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Nonlinear behavior of multiphase engineered/geological barriers in nuclear waste disposal

Comportement non linéaire des barrières ouvragée et géologique multiphasiques dans le stockage des déchets nucléaires

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ABSTRACT

A new suction-based mathematical model for thermo-hydro-mechanical behavior of unsaturated media is presented by Gatmiri (1997) and Gatmiri et al (1999). In this approach, heat and moisture transfer equations are given in an alternative form based on water and air pressures. Temperature-dependent state surface formulations are given for void ratio and degree of saturation variations within porous media. The coupling effects of temperature and moisture content on deformation of skeleton, and the inverse effects are included in this model via thermal state surface concept. The non-linear constitutive law for strain-stress relationship is considered. In this new form of formulation, the soil non-homogeneity and hysteretic effect can be included. The phase change between liquid and vapor phases is taken into account. This approach has been integrated in **Code_Aster** which is a finite element code prepared by the development and research department of Electricity of France (EDF). In the present paper, the results of an application on a real case will be presented after a brief description of the proposed THM formulation. The coupling effects are illustrated and the role of the temperature-dependent state surfaces will be shown.

RÉSUMÉ

un modèle numérique du comportement thermo – hydro – mécanique complètement couplé des milieux poreux polyphasique a été développé et présenté, Gatmiri (1997) and Gatmiri et al (1999). Les surfaces d'état de l'indice des vides et du degré de saturation introduites dans ce modèle, dépendent de la température. Le squelette solide a un comportement élastique non linéaire. Les équations du modèle tiennent compte du changement de phase entre le liquide et la vapeur ainsi que les transferts de l'énergie par toutes les phases existant dans le milieu. Vu la complexité des équations différentielles obtenues, une résolution par la méthode des éléments finis avec les formes intégrales de ces équations comme les formes de base pour la discrétisation dans le temps et dans l'espace, a été adopté. Ce modèle a été implanté dans le **Code_Aster**, développé par EDF. Dans cet article, les résultats d'une application à un cas réel sont présentés après une brève description du modèle.

1 INTRODUCTION

Since the soil is continuously under the effect of temperature changes in its natural environment, a great deal of attention has been paid to the phenomenon of moisture transport due to thermal gradient from at least the beginning decades of the present century. In the earlier investigations the critical role of unsaturated zone near the soil surface in the groundwater recharge, surface runoff and evapo-transpiration of the precipitation was the center of attention, but in the latter studies major attentions have been focused on geothermal energy extraction, contaminant transport and specially the safe disposal of high-level radioactive waste. The engineered clay barriers are currently used for filling and sealing of the underground nuclear waste repositories. Considering the unsaturated state of such deformable materials, a deep understanding of coupling effects of moisture, heat, air and soil deformation seems to be an absolute necessity.

The phase changes between liquid and gas, evaporation, condensation, induced moisture transfer under thermal and pore pressure gradients and the effects of moisture distribution on the heat flow are important aspects in non-deformable unsaturated porous media. If the deformation of porous media, which is significant in engineered clay barriers is considered, the coupling effects among deformation, moisture, and heat should also be addressed in addition of all above aspects.

The theory of Philip and de Vries (1957) and de Vries (1958) is a comprehensive theory of moisture and heat movement in an incompressible porous medium. Based on Philip and de Vries theory, a new suction-based mathematical model for thermo-hydro-mechanical behavior of unsaturated media is presented by Gatmiri(1997), Gatmiri et al (1997, 1999) and Gatmiri (2000, 2002). In this approach, heat and moisture transfer equations are given in an alternative form based on water and air pressures. This model has been developed by using the two widely used independent variables, net stress and suction as the state variables in order to describe the water and air pore pressures distribution and deformation of skeleton. The coupling effects of temperature and moisture content on deformation of skeleton, and the inverse effects are included in this model via thermal state surface concept. Temperature-dependent state surface formulations are given for void ratio and degree of saturation variations within porous media. The non-linear constitutive law for strain-stress relationship is considered. In this new form of formulation, the soil non-homogeneity and hysteretic effect can be included. The phase change between liquid and vapor phases is taken into account.

After several validation tests by in-home codes, this approach has been integrated in **Code_Aster** which is a finite element code prepared by the development and research department of Electricity of France (EDF) (Gatmiri 2000). The results of an application on a real case will be presented in this paper.

2 THE PROPOSED MODEL

This model has been described in details in [3,4,and 6].The field equations can be formulated as followings:

2.1 *Solid skeleton behavior*

Considering the two stress state variables as suction and net stress, equilibrium equation and constitutive law for a non-isothermal isotropic and non-linear case can be written as follow:

$$(\sigma_{ij} - \delta_{ij} p_g)_{,j} + p_{g,i} + b_i = 0 \qquad (1)$$

The constitutive law for solid skeleton in unsaturated soil which is under suction and thermal effect, assuming a small deformation, can be written as:

$$d(\sigma_{ij} - \delta_{ij} p_g) = Dd\varepsilon - Fd(p_g - p_w) - CdT \qquad (2)$$

-Thermal void ratio state surface:

$$e = \frac{(1+e_0)\exp[-c_e(T-T_0)]}{\exp[\dfrac{[a(\dfrac{\sigma - p_g}{p_{atm}}) + b(1 - \dfrac{\sigma - p_g}{\sigma_c})(\dfrac{p_g - p_w}{p_{atm}})]^{1-m}}{K_b(1-m)}]} - 1 \qquad (3)$$

-Thermal degree of saturation state surface:

$$S_r = 1 - [a_s + b_s(\sigma - p_g)][1 - \exp(c_s(p_g - p_w))]\exp(d_s(T - T_0)) \quad (4)$$

Where as, bs, cs and ds are constant.

2.2 *Gas phase equations*

The governing differential equation of the mass conservation of gas phase in a control volume of an unsaturated porous medium can be given as the following:

$$\frac{\partial}{\partial t}\left[n\rho_g(1 - S_r + HS_r)\right] = -div(\rho_g V_g) - div(\rho_g HU) + \rho_w divV \qquad (5)$$

where H is Henry's constant which corresponds to the dissolution of air in water.
Considering the generalized Darcy's law for the motion of gas in the soil, the gas flow equation is:

$$V_g = \frac{q_g}{\rho_g} = \frac{-K_g}{\gamma_g}\frac{\partial P_g}{\partial T}\nabla T - K_g\left(\nabla\left(\frac{P_g}{\gamma_g}\right) + \nabla Z\right) \qquad (6)$$

where V_g is the vector of velocity, q_g is the vector of flow, ρ_g is the density, $K_g = (b\gamma_g/\mu_g)[e(1-Sr)]^c$ is the air permeability, P_g is the pressure and γ_g is the specific weight of the gas.

2.3 *Moisture phase equations*

For the moisture mass conservation equation, the following form is proposed:

$$\frac{\partial(\theta\rho_w + (n-\theta)\rho_v)}{\partial t} = \frac{\partial(nS_r\rho_w + n(1-S_r)\rho_v)}{\partial t} = -div(\rho_w(U+V)) \qquad (7)$$

θ is the volumetric water content, n is the porosity, S_r is the degree of saturation in water and ρ_w and ρ_v are the water and the water vapor densities, respectively.

The total moisture movement in unsaturated soil as a sum of liquid and vapor velocities can be written as follows:

$$\frac{q}{\rho_w} = -D_T\nabla T - D_\theta\nabla\theta - D_w\nabla Z \qquad (8)$$

where DT is thermal moisture diffusivity which is equal to the sum of thermal vapor and water diffusivities, Dθ is isothermal moisture diffusivity which is equal to the sum of isothermal vapor and water diffusivities and Dw• Ƶ (Dw = Kw = Kwz0 [(Sr-Sru)/(1- Sru)]b(νr /νT) where ν is the dynamic viscosity of water and Kwz0 is the saturated soil water permeability) is the gravitational part of the equation. More details about these parameters can be found in Gatmiri (1997) and Gatmiri et al. (1997, 1999).

2.4 *Heat equations*

The energy conservation equation in a porous medium can be expressed by:

$$\frac{\partial\varphi}{\partial t} + divQ = 0 \qquad (9)$$

(3)

Where Q is the heat flow and φ is the volumetric bulk heat content of medium which can be defined as:

$$\varphi = C_T(T - T_0) + (n - \theta)\rho_v h_{fg} \qquad (10)$$

C_T is the specific heat capacity of unsaturated mixture and can be written as:

$$C_T = (1-n)\rho_s C_{ps} + \theta\rho_w C_{pw} + (n-\theta)\rho_v C_{pv} + (n-\theta)\rho_g C_{pg}\,. \qquad (11)$$

Total flow of latent and sensible heat in an unsaturated porous medium can be given by:

$$Q = -\lambda gradT + \rho_w h_{fg}V + \rho_v V_g h_{fg} + \left[C_{pw}\rho_w U + C_{pv}\rho_w V + C_{pg}\rho_g V_g\right](T - T_0) \qquad (2)$$

where C_{pw}, C_{pv} and C_{pg} are the water, vapor and gas heat capacities, T_0 is an arbitrary reference temperature, h_{fg} is latent heat of vaporization and λ accounts for Fourier heat diffusion coefficient. It can be evaluated by the following proposed equation:

$$\lambda = (1 - n)\lambda_s + \theta\lambda_w + (n - \theta)\lambda_v \qquad (13)$$

λ_s, λ_w and λ_v denote soil, water and vapor heat diffusion coefficients, respectively.

3 ONE DIMENSIONAL MODELING OF A HORIZONTAL CUT OF SOIL UNDER THERMAL LOADING

In this case study, a special concept of waste disposal, currently used in France, has been investigated. In this concept the cylindrical canister, typically 0.7 m in diameter, are embedded vertically in small diameter wells which are related together by the lined galleries. The canister is assumed to be nearly rigid in comparison to the surrounding soils. The finite length of canister, which is on the order of 14 m long, is not considered in the analysis. An axisymmetric modeling is chosen. Vertical axis of the stocking well is considered as the axis of symmetry. The outer boundary of the soil is set at a radial distance of 200 m from the center of canister. The height of the elements is 2 m. Two types of materials are modeled in the mesh, 0.3 m engineered barrier and geological barrier up to outer boundary. Initial conditions (pore pressure and effective stresses) have been determined by considering a depth of 500 m for this axisymmetric modeling.

3.1 *Geometry*

The following dimensions are taken for the finite element model:
External radius of the mode R_{ext}=200 m
Internal radius in the back of E.B.: R_{int}=0.41 m
Thickness of E.B.: e=0.30 m
The rayon of excavated well: R_{excav}=0.71 m

3.2 *Initial and Boundary Conditions:*

All initial and boundary conditions are illustrated in figure 1. In table 1 the temperature flow as a function of time is given.

3.3 *Mechanical, hydraulic and thermal parameters*

In this analysis a hyperbolic temperature-stress dependent model is used. In tables 2, 3 and 4 the mechanical, hydraulic and thermal properties used in this modelling are given.

Table 1: Temperature flow in time

Instant (sec)	Thermal flow
0.	149,8
31536.E4	121,1
63072.E4	95,1
94608.E4	78,8
126144.E4	66
157680.E4	51,4
220752.E4	33,6
283824.E4	23,9
378432.E4	15,7
473040.E4	10,95
630720.E4	7,88
946080.E4	4,89

Table 2: Mechanical parameters

Parameter	EB	GB
K_l	399	1678
K_u	399	1678
K_b	519	3281
$1/K_S$	7,1 E -10	7,1 E -10
R_f	0,75	0,75
n	0,6	0,6
m	0,4	0,4
m 1	0	0
m 2	0	0
ρ_s	2670 Kg/m^3	2670 Kg/m^3
ρ	2200 Kg/m^3	2410 Kg/m^3
ν	0,2	0,3

Table 3: Hydraulic parameters

Hydraulic Parameters		
Parameter	EB	GB
$1/K_w$	5,0E-10	5,0E-10
K_{int}	1,0E-20	1,0E-19
μ_g	1,8E-5	1,8E-5
μ_w	1,0E-3	1,0E-3
ρ_w	1000,0	1000,0

Table 4: Thermal parameters

Thermal Parameters		
Parameter	EB	GB
h_{fg}	2,4E6 J/Kg	2,4E6 J/Kg
λ_a	0,0258 J/m/s/°C	0,0258 J/m/s/°C
λ_s	1,77 J/m/s/°C	2,0 J/m/s/°C
λ_{ws}	0,6 J/m/s/°C	0,6 J/m/s/°C
C_{pw}	659,0 J/Kg/°C	575,0 J/Kg/°C
C_{pv}	4180,0 J/Kg/°C	4180,0 J/Kg/°C
C_{pa}	1870,0 J/Kg/°C	1870,0 J/Kg/°C
C_p	1000,0 J/Kg/°C	1000,0 J/Kg/°C
α_s	2,0E-5/°C	2,0E-5/°C
α_w	1,0E-4/°C	1,0E-4/°C

3.4 *Relative permeability and saturation degree state surfaces*

The relative water and air permeability curves are given in the figure 2. State surfaces of degree of saturation for engineered barrier and geological barriers at two different temperatures are shown in figure 3.

3.5 *Result and Interpretation*

This analysis is performed by using the hyperbolic temperature-stress dependent model. The results of this analysis are presented in figures 4 to 9.

The profiles of radial displacements are shown for different instants on figure 4. The maximum of observed displacement is about 28 mm which is clearly higher than the same value obtained in linear analysis. We should indicate that this maximum value is observed later by linear model. This delay is due to the pore pressure dissipation delay.

The temperature profiles presented in figure 5 do not indicate a significant difference between the results of non linear and linear model which has been performed but is not presented here. This confirms that the thermal kinematics is independent from mechanical behavior. The pore water and air pressure profiles in different instants are shown on figures 6 and 7, respectively. The profiles of suction and vertical stresses along the model in different time are presented in figures 8 and 9.

4 CONCLUSION

An application of the complete set of suction-based equations of THM behavior of multiphase media on the engineered and geological barriers has been presented. The results are coherent and in good agreement with the observations made in the twenty past years which is very short time for this phenomenon.

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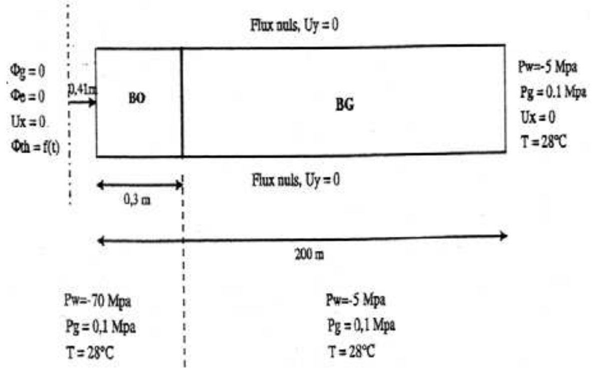

Figure 1: Schematic model with the Boundary conditions

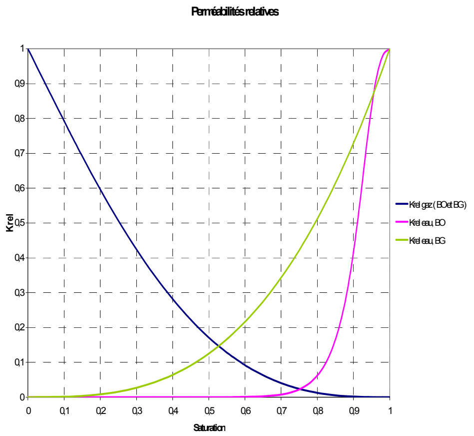

Figure 2: Relative permeability of GB and of EB

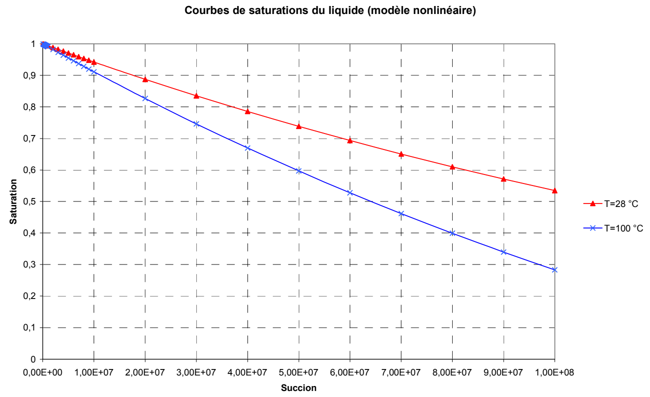

Figure 3: State surface of degree of saturation

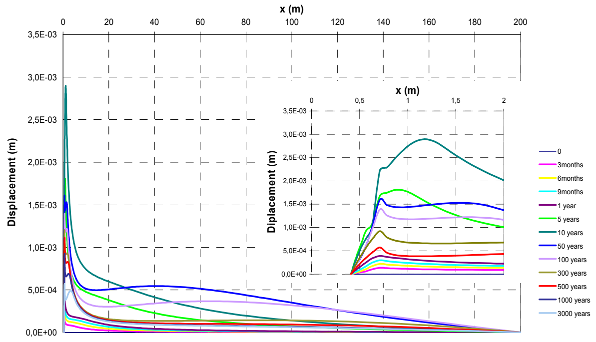

Figure 4: Radial displacement

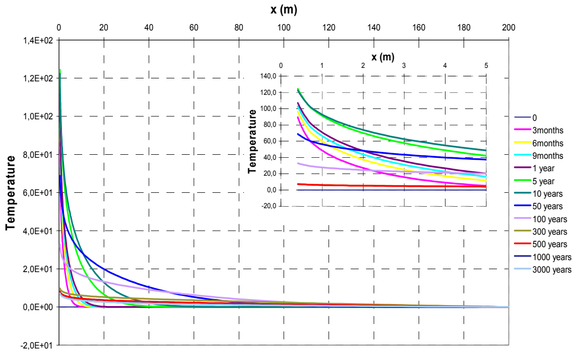

Figure 5: Temperature distribution

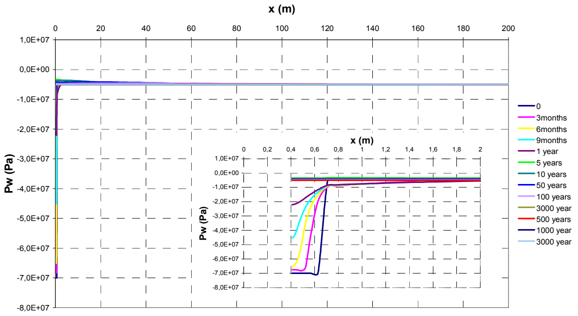

Figure 6: Water pore pressure variation

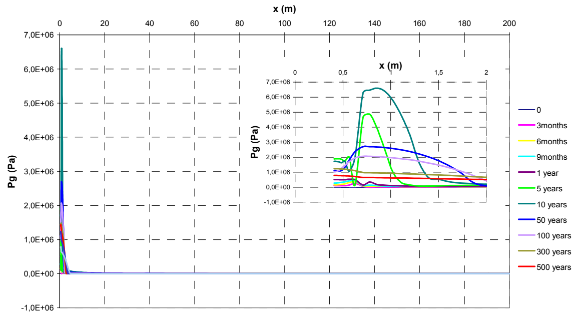

Figure 7 : Air Pore Pressure

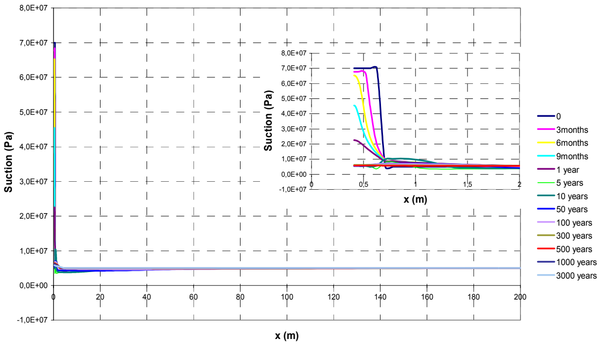

Figure 8 : Suction distribution

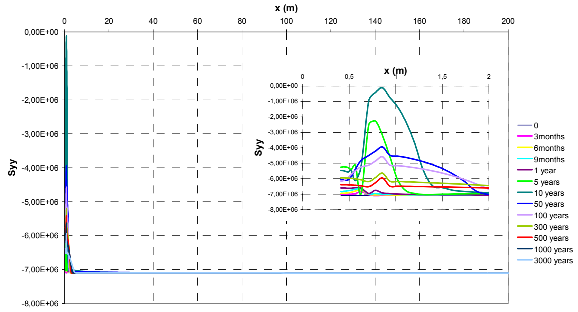

Figure 9 : Profiles of vertical normal stress Syy