Analysis of Thermo-Hydro-Mechanical behavior of an unsaturated geological barrier

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Summary

Variation of temperature produces water, air, soil skeleton movement in geomaterials. The geomaterials are viewed as a multiphase continuum consisting of a solid skeleton and pores filled by water, air and vapor. In this paper, the fully coupled Thermo-Hydro-Mechanical response of a multiphase geological barrier is analyzed. The results of a real case application are presented and discussed.

Introduction

One of the important aspects of studying non-isothermal behavior of porous media is the simultaneous moisture and heat movement. In fluid-saturated soils, all transfers take place in the liquid phase but in unsaturated soils, movements occur in both vapor and liquid phases. As the nature of pore spaces and force fields acting on the vapor and water held herein are so complex, this process is much more complicated in unsaturated media. The theory of Philip & de Vries [1] is known as a basic framework and a comprehensive theory of moisture and heat movement in an incompressible porous medium. In this theory, moisture and heat transfer equations are formulated in terms of temperature (T) and volumetric water content (θ). In this theory, in the absence of water continuity all transfers are in vapor phase and with increasing moisture content, the liquid phase transfer becomes dominant.

A suction based-formulation of fully coupled behavior of a deformable unsaturated porous medium under heating is used (Gatmiri [2]). The nonlinear behavior and phase change (vapor and liquid) are considered. The coupling effects of skeleton, suction and temperature via the concept of state surface of void ratio and degree of saturation are included (Gatmiri [4]). What is presented in this paper is a part of research program performed by the first author on fully coupled THM behavior of saturated and unsaturated porous media with different constitutive laws with EDF (France) since 1994.

Field equations

Equations are briefly presented here. Assumptions, development of the equations and complete notation can be seen in [3], [4].Moisture mass conservation and moisture movement are as following:

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$$\frac{\partial \rho_m}{\partial t} = -\mathrm{div}\left(\rho_w (U+V)\right) \tag{1}$$

$$\rho_m = \theta\rho_w + (n-\theta)\rho_v = nS_r\rho_w + n\left(1-S_r\right)\rho_v, \tag{2}$$

$$U + V = -D_T\nabla T - D_\theta\nabla\theta - D_w\nabla Z \tag{3}$$

Where U is water velocity, V is vapor velocity, ρ_w is water density, ρ_v is vapor density, S_r is degree of saturation, D_T is thermal moisture diffusivity, D_θ is isothermal moisture diffusivity and D_w is gravitational diffusivity. Equation of mass conservation and movement of gas in a control volume of unsaturated porous media can be given as:

$$\frac{\partial}{\partial t}\left[n\rho_g\left(1-S_r+HS_r\right)\right] = -\mathrm{div}\left(\rho_g V_g\right) - \mathrm{div}\left(\rho_g HU\right) + \rho_w \mathrm{div}V. \tag{4}$$

$$V_g = \frac{-K_g}{\gamma_g}\frac{\partial P_g}{\partial T}\nabla T - K_g\left(\nabla\left(\frac{P_g}{\gamma_g}\right) + \nabla Z\right). \tag{5}$$

Where H is Henry constant, V_g is vector of gas velocity and ρ_g is gas density. Energy conservation and heat transfer equations in a porous medium can be expressed by:

$$\frac{\partial \varphi}{\partial t} + \mathrm{div}Q = 0. \tag{6}$$

$$Q = -\lambda \mathrm{grad}T + \rho_w h_{fg}V + \rho_v V_g h_{fg} + \left[C_{Pw}\rho_w U + C_{pv}\rho_w V + C_{pg}\rho_g V_g\right]\left(T-T_0\right). \tag{7}$$

$$\varphi = C_T\left(T-T_0\right) + (n-\theta)\rho_v h_{fg}, \tag{8}$$

$$C_T = (1-n)\rho_s C_{Ps} + \theta\rho_w C_{Pw} + (n-\theta)\rho_v C_{Pv} + (n-\theta)\rho_g C_{Pg} \tag{9}$$

$$\lambda = (1-n)\lambda_s + \theta\lambda_w + (n-\theta)\lambda_v \tag{10}$$

in which Q is heat flow, φ is the volumetric bulk heat content of medium, C_{Ps}, C_{Pw}, C_{Pv} and C_{Pg} are specific heat capacity of solid, liquid, vapor, gas respectively. T_0 is an arbitrary reference temperature and, h_{fg} is latent heat of vaporization. Equilibrium equation, constitutive law, void ratio and degree of saturation state surfaces can be written as:

$$(\sigma_{ij} - \delta_{ij}p_g)_{,j} + p_{g,j} + b_i = 0. \tag{11}$$

$$d(\sigma_{ij} - \delta_{ij}p_g) = Dd\varepsilon - Fd(p_g - p_w) - CdT \tag{12}$$

$$F = D\,D_s^{-1} \text{ with } D_s^{-1} = \beta_s m \text{ in which } \beta_s = \frac{1}{1+e}\frac{\partial e}{\partial(p_g - p_w)} \tag{13}$$

$$C = D\,D_t^{-1} \text{ with } D_t^{-1} = \beta_t m \text{ in which } \beta_t = \frac{1}{1+e}\frac{\partial e}{\partial(T)} \text{ and } m=[1\ 1\ 0] \tag{14}$$

$$e = \frac{(1+e_0)\exp[-c_e(T-T_0)]}{\exp([a_e(\frac{\sigma - p_g}{p_{atm}}) + b_e(1-\frac{\sigma - p_g}{\sigma_c})(\frac{p_g - p_w}{p_{atm}})]^{1-m} / K_b(1-m))} - 1 \tag{15}$$

$$S_r = 1 - [a_s + b_s(\sigma - p_g)][1-\exp(c_s(p_g - p_w))]\exp(d_s(T-T_0)) \tag{16}$$

Where σ is stress tensor, p_g is pressure of gas, p_w is pressure of water, σ_c is preconsolidation stress, K_b, m, a_e, b_e, c_e, a_s, b_s , c_s and d_s are the parameters of void ratio and degree of saturation state surfaces.

Application and results

This formulation has been integrated in Code_Aster (EDF) (Gatmiri[4]). In this section, an analysis of THM behavior of geological barriers in a deep nuclear waste disposal is presented (Gatmiri and Ghasemzadeh [5]).

In this modeling, a horizontal section of un unsaturated deposit located at 500 meters of depth was considered. This horizontal cut of ground consists of the bedrock as the geological barrier (GB) with a width of 200 meters. A one-dimensional axisymmetric analysis is performed. The axis of symmetry is the vertical axis of the well of storage.

The first step of modeling is excavation of well of 0.71m diameter and the second step is the application of thermal loading on the inner boundary. The Geometry and Outer boundary condition have been shown in Fig 1-a. The temperature imposed on the inner boundary in the different time steps is presented in Fig. 1-b. This curve has been obtained from another analysis in which a bi-material (geological and engineering barriers) are used [5].

Material properties of GB are: elasticity modulus: 2166MPa, bulk modulus: 1805, ρ_s = 2410 Kg/m^3, porosity: 0.14, initial suction 5 MPa, water permeability= S_r^3 and air permeability= $(1-S_r)^2 * (1-S_r^{5/3})$. Parameters for state surface of degree of saturation are a_s= 1.0, b_s= -2.088E-8, c_s= -5.05E-9, d_s= 6.0E-3. Parameters for state surface of void ratio are; a_e= 1.0, b_e= 0.0, c_e= 0.3E-6. Thermal parameters are C_{PS} = 575.0 J/kg°K, C_{Pw} = 4180 J/kg °K, C_{Pv} = 1870 J/kg°K, C_{Pg} = 1000 J/kg°K,λ_s = 2.0 W/m°K, λ_w = 0.6 W/m °K, λ_a =0.0258 W/m°K, h_{fg}= 2.4×10^6 J/kg, Henry constant H=.02.

The profiles of radial displacement at various times are shown on Fig. 2. The maximum of displacement is around -2,5 mm which was generated by the excavation. The maximum of pure displacement of the thermal loading is approximately 0.3 mm. The variation of excess temperature relative to 28°, the ambient temperature, is presented in the Fig. 3. The maximum value of the excess temperature, resulting from the bi-material modeling, imposed on the inner part of the GB is about 100° and it decreases in the GB. One can see on each vertical cut of the fig. 3, the maximum temperature and time necessary to reach this value for each point of the solid mass is different according to the distance from the heat source. The profiles of suction are given on Fig. 4. A decrease in the suction under the coupled effect of heating, deformation and moisture transfer is observed.

Conclusion

The results of THM axisymmetric modeling of the unsaturated geological barrier were described. Calculation was performed with THM model of Gatmiri (CERMES) introduced in the Code_Aster. The results show the general evolution of the temperature, displacement and suction at different times in the solid mass. The quasi-independence of the thermal kinematics relative to the other phenomena is observed. The financial support of EDF-CIH is acknowledged.

Reference

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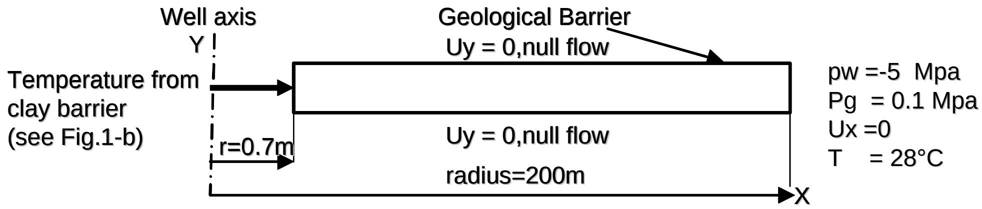

Fig. 1-a Geometry of axisymetric geological barrier

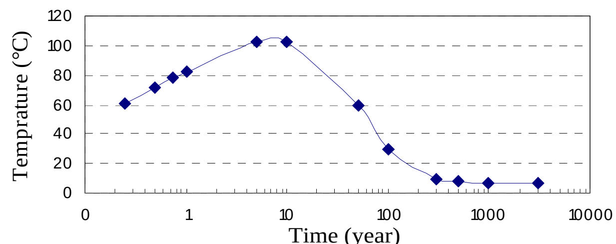

Fig 1-b : Temprature on the boundary of BG

Fig. 1 Geometry and boundary conditions of geological barrier in the model

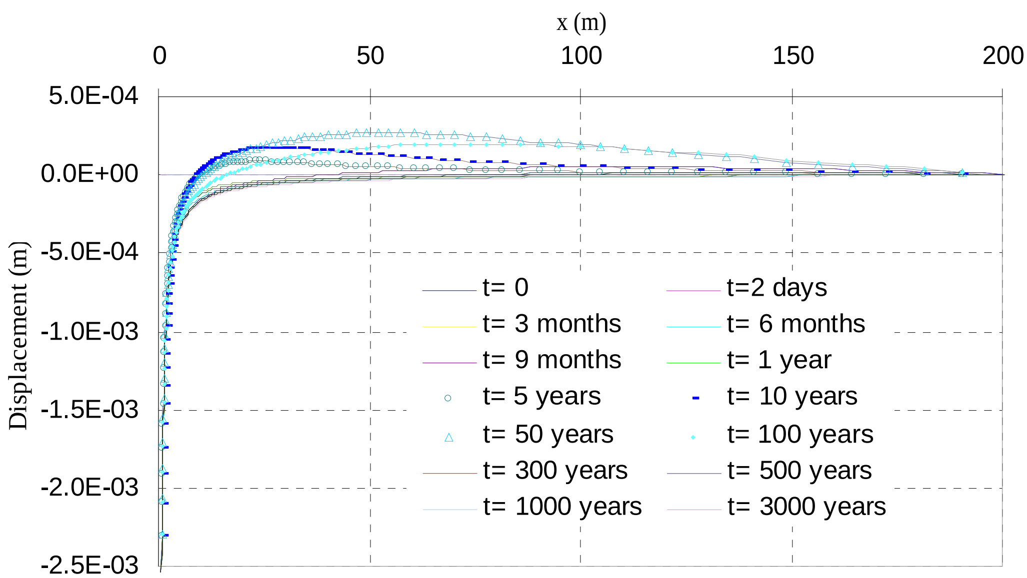

Fig. 2- Radial displacement in the geological barrier

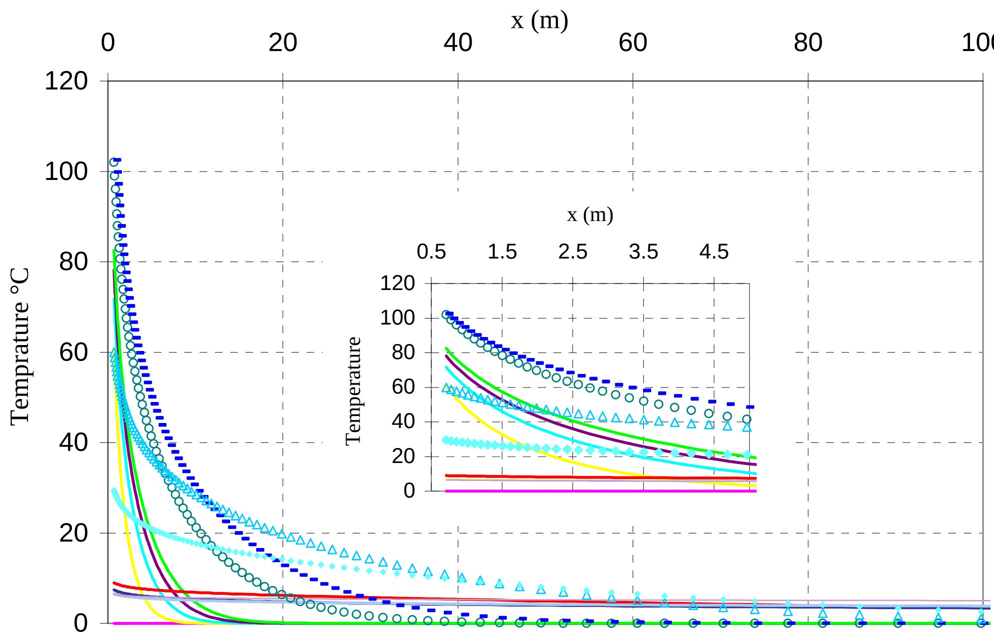

Fig. 3- Temperature in the geological barrier(legend on the Fig.2)

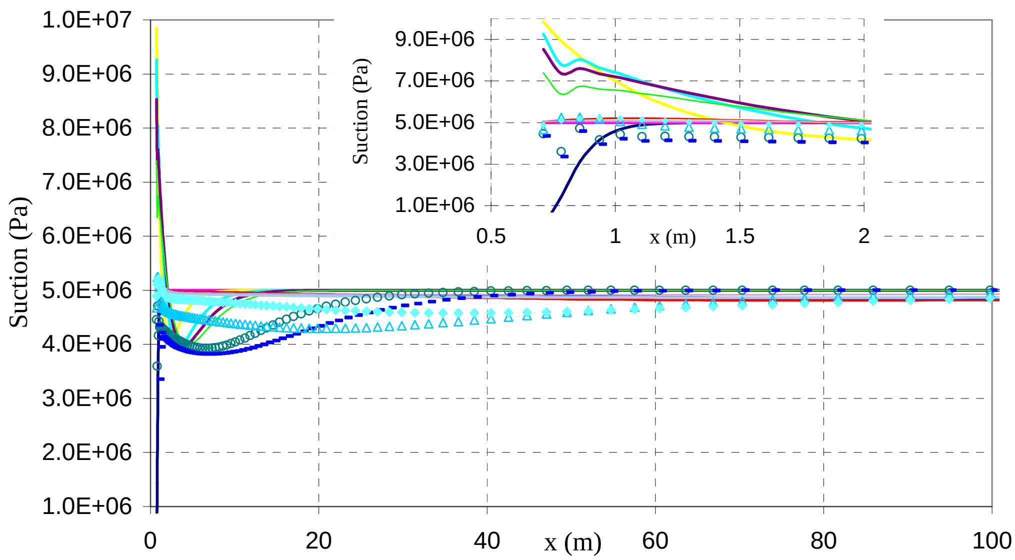

Fig. 4- Sustion in the geological barrier(legend on the Fig.2)