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Analysis of Coupled Thermohydromechanical Damage in Unsaturated Porous Media

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ABSTRACT

In this study the theoretical framework of a thermohydromechanical damage model (THHMD model) for non-isothermal unsaturated porous media is presented. The framework of this model is based on the use of independent state variables (net stress, suction and thermal stress). The damage behavior law stems from phenomenological and micro-mechanical concepts. The stress-strain thermodynamic conjugation relations are derived from the free energy, which is written as the sum of damaged elastic deformation energies and of residual strain potentials. The damaged mechanical rigidities are computed by applying the Principal of Equivalent Elastic Energy (PEEE) for each stress state variable. The influence of damage on liquid water and vapor transfers is accounted for by introducing damage-induced intrinsic conductivities. In this paper after the review of the mentioned model, a parametric study is performed to assess the influence of the Excavated Damage Zone (EDZ) on the response of the nuclear waste repository during the heating phase. The trends meet the theoretical expectations.

KEYWORDS:

Unsaturated soil, Thermohydromechanical damage model, Multiphase porous media, Finite Element Method, Micromechanics.

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1- INTRODUCTION

When an underground chamber receives heated materials, for example, it may experience mechanical, thermal, and hydrological processes that interact to influence the overall performance of the structure. This study is motivated by the necessity to predict the behavior of Excavated Damage Zone (EDZ) surrounding nuclear waste disposals. The geological barriers, often made of quasi-brittle material like granite or clay-rock, undergo damage during the excavation phase. A representation of damage is required to predict the evolution of fracturing in the neighboring of excavated galleries [1].

In Continuum Damage Mechanics, almost all models developed for unsaturated media are based on Bishop's definition of stress [2]. Some important aspects of the behavior of unsaturated soils, like wetting collapse, cannot be represented by this theoretical frame. Alternatively, the THHMD model developed by Arson and Gatmiri, involves independent state variables (net stress, suction and thermal stress), in order to emphasize the role of suction rigidity. Damage is assumed to grow with tensile strains due to net stress with tensile strains due to net stress, with pore shrinkage due to suction and with thermal dilatation. Correspondingly, the strain tensor is split into two independent thermodynamic strain components. The behaviour law stems from both micromechanical and phenomenological concepts. Damage rigidities associated with the state variables are computed by applying the principal of equivalent elastic energy, which is widely used in micromechanics. Homogenized cracking parameters are also included in the expression of the intrinsic liquid permeability of the medium, in order to represent the intrinsic liquid permeability of fluid transfers [3].

Saturation variations around galleries influence the Excavation Damaged Zone by changing permeabilities. That is why damage has to be included in hydraulic transfer models and mechanical damage theories have to be extended to unsaturated porous media. Waste is a heat source which can generate traction, and thus cracks; therefore, the design of deep nuclear waste repositories requires the modeling of the effects of thermal loadings in the Excavation Damaged Zone (EDZ). The theoretical frame is briefly recalled in the first part of this paper, also the numerical parametric study is performed in order to determine the effect of damage on the permeability of specimen and the generation of damage in THHMD model.

2- THEORETICAL APPROACH, DISCUSSION, RESULTS

In the following, the damage variable has been defined as the crack density tensor expressed in a principal base [10]:

$$\Omega_{ij} = \sum_{k=1}^{3} d^k \, n_i^k \, n_i^k \tag{1}$$

The Representative Elementary Volume is damaged by multiple micro-cracks, which have been conceptually gathered into three main families of approximately parallel planar fissures. Each meso-crack has been characterized by a direction n^k (normal to the crack plane) and a volumetric fraction d^k.

The water permeability tensor has been split in an intrinsic part and in relative components:

$$K_{w\,ij} = k_T(T) k_r(S_w) K_{\text{int}\,ij}(n, \Omega_{pq}) \tag{2}$$

The thermal and capillary relative permeabilities $k_T(T)$ and $k_r(S_w)$ have been related to heat and to the behaviour of pore fluids as follows:

$$k_T(T) = \frac{\mu_w(T)}{\mu_w(T_{ref})}$$

$$k_r(S_w) = \left(\frac{S_w - S_{w,r}}{1 - S_w}\right)^3 \tag{3}$$

In which $\mu_w(T)$ is the dynamic viscosity of liquid water, and $S_{w,r}$ is the residual water saturation degree. The water saturation degree S_w evolves on a thermo-hydraulic state surface. This latter has been defined by Van Genuchten [4] and assumption of exponential thermal effects done by Gatmiri [1]:

$$\begin{aligned} S_w &= [(1 - S_{w,r})(1 + (\alpha_{VG} s)^{n_{VG}})^{-1+\frac{1}{n_{VG}}} \\ &\quad + S_{w,r}] \exp(d_s (T - T_0)) \quad if \quad s \geq 0 \\ S_w &= 1 \quad if \quad s < 0 \end{aligned} \tag{4}$$

Only the intrinsic water permeability, which depends on the behaviour of the solid skeleton, is influenced by damage [3]:

$$\begin{aligned} K_{\text{int}\,ij}(n, \Omega_{pq}) &= k_{w0} 10^{\alpha_w e^{rev}} \delta_{ij} \\ &\quad + k_{2ij}(n^{frac}, \Omega_{pq}) \end{aligned} \tag{5}$$

Damage affects flows indirectly and isotropically,

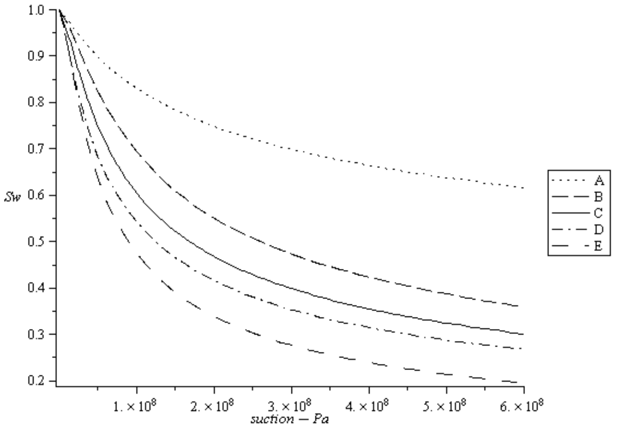

Figure 1. Five used Van Genuchten water retention curves

through the damaged porosity.

Here we are interested in the effects of different Van Genuchten water retention curves introducing by A to E in Fig. 1, on the variation of different parameters of damage model. Table 1 represents the parameters chosen in the five water retention curves.

The numerical simulation has been inspired by the laboratory test of Pintado (2002) [5], and the simulation has been performed by damage model integrated in θ-Stock Finite Element code [1]. A thermal source is installed between two cylinder-shaped bentonite samples with diameters of 38mm and heights of 76mm which are both wrapped in isolate foam. Since the provided geometry and loading are both symmetrical and the calculations are performed through axial symmetry, the thermal source is modeled through the boundary conditions of Newman applied to the nodes of the external boundary of the sample. To consider the effect of the isolate foam, a thermal current of zero is exerted on the external lateral boundary. The bottom being maintained at a constant temperature. The initial pore water pressure (p_{w0}) is calculated by inversion of the function of the degree of saturation state surface. The initial saturation degree S_{w0} is equal to 0.63 like in the experiment conditions. After a heating period of one week, a relaxation period of seven weeks is observed. In order to investigate the trend of water permeability, the variation of this parameter due to saturation degree, temperature, and damage is represented for an element near the heater.

This element is near the heat source, so it is in the upside part of the samples. Using the water retention curves (Fig. 1), A is the wettest sample and the samples get drier respectively; therefore, that E is the driest one. All of the samples initiate from the initial degree of saturation of 0.63. During the heating stage, in this close heater element, pore water move downward due to thermal gradient and gravity; therefore, degree of saturation drops. While degree of saturation decreases, water permeability falls. Over the recovery stage, degree of saturation grows due to reversing the orientation of water in the samples, thus water permeability increases.

Table 1. Parameters of the five Van Genuchten water retention curves

Graph	α(VG)	n (VG)
A	$1.857.10^{-8}$	1.2
B	$1.857.10^{-8}$	1.429
C	$2.857.10^{-8}$	1.429
D	$3.875.10^{-8}$	1.429
E	$3.875.10^{-8}$	1.5

Water permeability reduces from A toward E. This is why the specimens get dry from A to E. First that there is no crack in samples, and pores are in their initial size, increasing of saturation degree leads to water permeability reduction. After occurrence of cracks, pores get larger. This factor prompts to grow the permeability, but graphs trend shows that the saturation degree reduction conquers this factor. Therefore, the coupling of these two parameters causes falling trend in water permeability. After removing thermal loading, the magnitude of damage almost remains constant, while by reversing water direction in samples, saturation degree rises and therefore permeability increases.

Based on the numerical results of this simulation, at the times after the time =100 hours, the amount of permeability in the near heat source elements (upper 9% of height of the specimen), is more than it in the farer elements. This fact is because of the influence of the damage on the increase of the permeability. After the mentioned time, the pores in upper part of the sample have got big enough to influence the permeability.

3- CONCLUSIONS

The THHMD model is a fully coupled thermohydromechanical damage model dedicated to unsaturated porous media (Arson and Gatmiri 2008).

The THHMD model has been implemented in θ-Stock Finite Element code (Arson and Gatmiri 2008). A comprehensive numerical investigation has been performed in order to assess the trends of damage in unsaturated host geomaterial. The distribution of damage parameter, degree of saturation, and water permeability in bentonite sample has been presented and discussed.

It is concluded from the results of THHMD model that coupling of suction and heating, effects on the generation and improvement of damage: heating produces thermal strain, while suction because of producing confining stresses, diminishes tensile stresses. During the heating stage, in this close heater element, pore water move downward due to thermal gradient and gravity; therefore, water permeability falls. Over the recovery stage, water permeability increases.

4- REFERENCES

[1] Gatmiri, B., and Arson, C., “Theta-Stock, a powerfull tool for themohydromechanical behaviour and damage modeling of unsaturated porous media”, Computers and Geotechnics 35, 890-915, 2008.

[2] Arson, C., Gatmiri, B., “On damage modelling in unsaturated clay rocks”, Phys. Chem. Earth 33 S407-S415, 2008.

[3] Arson, C., Gatmiri, B. (2009). “A mixed damage model for unsaturated porous media”, Competes-Rendus de l’Académie des Sciences de Paris, Section Mécanique 337, 68-74.

[4] VanGenuchten M. TH., “A closed-form equation for predicting the hydraulic conductivity of unsaturated soils”, Soil Science Society of America Journal, 44: 892-898, 1980.

[5] Pintado, X., Ledesma. A., Lloret. A., “Backanalysis of thermohydraulic bentonite properties from laboratory tests”, Engineering Geology, 64:91–115, 2002.