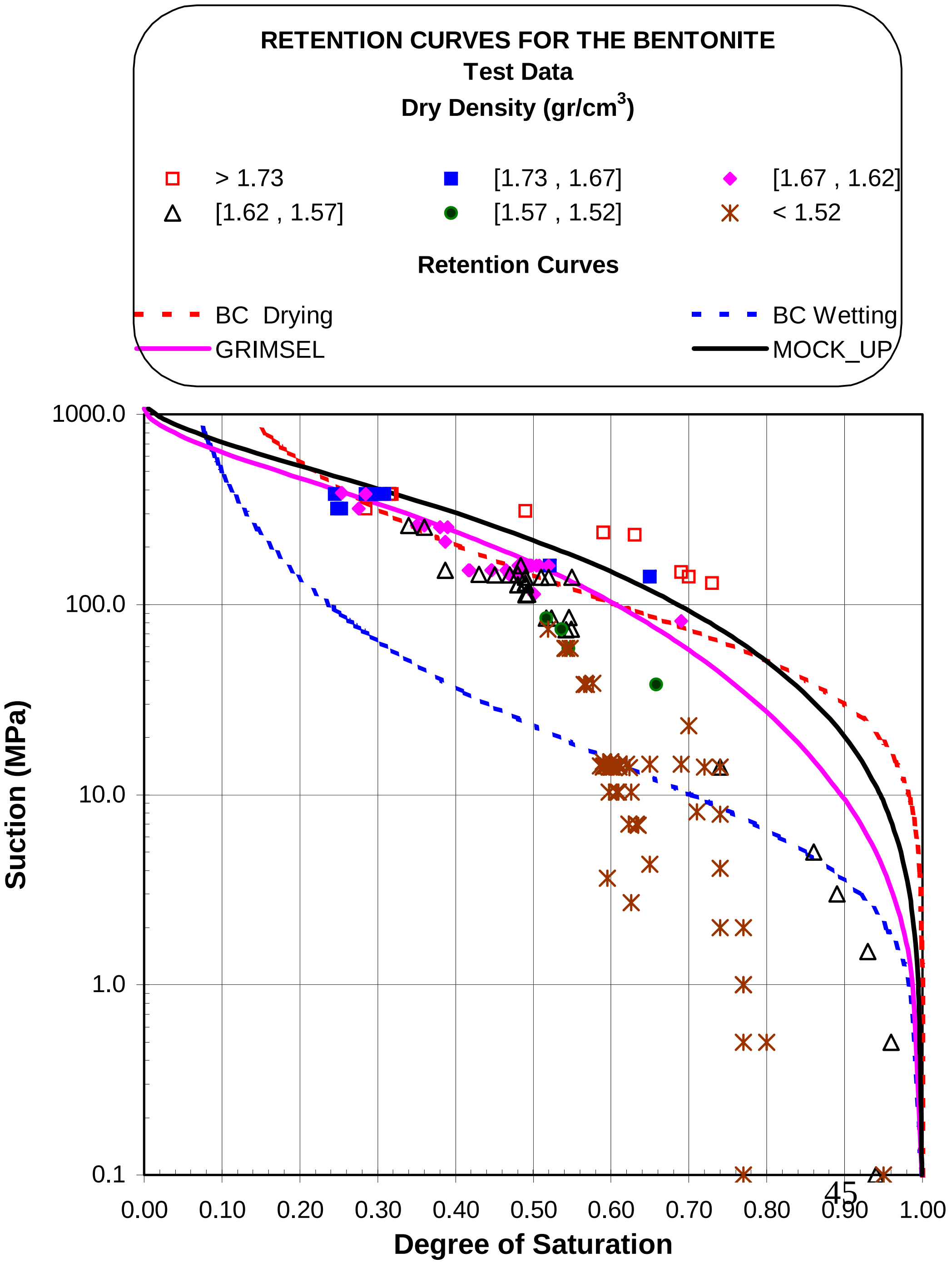
where σ is surface tension and r is the curvature radius of the meniscus.

Experimental retention curve

Van Genuchten law

Different densities

Swelling not permitted (except in low density samples)



Darcy's law

Advective fluxes of liquid and gas are calculated using darcy's law in the generalized form:

$$\mathbf{q}_\alpha = -\frac{\mathbf{k} k_{r\alpha}}{\mu_\alpha}\left(\nabla P_\alpha - \rho_\alpha \mathbf{g}\right)$$

Where α = *l, g* if the law is used for liquid or gas phase. Intrinsic permeability (**k**) relative permeability ($k_{r\alpha}$) and viscosity (μ_α) should be calculated.

Intrinsic permeability

This parameter depends primarily on the porous medium structure.

$$\mathbf{k} = \left[\mathbf{k}_o \frac{(1-\phi_o)^2}{\phi_o^{\ 3}}\right] \frac{\phi^3}{(1-\phi)^2} = \mathbf{a}\frac{\phi^3}{(1-\phi)^2}$$

where ϕ_o is a reference porosity and $\mathbf{k}_o$ is the intrinsic permeability at the reference porosity.

Intrinsic permeability

For a continuum medium (Kozeny's model)

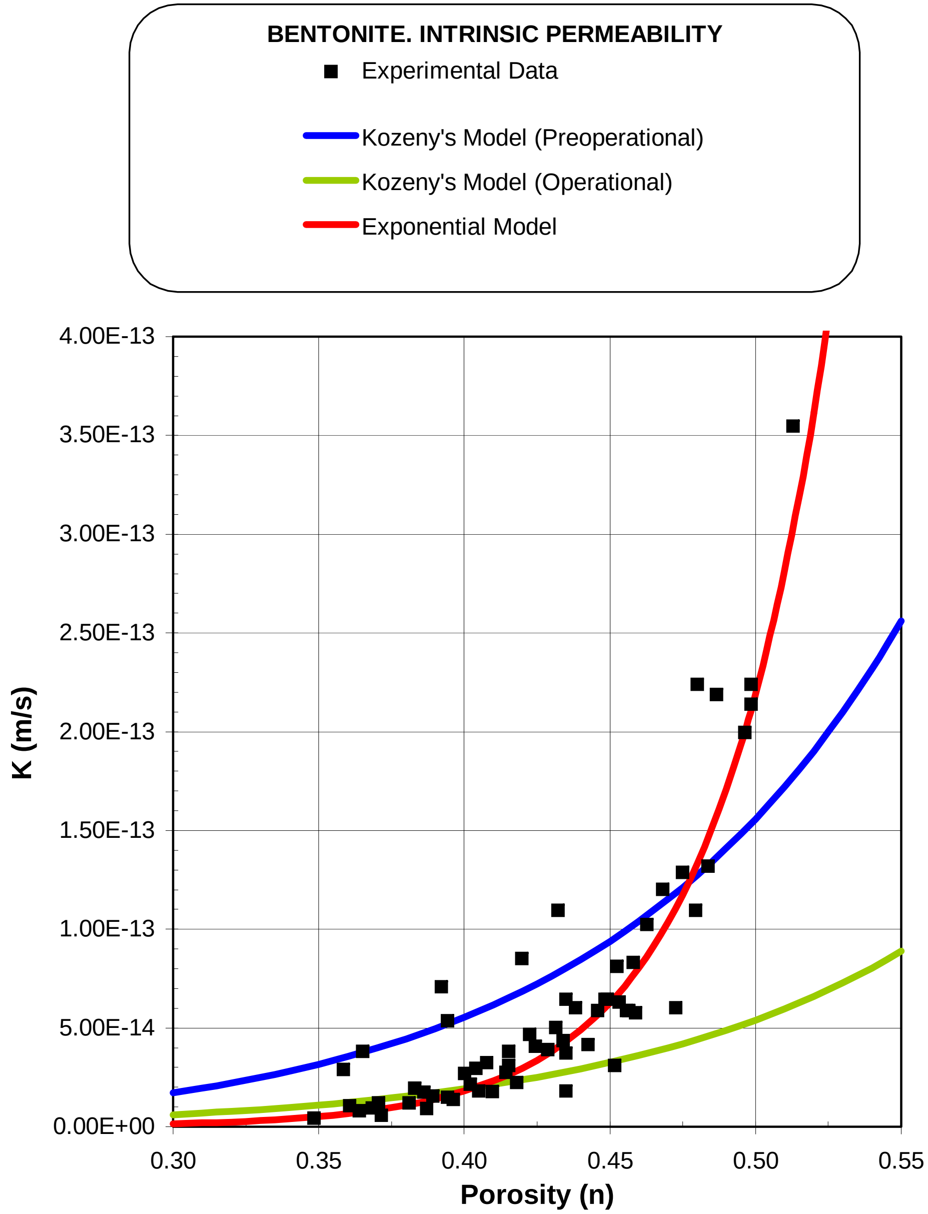
$$\mathbf{k} = \mathbf{k}_o \frac{\phi^3}{(1-\phi)^2} \frac{(1-\phi_o)^2}{\phi_o^{\ 3}}$$

ϕ_o : reference porosity

$\mathbf{k}_o$: intrinsic permeability for matrix ϕ_o

which is used in Darcy's law:

$$\mathbf{q}_\alpha = -\frac{\mathbf{k} k_{r\alpha}}{\mu_\alpha}\left(\nabla P_\alpha - \rho_\alpha \mathbf{g}\right)$$



Liquid viscosity

Water viscosity is required in Darcy's law.

$$\mu_l = A \exp\left(\frac{B}{273.15 + T}\right)$$

Where A = 2.1 10^{-2} MPa s and B = 1808.5 K^{-1}.

Gas viscosity

$$\mu_g = \frac{A\sqrt{273 + T}}{\left(1 + \frac{B}{273 + T}\right)} \frac{1}{1 + \frac{b_k}{P_g}} \qquad b_k = C - Dk \geq 0 \quad (k: \text{ intrinsic permeability})$$

Where A = 1.48 10^{-12} MPa s, B = 119.4 K^{-1}, C = 0.14 and D = 1.2 10^{15}. A reduction coefficient takes into account the possibility of Knudsen diffusion (Klinkenberg effect). As the mean free path of the gas particles becomes comparable to the pore size (low permeability material) slip effects (non laminar flow) may result in an apparent lower viscosity (apparent higher gas conductivity).

$$\mathbf{q}_\alpha = -\frac{\mathbf{k}k_{r\alpha}}{\mu_g^o}\left(1 + \frac{b_k}{P_g}\right)\left(\nabla P_\alpha - \rho_\alpha \mathbf{g}\right) = -\frac{\mathbf{k}k_{r\alpha}}{\mu_g^o}\left(\nabla P_\alpha - \rho_\alpha \mathbf{g}\right) - \left(\frac{\mathbf{k}k_{r\alpha}}{\mu_g^o}\frac{b_k}{P_g}\right)\left(\nabla P_\alpha - \rho_\alpha \mathbf{g}\right)$$

Fick's Law. Molecular Diffusion

To calculate vapor and dissolved air migration:

$$\mathbf{i}_{\alpha}^{i} = -\left(\phi \rho_{\alpha} S_{\alpha} \tau D_{m}^{i} \mathbf{I}\right) \nabla \omega_{\alpha}^{i}$$

where α=*l*, *g* and *i*=*a, w* depending if diffusion takes place in the liquid (dissolved air) or in the gas phase (vapor).

$$D_{m}^{vap} = D\left(\frac{\left(273+T\right)^{n}}{P_{g}}\right)$$

where τ is a tortuosity reduction coefficient, $D = 5.9\ 10^{-6}$ m^2/s/K^{-n}Pa and n=2.3.

In the case of dissolved air, the following expression is used for molecular diffusivity:

$$D_{m} = D \exp\left(\frac{-Q}{R\left(273+T\right)}\right)$$

Where τ is a tortuosity reduction coefficient, $D = 1.1\text{x}10^{-4}$ m^2/s and Q =24530 J/mol.

Mechanical constitutive model

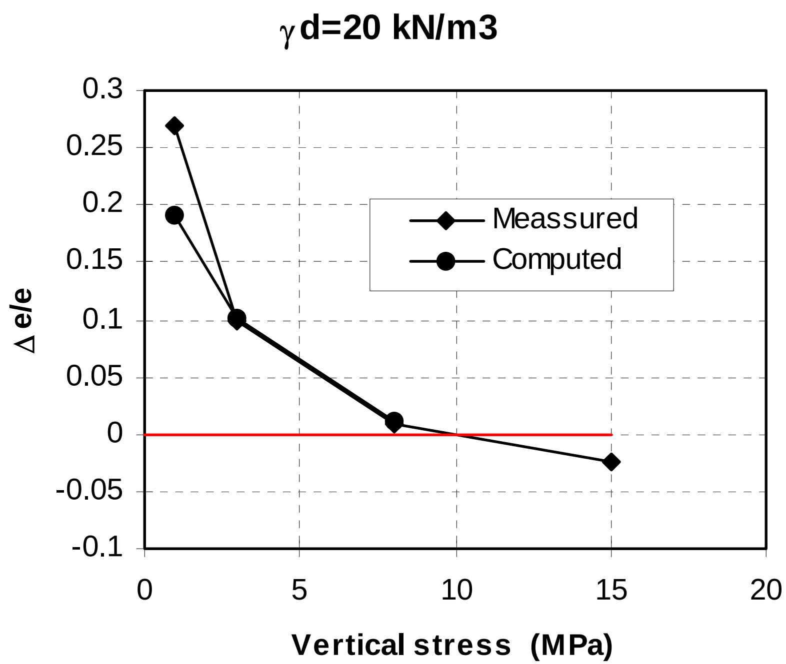
Stress-strain relationship: irreversible

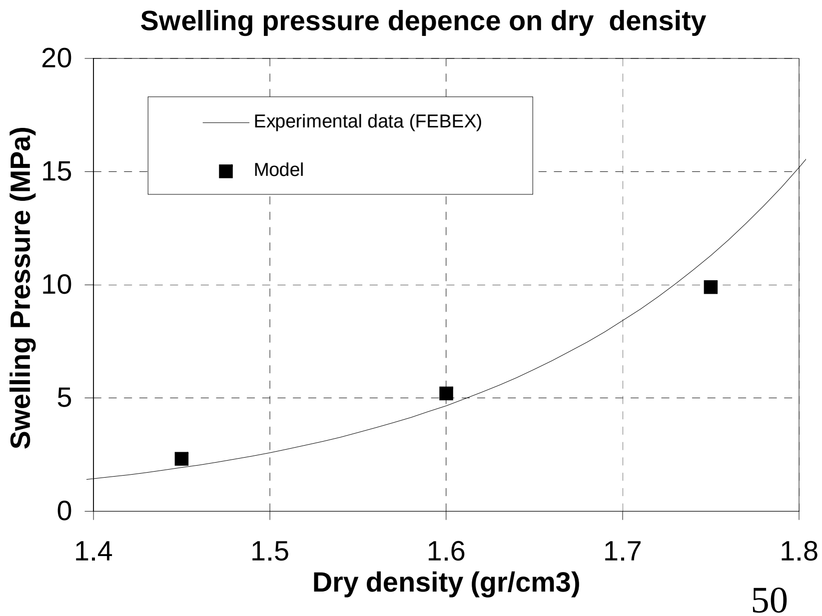
Suction induces swelling and/or collapse

Strength depends on suction

Effective stress, suction, temperature

Nonlinear laws

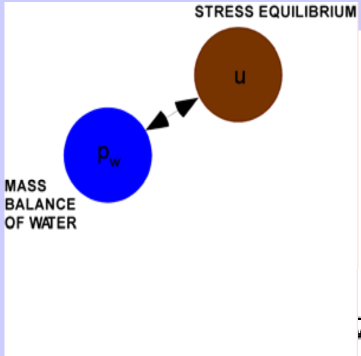


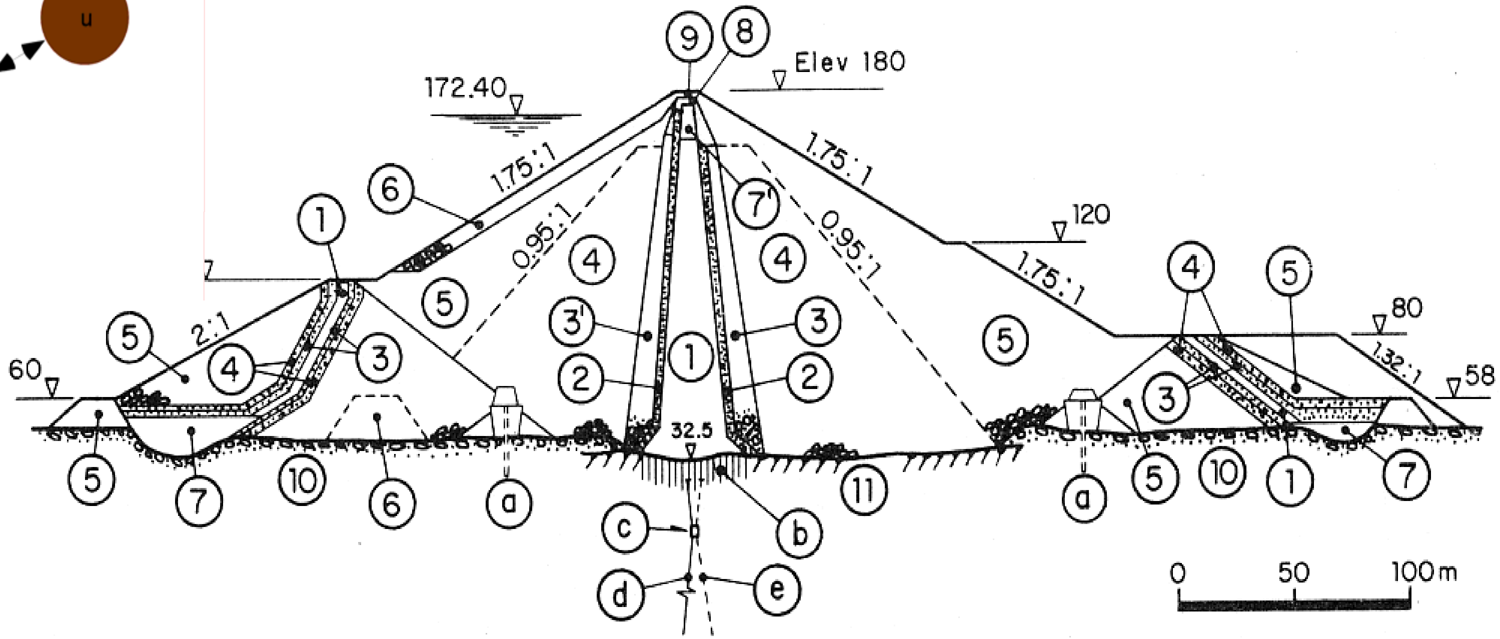


3. Algunos ejemplos

- Earth dams (2 types)
- Two phase flow
- Rock deformation at great depth
- Radioactive Waste disposal

HM problem: earth dams





a Pantallas de concreto (pilotes secantes)
Cut-off wall (secant piles)

b Tapete de inyecciones
Grout blanket

c Galería G-4
Gallery G-4

d Perforaciones de inyección
Grout holes

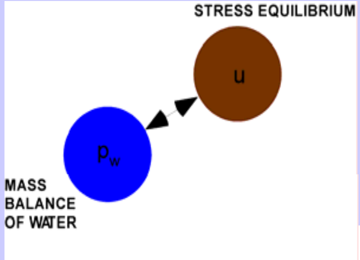
e Perforaciones para drenaje
Drainage holes

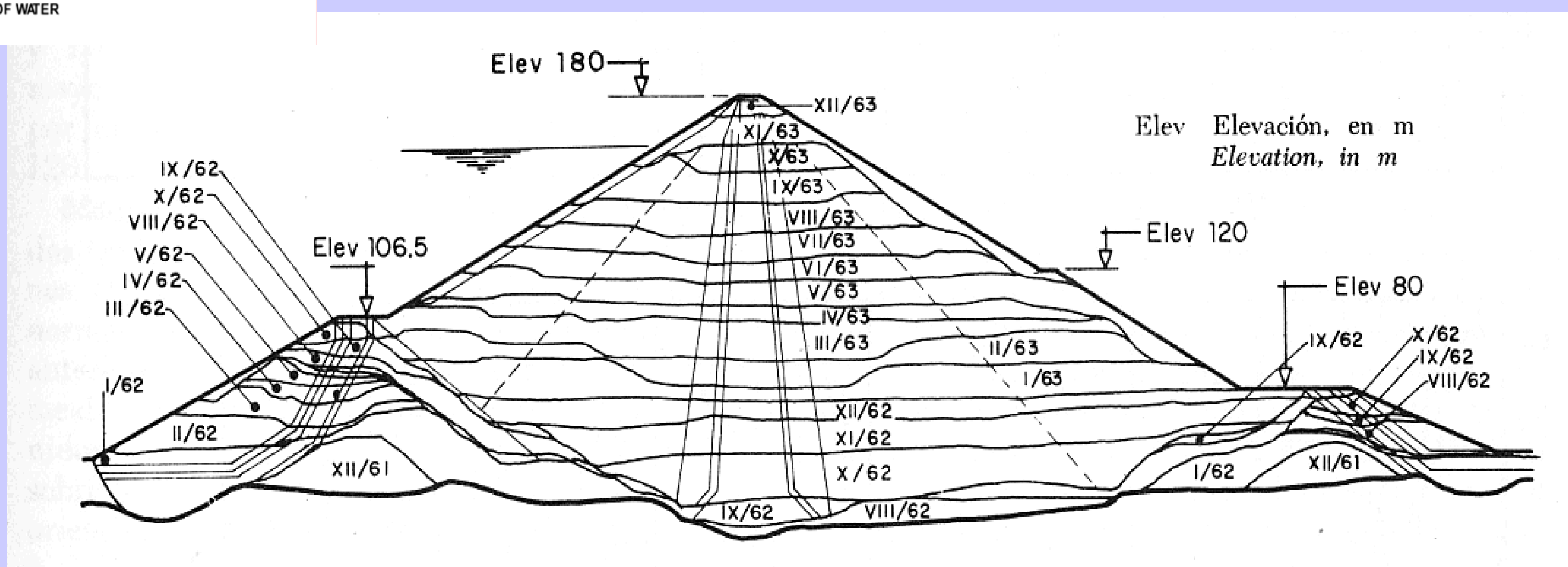
Elev Elevación, en m
Elevation, in m

Nota: La numeración se describe en la tabla 7.1
Note: See table 7.1 for materials description

El Infiernillo, Mexico

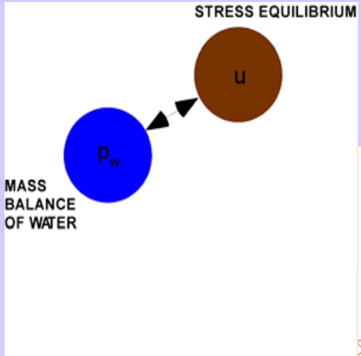
HM problem: earth dams

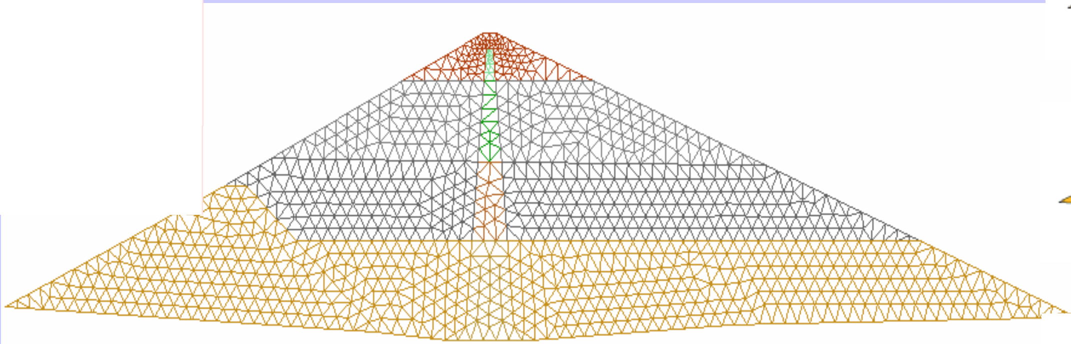


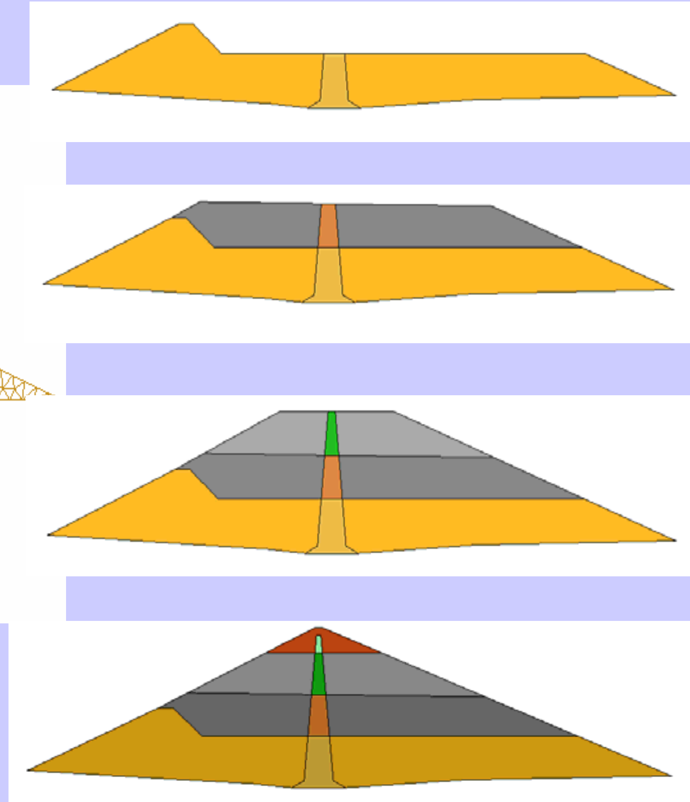


Construction history

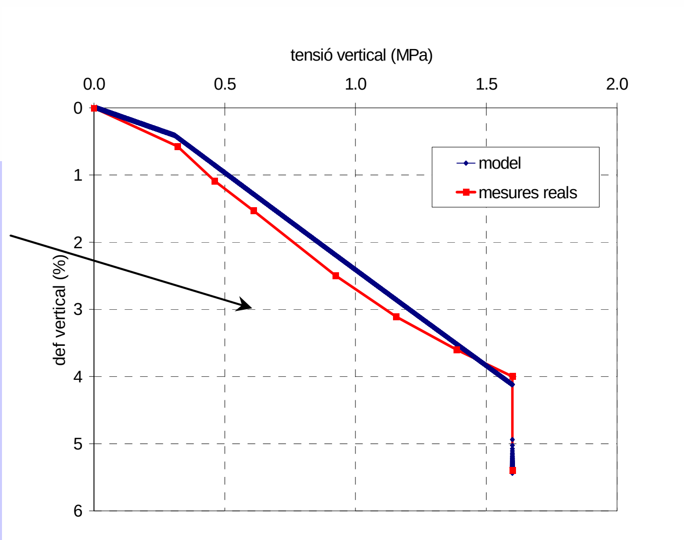
HM problem: earth dams



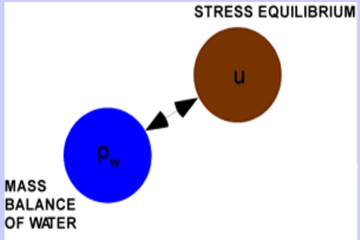


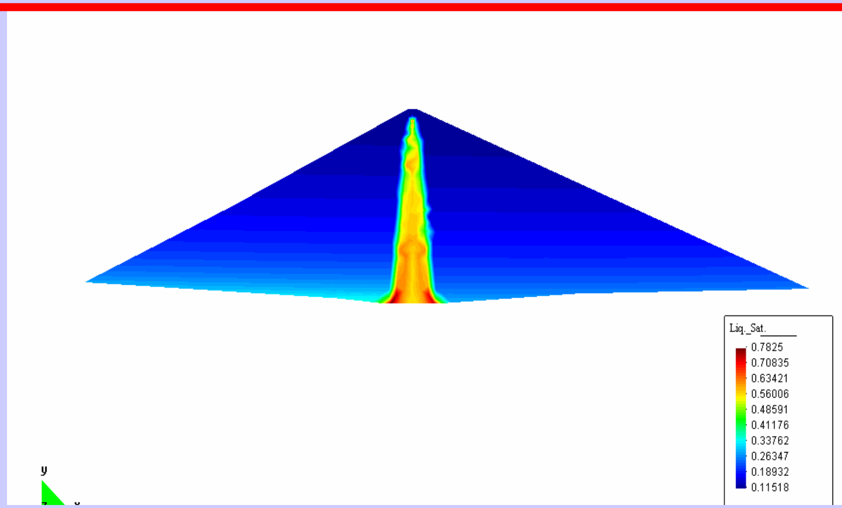


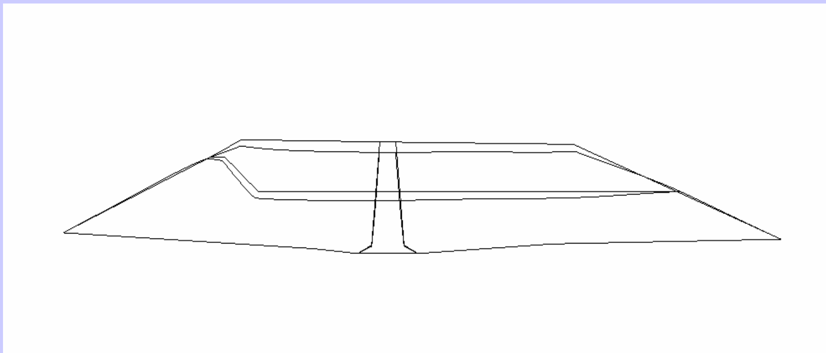
Compression and collapse

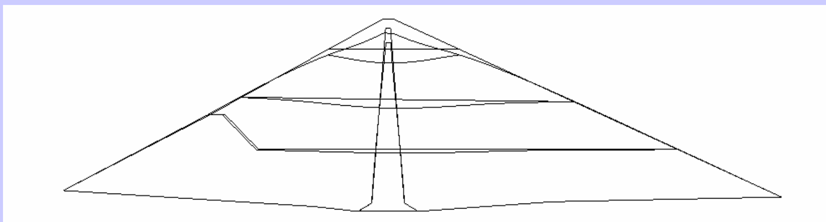


HM problem: earth dams

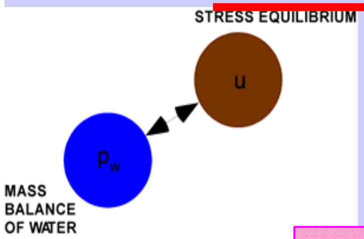


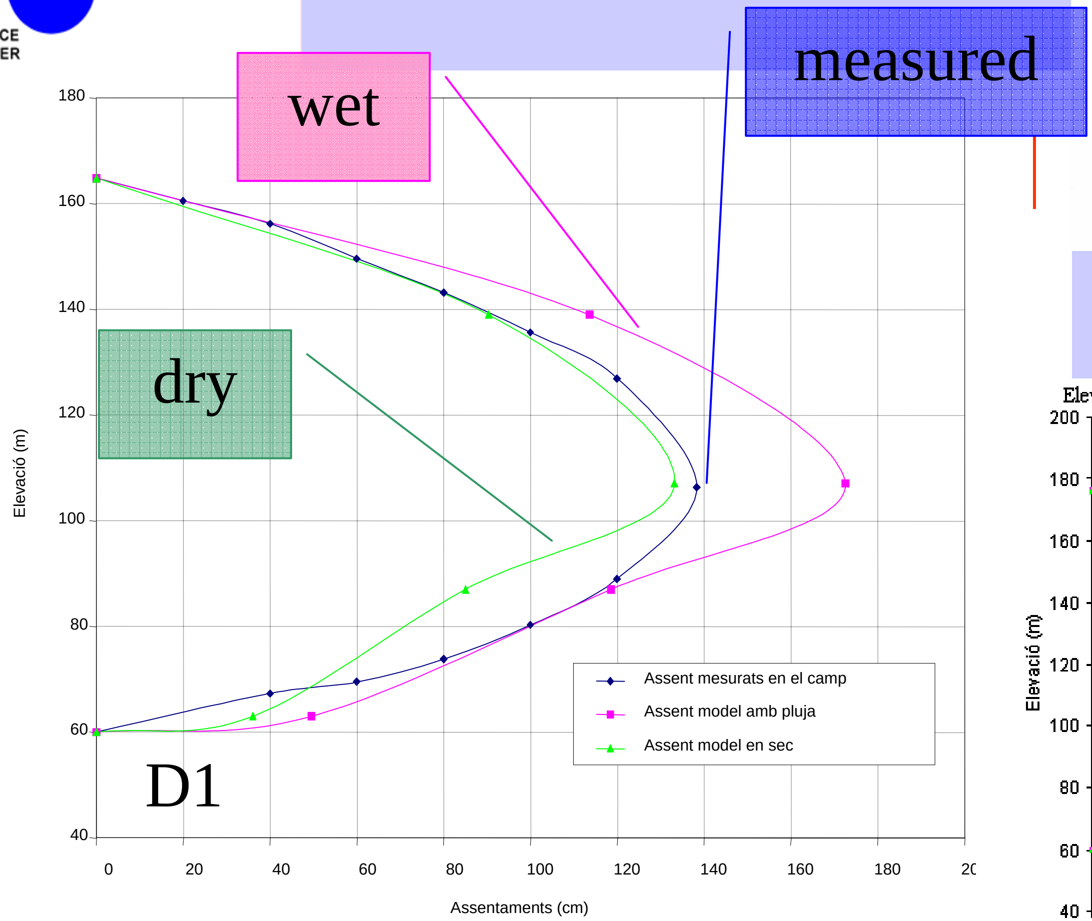


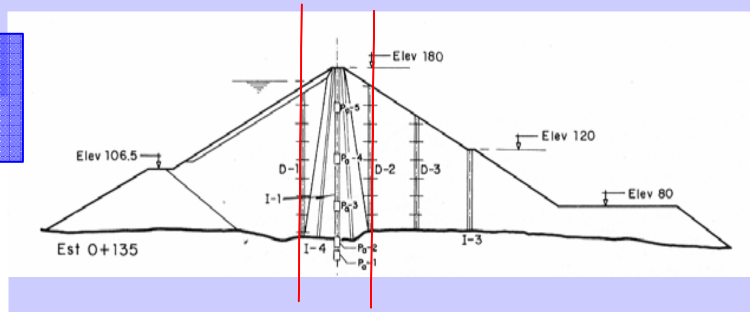


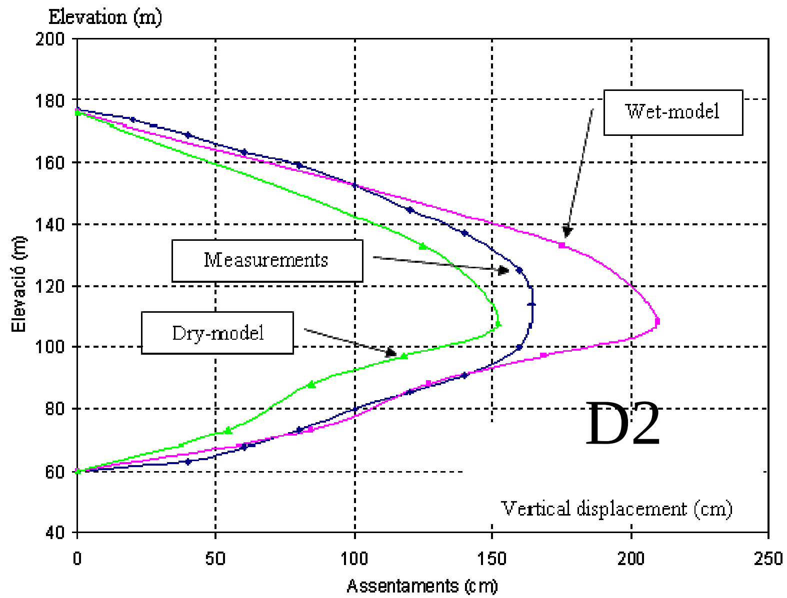


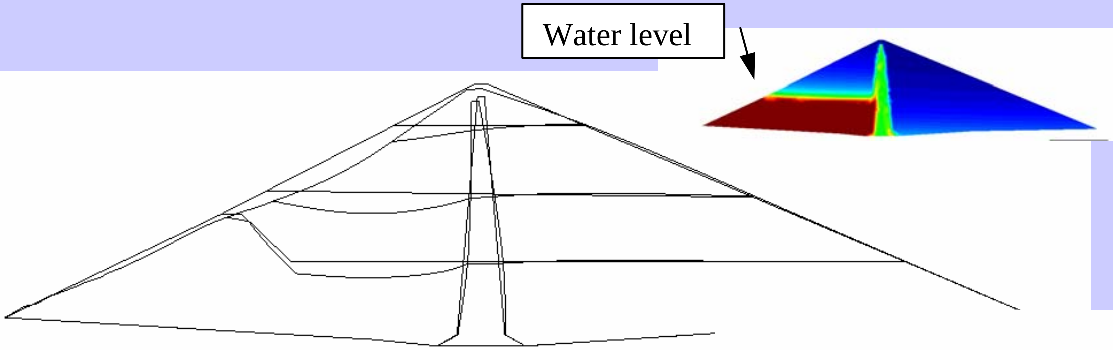
HM problem: dam construction

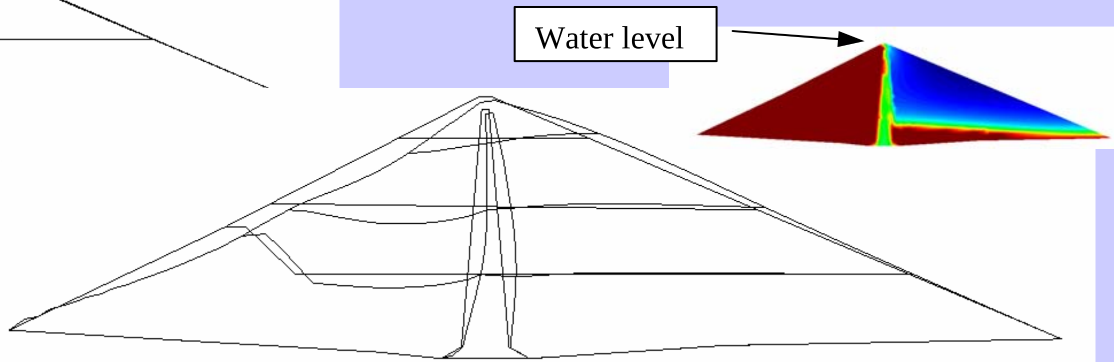


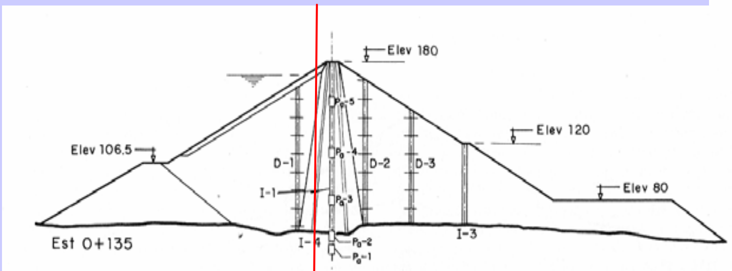


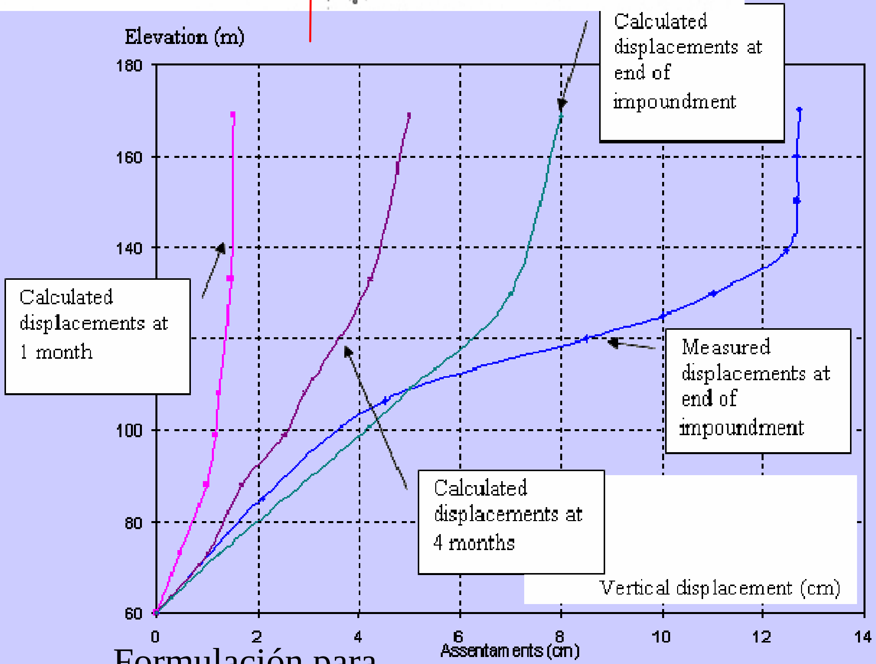


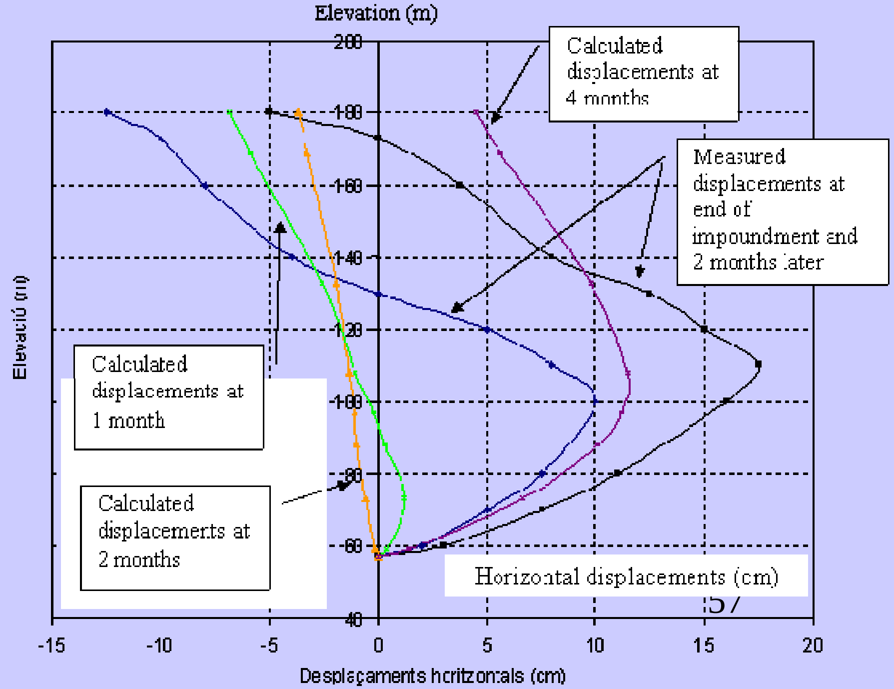






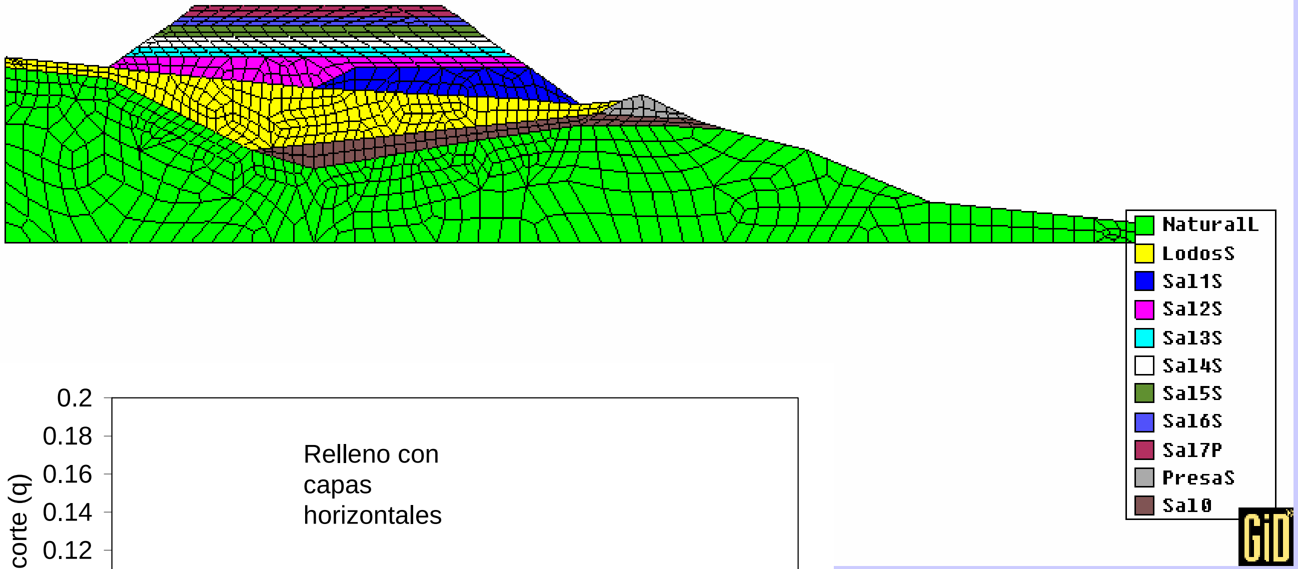


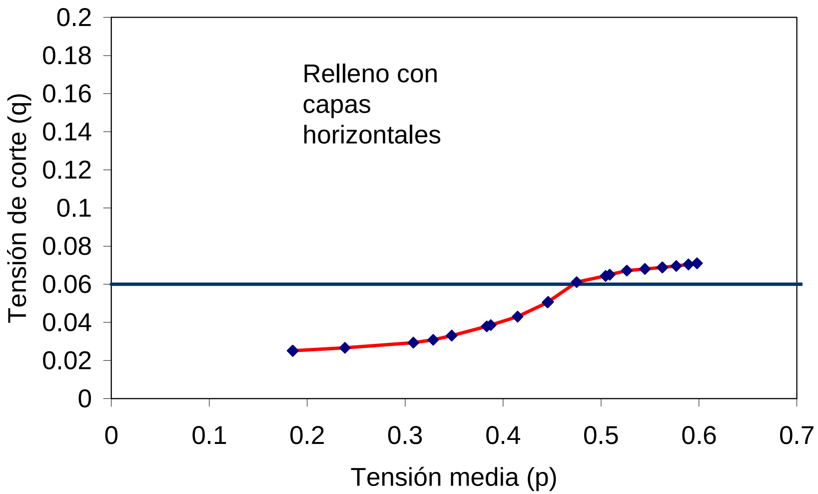


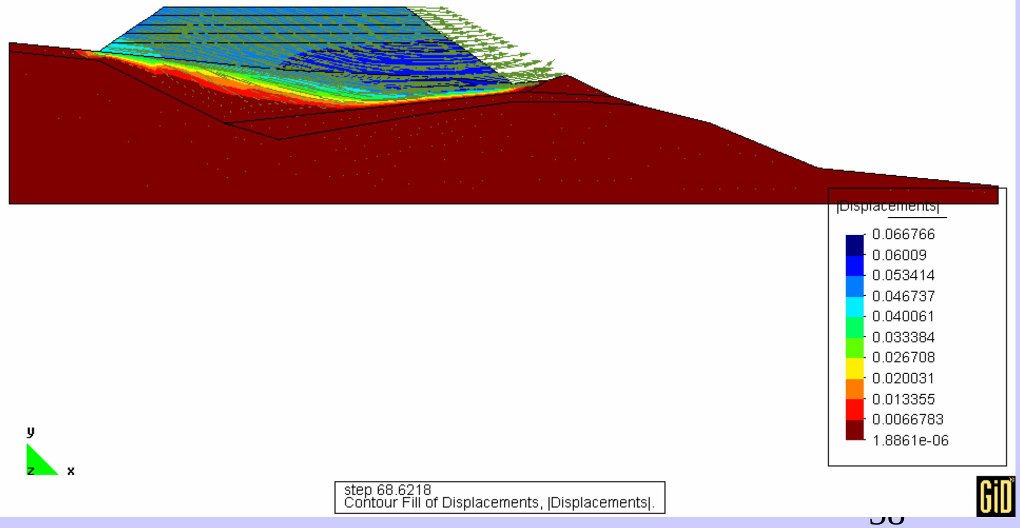


Formulación para problemas THM

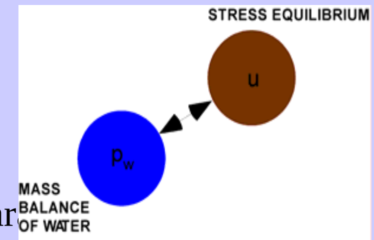
M y HM: Escombrera de residuos salinos sobre lodos mineros





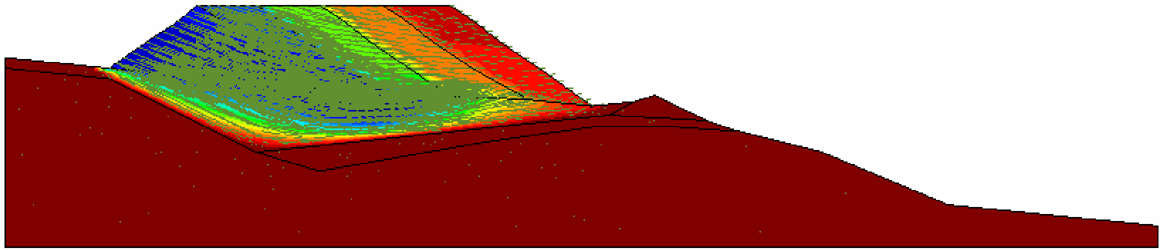


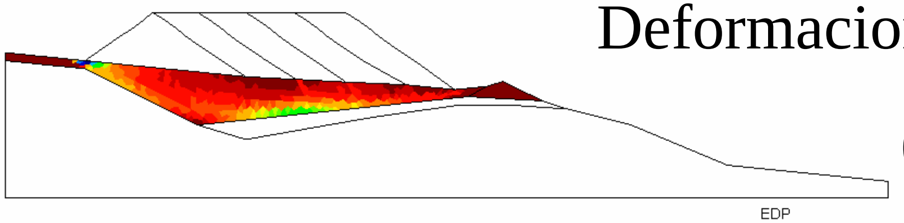
Cu = 30 kPa



Formulación par
problemas THM

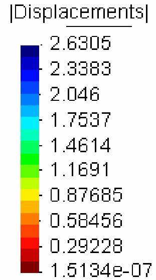
No drenado



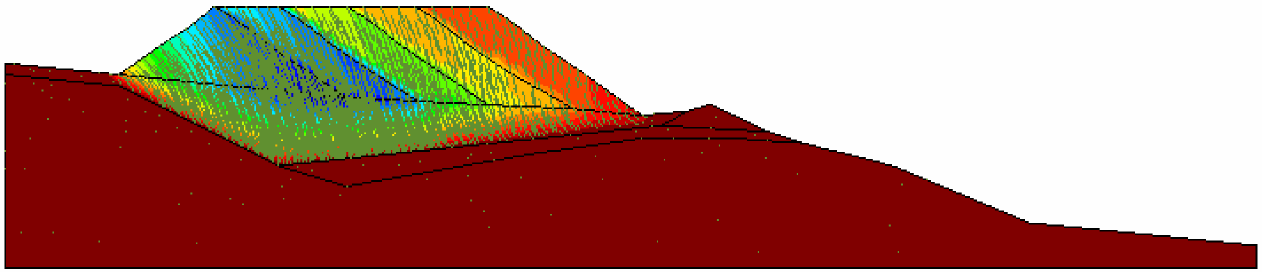


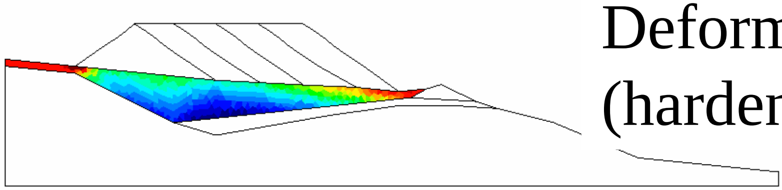
Deformaciones de corte.

(Vol =0)

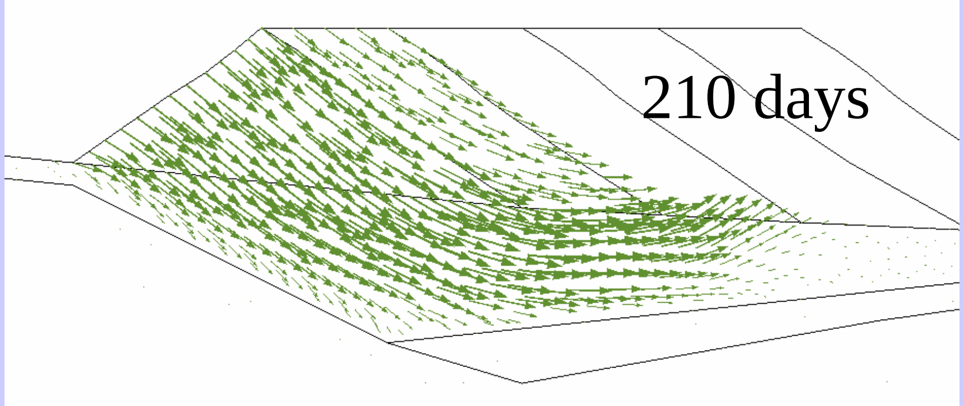


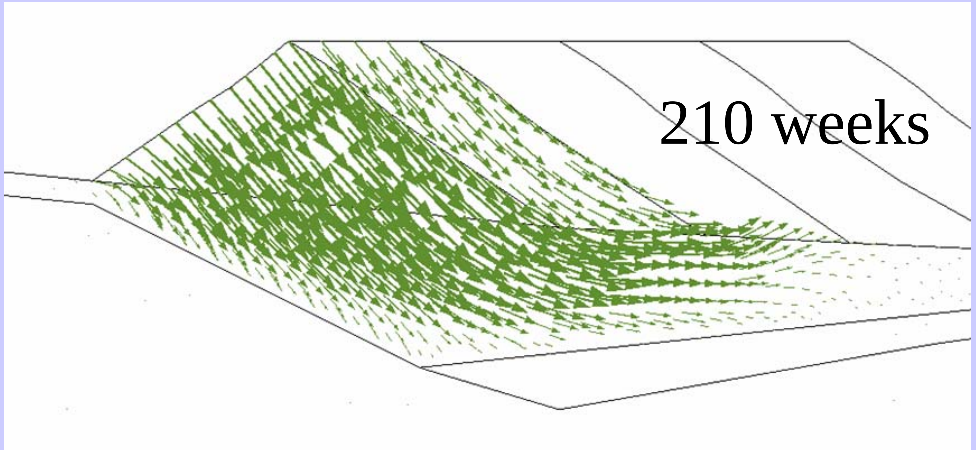
Drenado

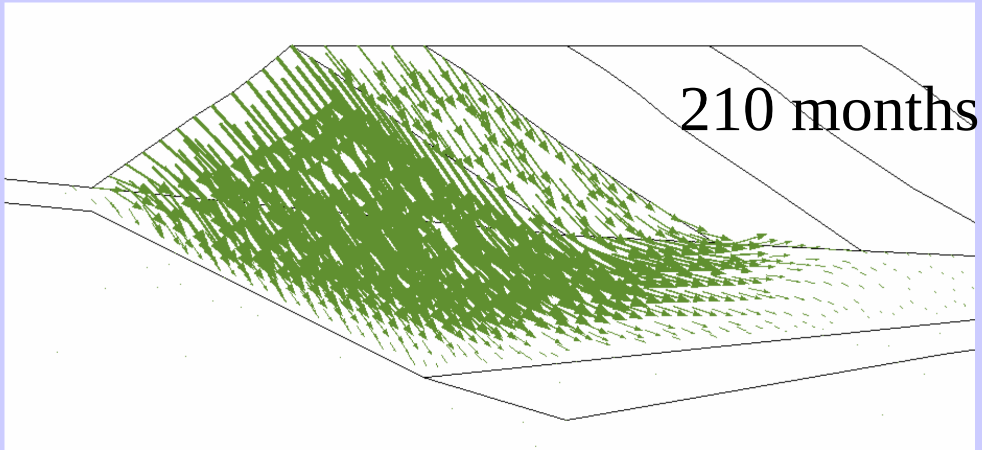




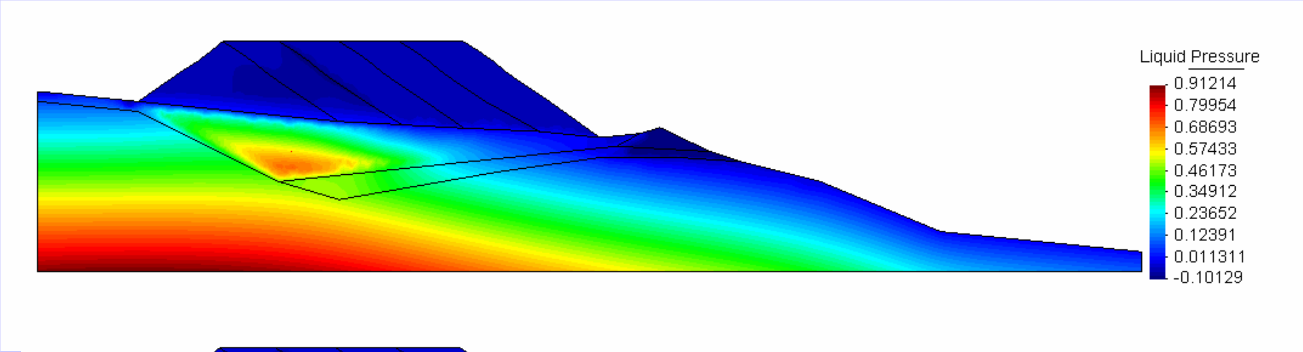
Deformaciones volumetricas (hardening)



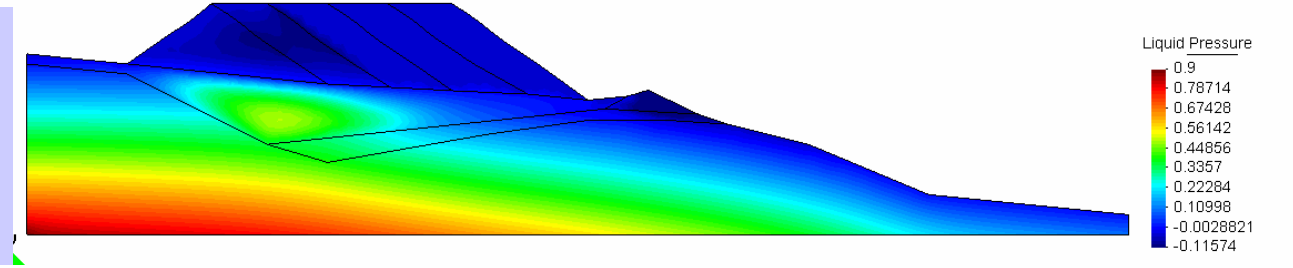




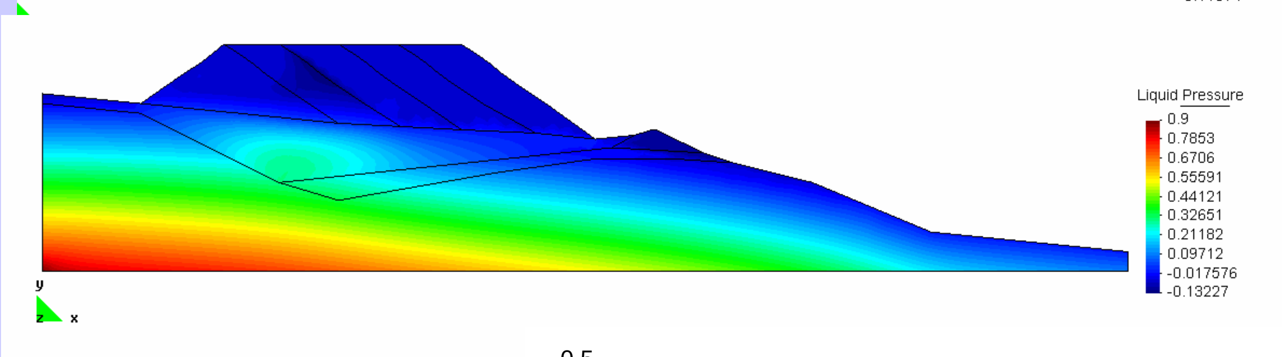
Desplazamientos para los casos analizados con 210 días (rápido), 210 semanas (lento) y 210 meses (muy lento) al final de la colocación de la 2ª etapa.



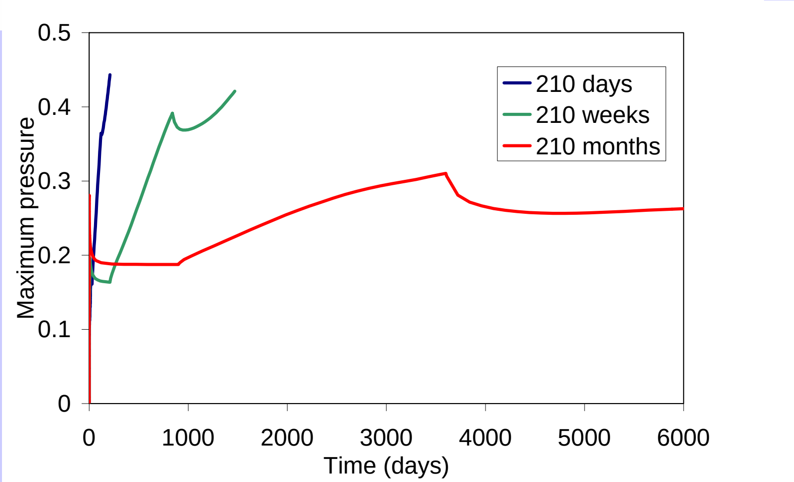
210 days

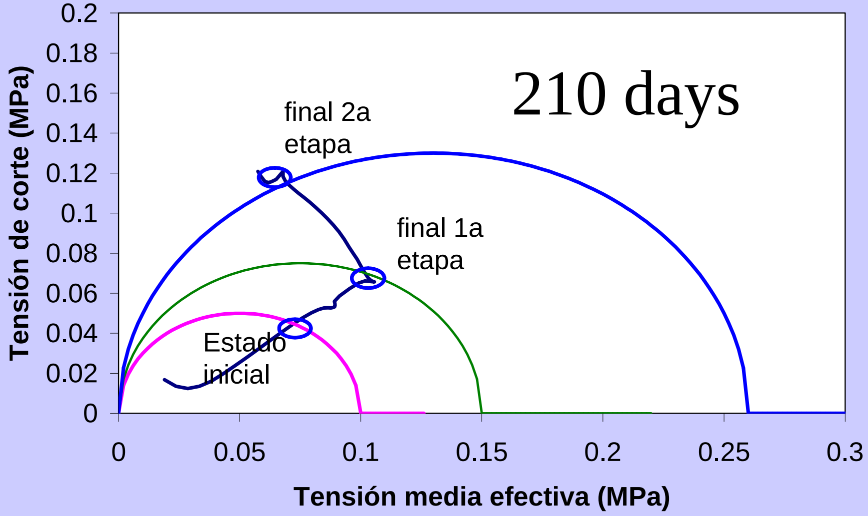


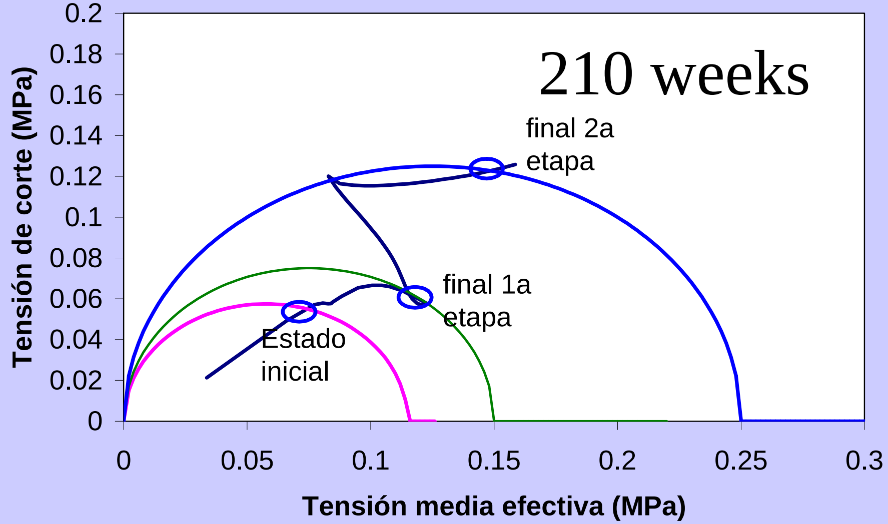
210 weeks

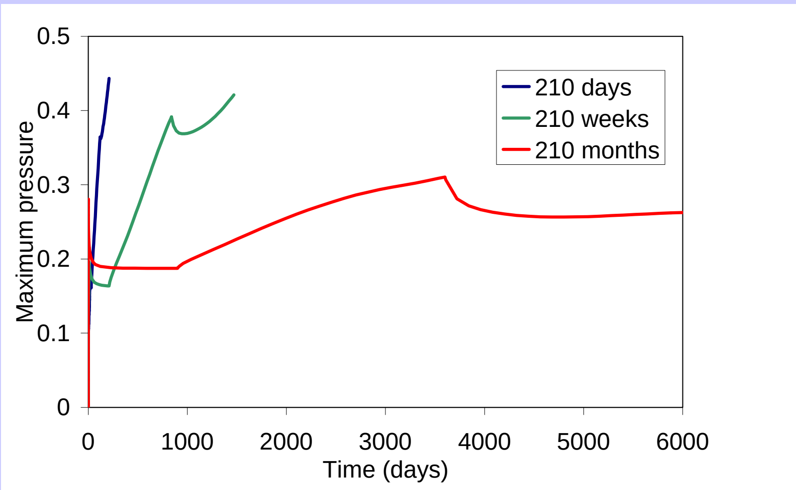


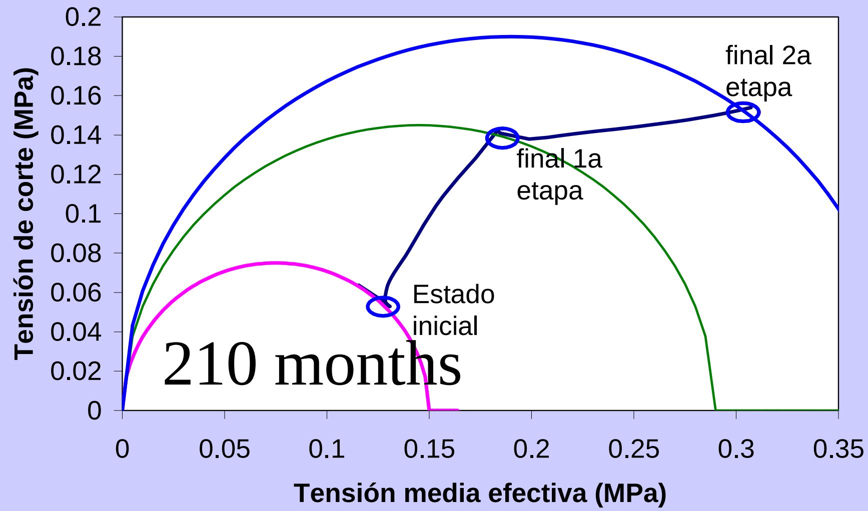
210 months



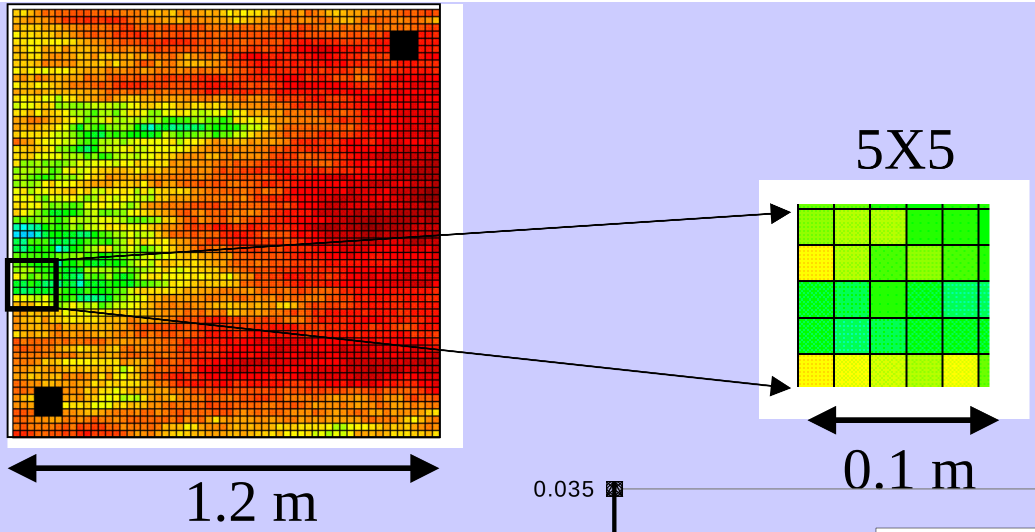

210 days
final 2a
etapa
final 1a
etapa
Estado
inicial
Tensión de corte (MPa)
Tensión media efectiva (MPa)
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2
0 0.05 0.1 0.15 0.2 0.25 0.3

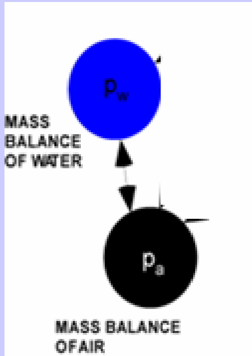

210 weeks
final 2a
etapa
final 1a
etapa
Estado
inicial
Tensión de corte (MPa)
Tensión media efectiva (MPa)
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2
0 0.05 0.1 0.15 0.2 0.25 0.3

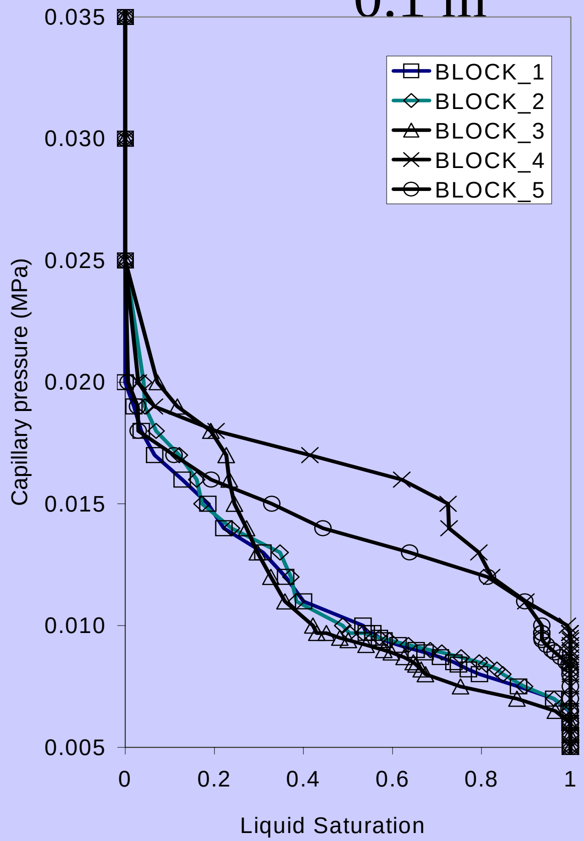

210 days
210 weeks
210 months
Maximum pressure
Time (days)
0 0.1 0.2 0.3 0.4 0.5
0 1000 2000 3000 4000 5000 6000

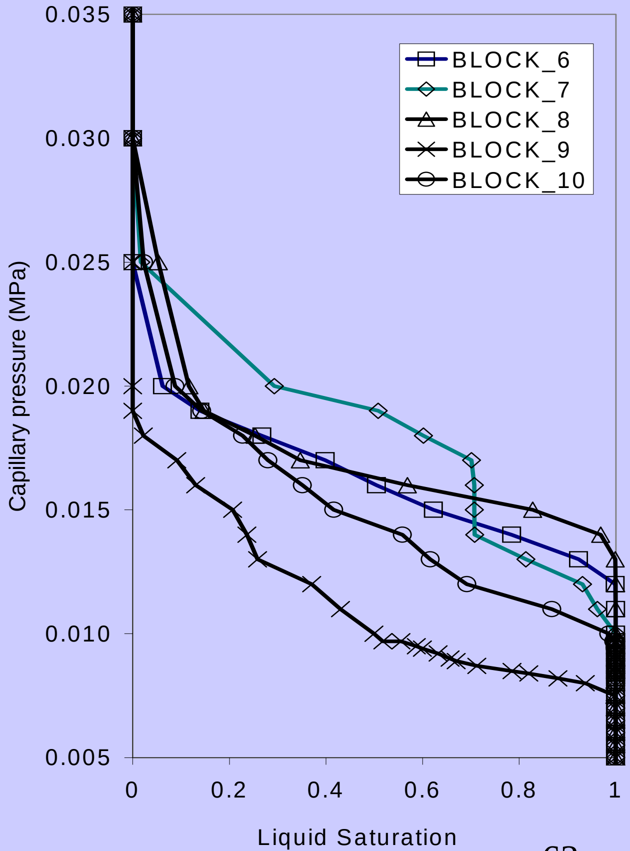

210 months
final 2a
etapa
final 1a
etapa
Estado
inicial
Tensión de corte (MPa)
Tensión media efectiva (MPa)
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35

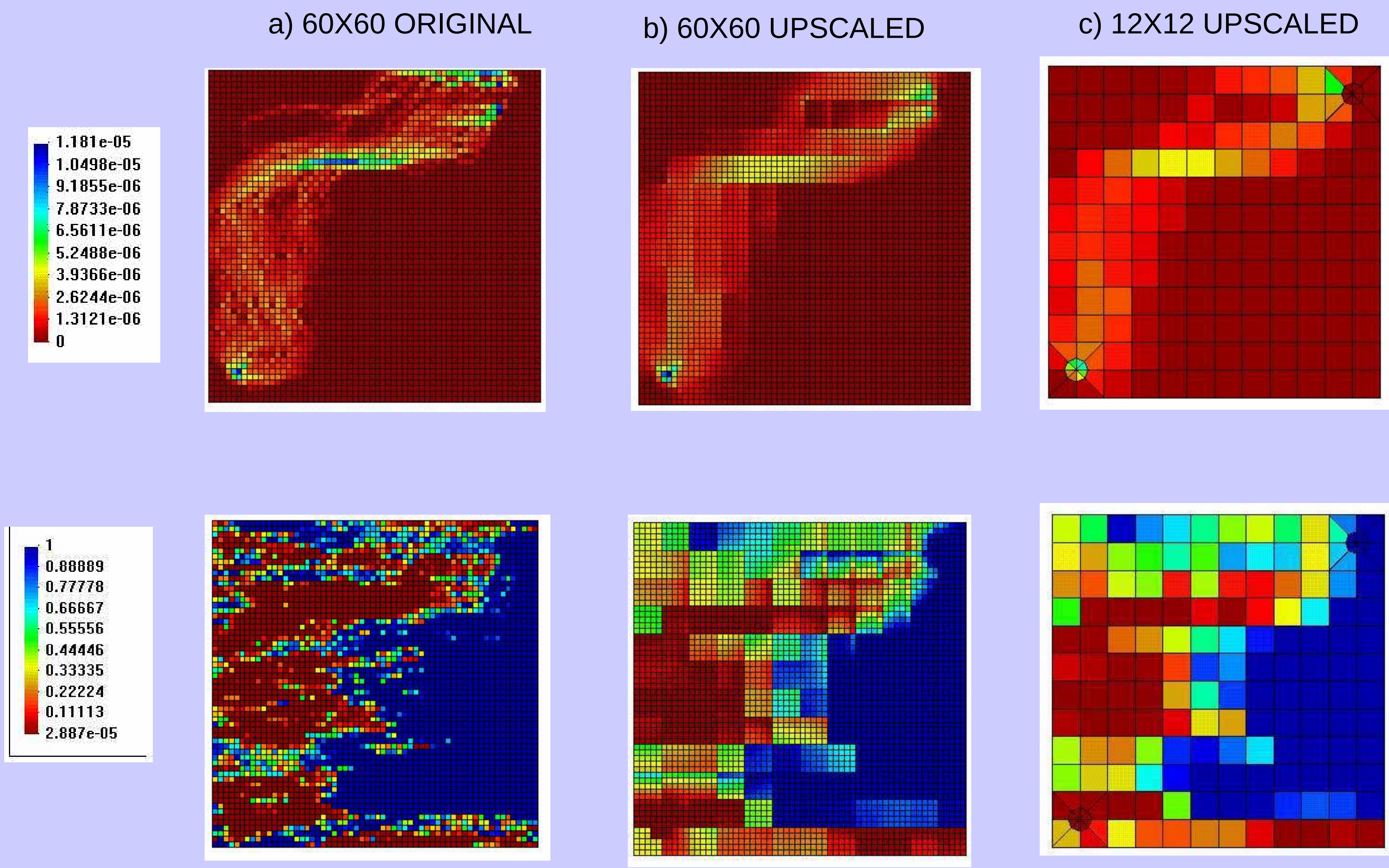
H: GAS AND WATER FLOW IN A PLANAR FRACTURE. THE UPSCALING PROBLEM





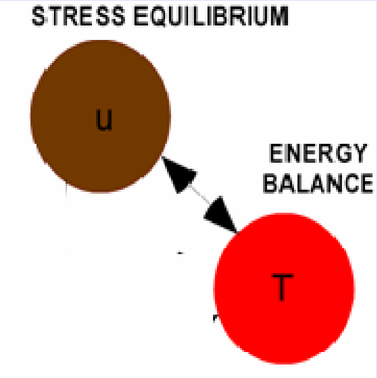


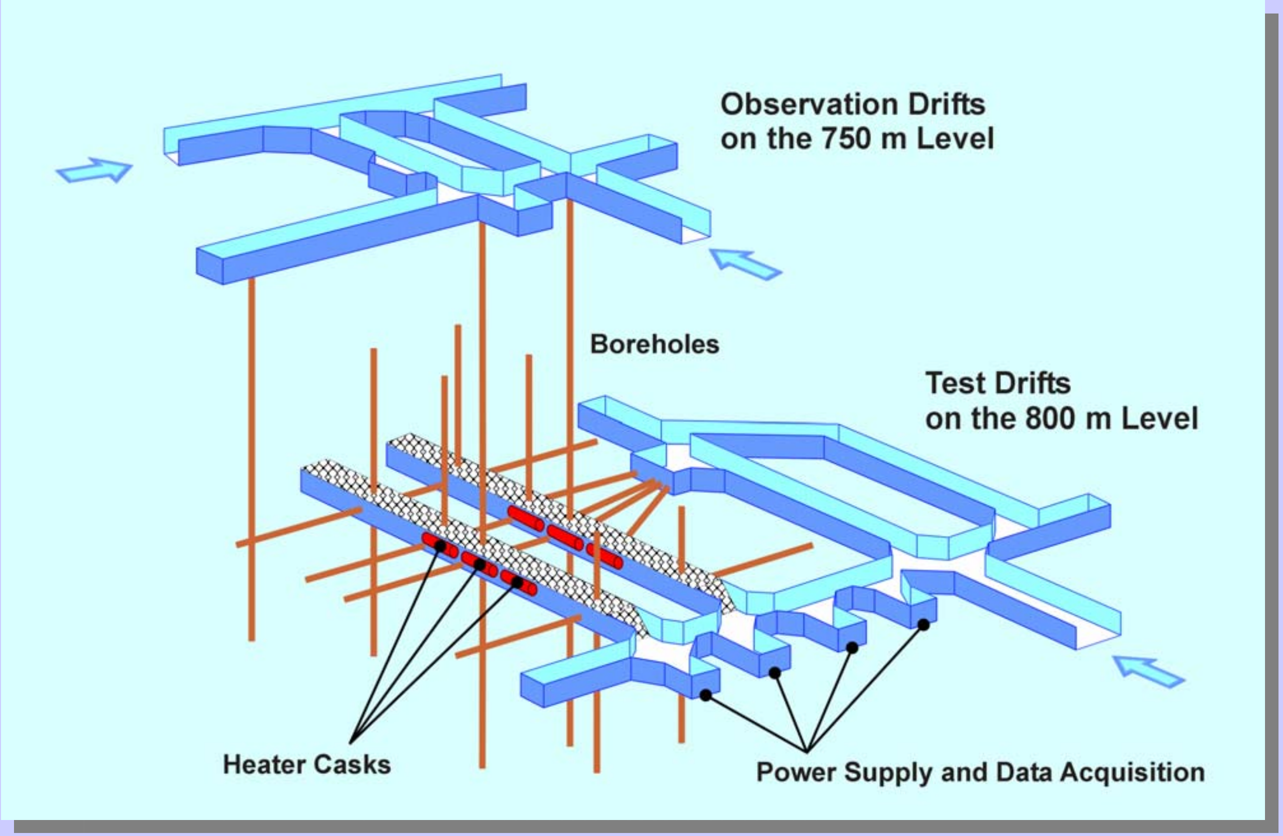




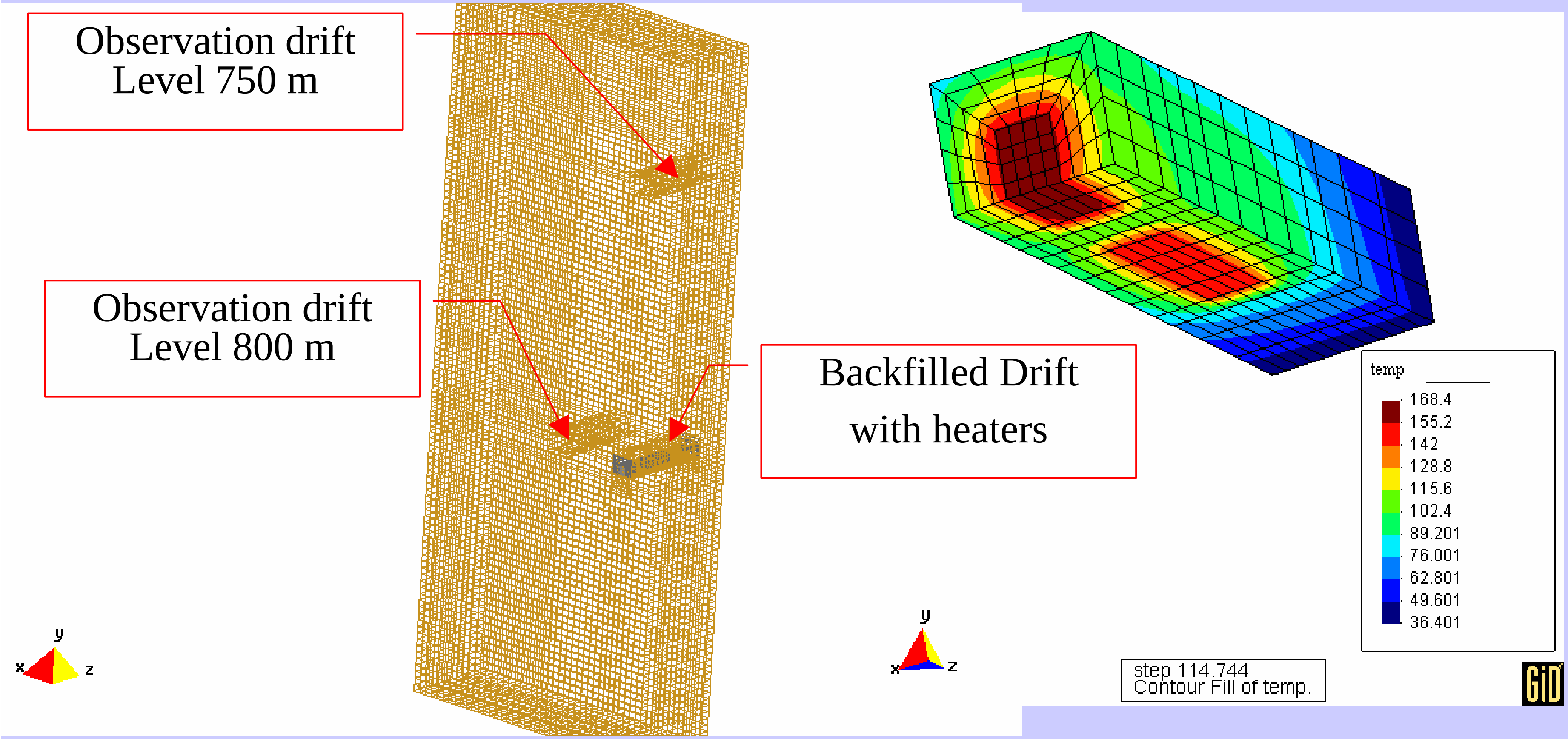
Gas fluxes and degree of saturation

TM: ROCK SALT IN SITU TEST

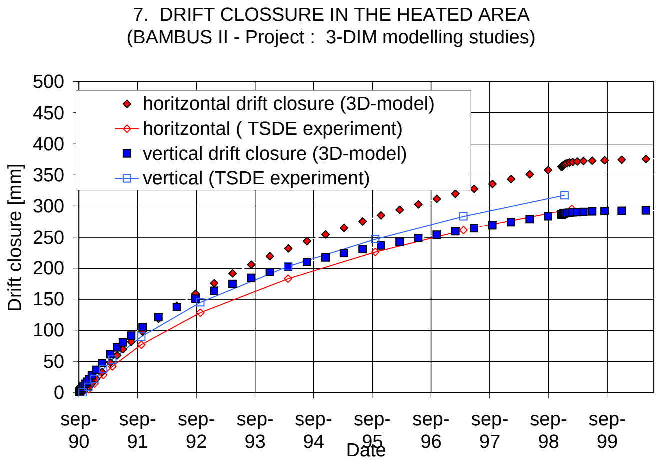




BAMBUS-I and BAMBUS-II: EC research project

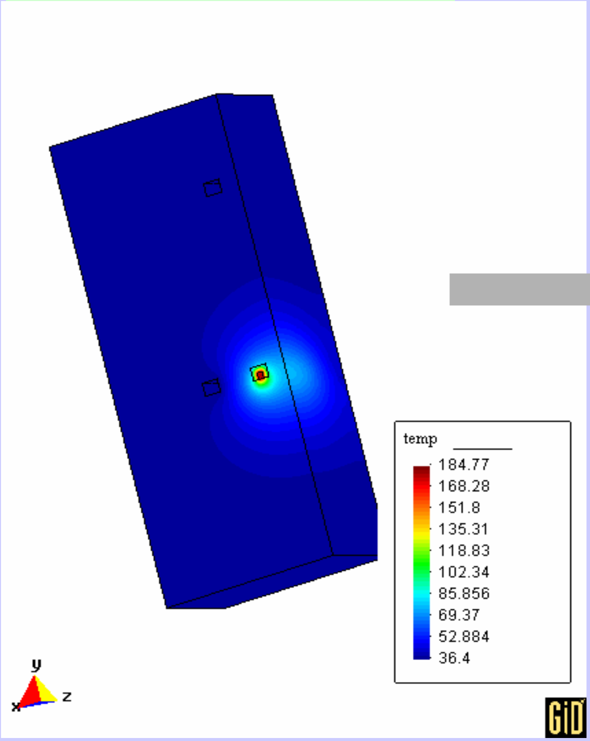


Features: Tunnel + Observation drifts, σ_{conf}= 12 MPa, Axial length: 25 m, hexaedral elements, regular mesh, 65,954 nodal points x 4 dof = 263,816 dof

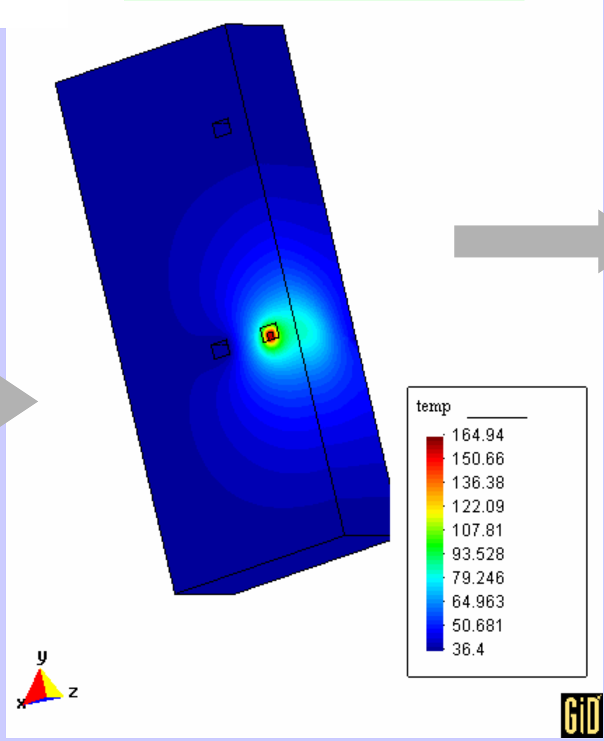


Temperature evolution (whole model)

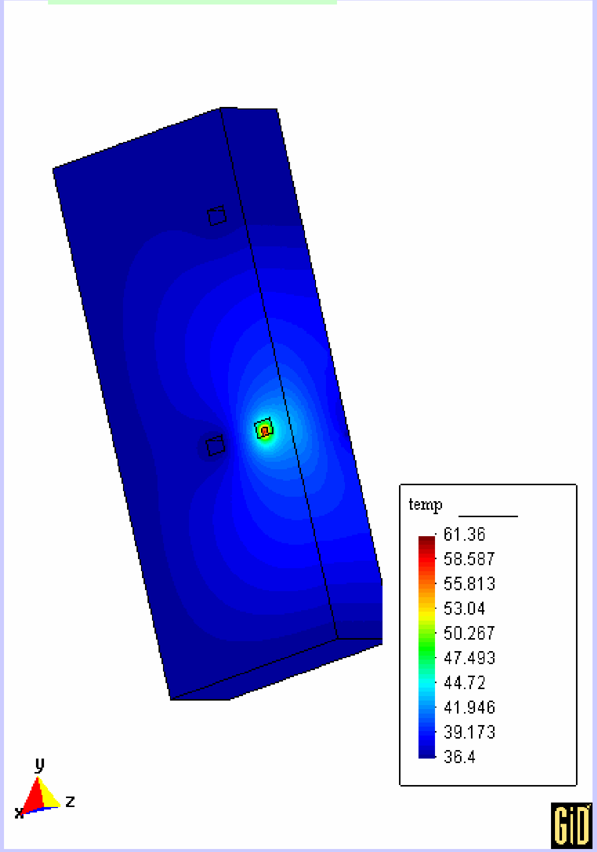
1.5 years of heating



9 years of heating

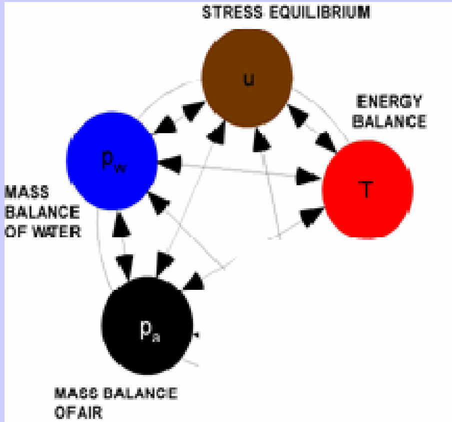


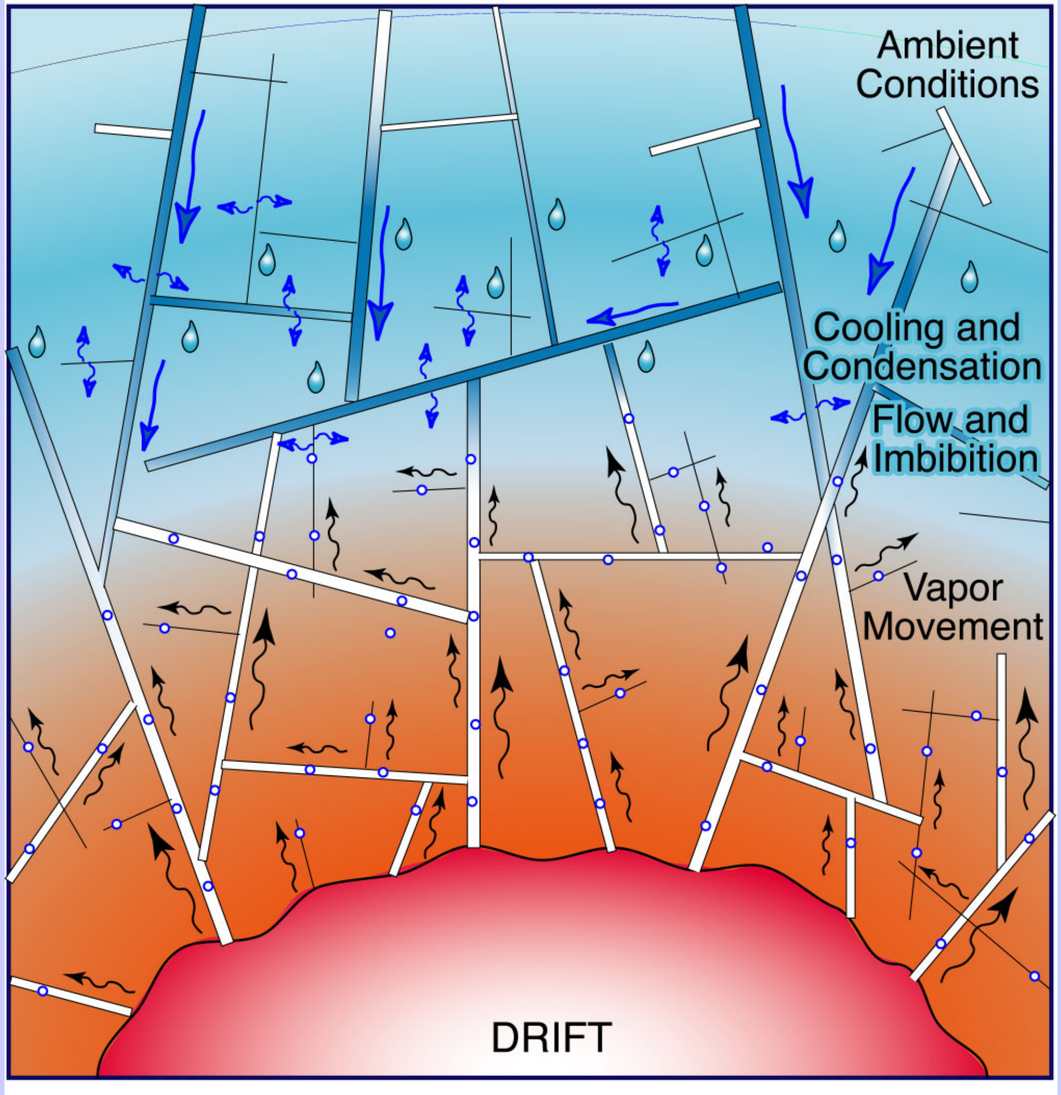
end process



(THM) Residuos Radioactivos en Roca fracturada

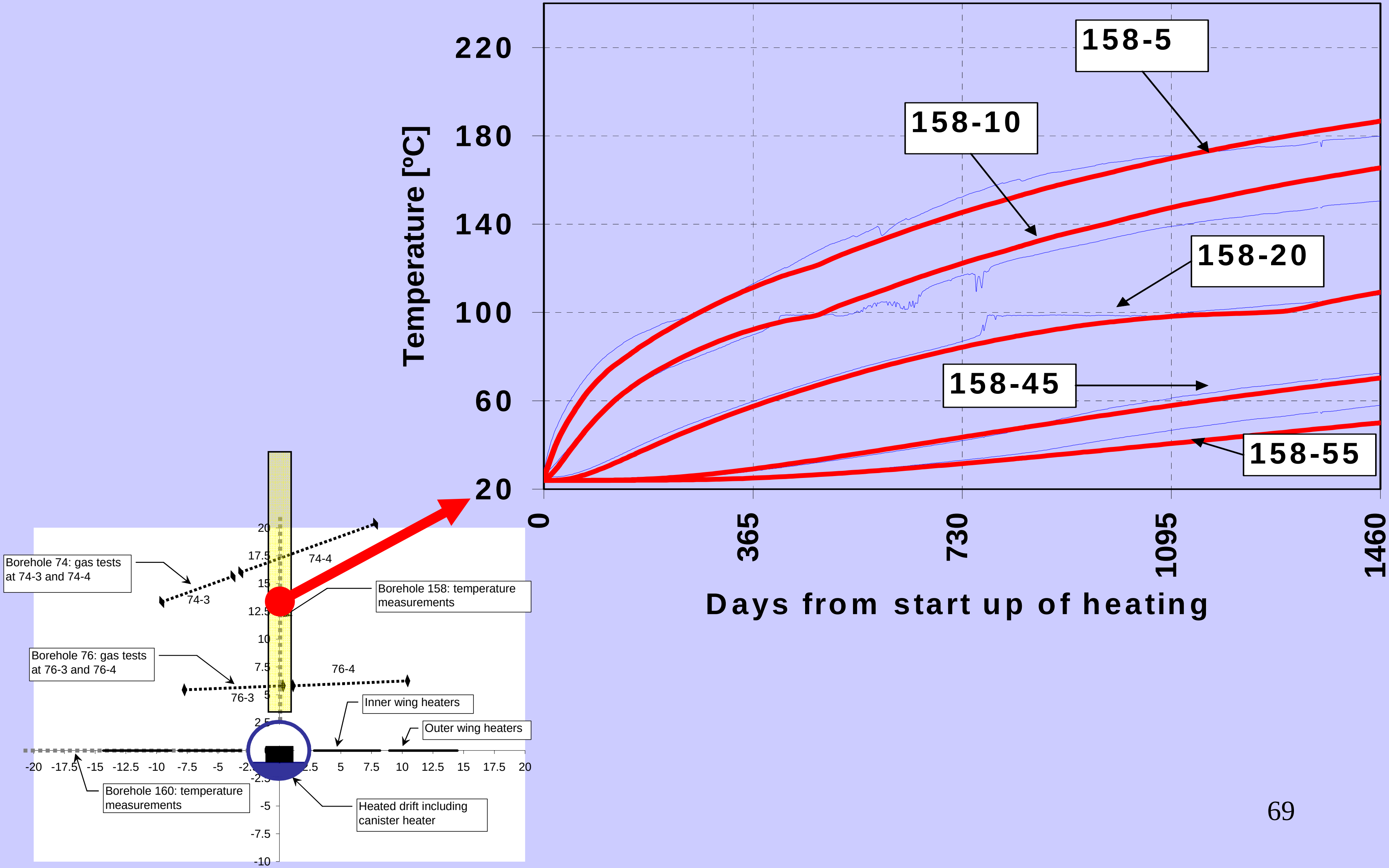
- Evaporation and condensation of water (fractured rock)





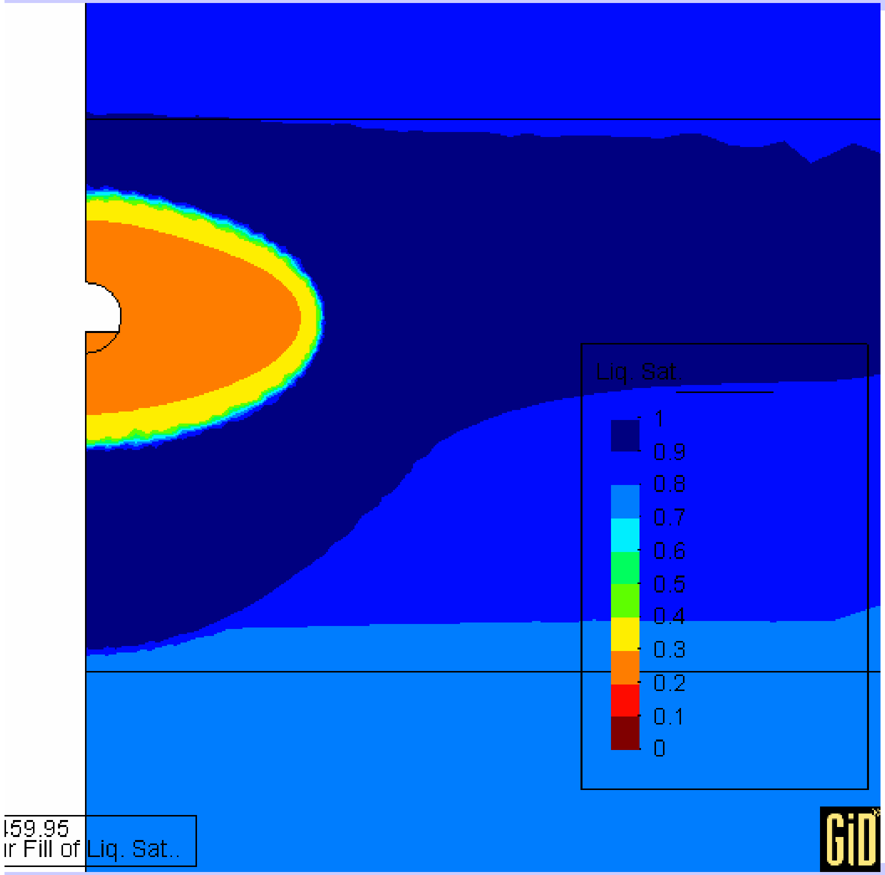
J. Rutqvist & C.-F. Tsang (2003)

Temperaturas



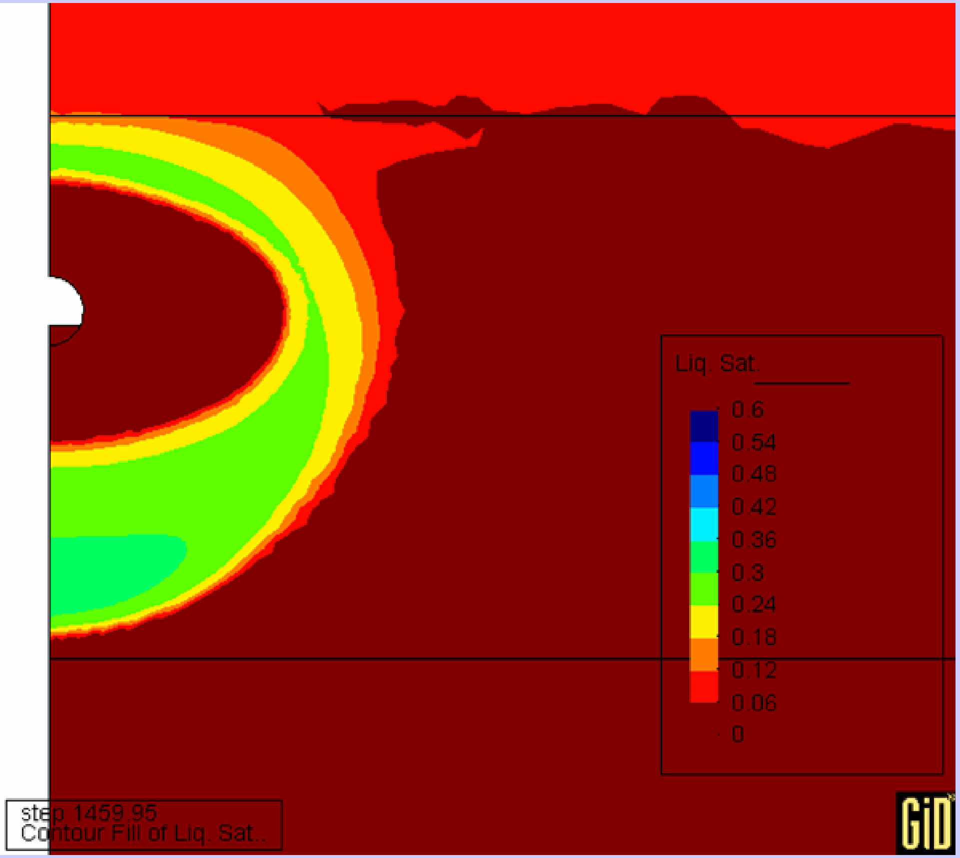
Grado de saturación en la roca y en las fracturas

- Degree of saturation (after 4 years)



Matrix

(initial degree of saturation = 0.92)

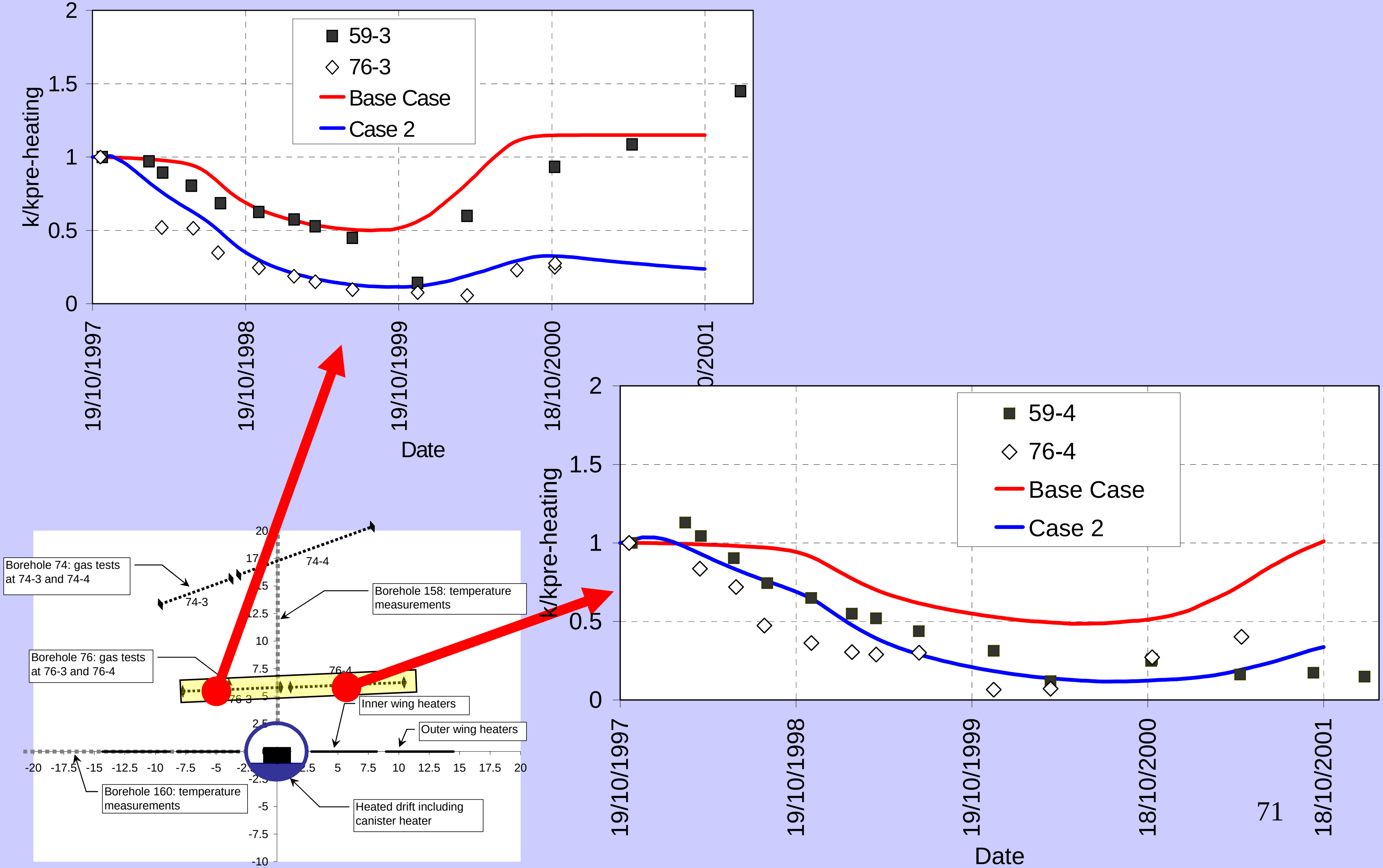


Fracture

(initial degree of saturation = 0.05)

Case 2 analysis (thermomechanical and mechanical coupling)

- Gas permeability variation near drift



Comentarios finales

- Es conveniente que se puedan elegir las ecuaciones a resolver y fenómenos a incorporar
- Las condiciones de solución numérica cambian mucho según el problema a resolver
- Todos los acoplamientos conocidos hay que incorporarlos en la formulación
- Fenómenos acoplados versus procesos acoplados