Hydromechanical coupling in the soil-structure interaction

Belbekri M.[1], Draoui B.[2], Berga A.[3]

[1]ENERGARID Laboratory
Tahri Mohamed University, Bechar, Algeria
belbekri.malika.1900@gmail.com

[2]ENERGARID Laboratory
Tahri Mohamed University, Bechar, Algeria
bdraoui@yahoo.fr

[3]FIMAS Laboratory
Tahri Mohamed University, Bechar, Algeria
berga.abdelmadjid@gmail.com

Abstract. *Historically, in civil engineering construction, the structural design takes account the gravity, overload and water pressure as fundamental forces. Becomes later the consideration of the dynamics effects as the machine vibration and the earthquake, the fire resistance…etc. After all, the survey of projects like building, road, pavement -as example- show that there is always appearance of various anomalies and damages that are evolutionary in time. Often, they can be due to the water cycle. The paper handles the hydro mechanical coupling case, shows how conducting the analysis and proof the feasibility of the structural design in these conditions. The results are obtained in the frame of the finite element analysis and they open the horizon for more improvements.*

Key words: Soil, structure, water, hydromechanical, interaction, Finite element method

1. Introduction

The structural mechanics is devoted to ensure strength and stability of structures. In spite of sophisticated methods of construction, there exits various problems of dysfunction, material damage, fissuring, distortion and out of use due to the soil-structure and the soil-water interactions. The problem is also aggravated by the climatic changes as water table variation, subsurface flow, flooding and dryness. The concerned structures are houses, light buildings, public institutions, urban substructures, roads, etc. In these circumstances, constructive arrangements are inefficient because they represent a prevention rules that are based upon limited cases without considering the scale of phenomena and theirs interdependences. Several disciplines are interested by the same questions but for various purposes as in hydrology [1], agronomy [2], [3] and biology [4], [5]. The aim of the present is to take account, for the design engineering, the hydromechanical interaction. To do, we show the global methodology that allows a rigorous analysis of hydromechanical effects on structures using a simplified but efficient finite element model. After this introduction, a bibliographic section presents various researches in the thematic. The mathematical and the finite element models are then achieved. The application section shows the feasibility of the method and is followed by the conclusion and the references section.

2. Literature review

There exist relevant works even they are devoted for various targets, as in water management, the simulation of the subsurface soil water evaporation [1] and in Agronomy where the hydro thermal model is improved and validated by experimental measures [2], [3], the modeling of the root zone water redistribution [6], influence of the mulch layer on the soil-atmosphere interface water exchange [7], numerical modeling of a hydrothermal physical model [8], spatial and temporal variability of soil moisture applied to irrigation [9]. In geomechanics, constitutive and numerical modeling of the unsaturated soil with an elasto-plastic model [10]. In water management strategies, the numerical simulation of pesticide transport with application to groundwater anti-pollution [11].

In industry, hydrothermal modeling and experimentation on hydration operation of date palm fruits [5], simulation of heat and mass transfer during artificial ground freezing [12], modeling of food products shrinkage [13], modeling of biocalcification in non-saturated conditions [14], application to mint leaves drying [15]. Effect of the degree of saturation on the hydro-mechanical behavior of unsaturated soil [16], analytical modeling of the water content profile during evaporation where focus is made on the case of sandy soil with presence of water table [17], estimation of the soil water retention curve [18], modeling of the mechanical behavior of unsaturated soils using a genetic algorithm-based neural network [19], numerical modeling of multiphase fluid flow in porous media where the flow consists to a two immiscible compressible wetting and non-wetting pore fluids, and the application deals with seismic analysis of earth and rockfill dams [20], unconfined seepage through porous media, application to seepage problems through earth dams and to the dynamic consolidation of soil [21], soil-water coupled elasto-plastic analysis applied to bearing capacity of natural clay [22].

In waste management and anti pollution design, as modeling of the dilute species transport in porous medium with a thermo hydro chemical and geomechanical coupling [23], hydrodynamic processes coupled to pollutant transfer in unsaturated heterogeneous soil, with experimental and numerical analysis [24], heat and mass transfer in expansive clay with application to radioactive waste stocking [25]. Modeling of the dynamic of soil saturation by the moving boundary approach [26]. In Risk management as the estimation of the degree of saturation of shallow soils from satellite observations, heat and moisture balance and application to soil slip detection [27].

3. The mathematical model

The local problem is an initial value type involving the structural equilibrium coupled to a fluid diffusion through partially saturated porous medium. The diffusion problem in partially saturated medium is governed by the Richards equation. It is established according to the continuity or conservation equation associated to the Darcy law. Let h be the hydraulic head

$$h = \frac{s}{\gamma_w} + z \quad (1)$$

where z is the elevation and s is the suction defined as

$$s = s(\theta) = p_a - p_w \quad (2)$$

and θ is the liquid volume fraction

$$\theta = \frac{v_w}{v_t} \quad (3)$$

with v_w is the water volume, v_t the total volume, p_a is the air pressure and p_w is the water pressure. The Darcy law relates the liquid flux **q** or the velocity **u** to the hydraulic head by introducing the permeability coefficient k. In the case of isotropic behavior, the Darcy law is expressed by

$$\boldsymbol{q} = \boldsymbol{u} = -k(\theta)\, \boldsymbol{grad}\, h = -k(\theta)\, \boldsymbol{\nabla} h \quad (4)$$

where ∇ is the gradient symbol. The continuity equation for the water diffusion in both case of wetting or drying, without sink term is

$$\frac{\partial \theta}{\partial t} = -div\, \boldsymbol{u} = -\boldsymbol{\nabla} . \boldsymbol{q} \quad (5)$$

where t is the time variable. Using (4) and (5) one obtain the Richards equation :

$$\frac{\partial \theta}{\partial t} = \boldsymbol{\nabla}\left[k(\theta)\frac{\partial h}{\partial \theta}\boldsymbol{\nabla}\, \theta\right] + \frac{\partial k(\theta)}{\partial z} \quad (6)$$

This differential equation describes the flux of liquid in non saturated medium. The phenomenon depends, on the permeability propriety that varies with the liquid volume fraction k(θ), the characteristic of the liquid retention through the term $\frac{\partial h}{\partial \theta}$ that is the slope of the s(θ) curve. The $\frac{\partial k(\theta)}{\partial z}$ term express the gravity influence. The term $D(\theta) = k(\theta)\ \frac{\partial h}{\partial \theta}$ is the diffusivity. When the problem is expressed with pressure variable, the Richards equation can be written under the general form :

$$\rho\left(\frac{C_m}{\rho g} + S_e\, S\right)\frac{\partial p}{\partial t} + \boldsymbol{\nabla}.\rho\left[\frac{\kappa_s}{\mu}k_r(\boldsymbol{\nabla} p + \rho g\, \boldsymbol{\nabla} z)\right] = Q_m \quad (7)$$

in which p is the pressure variable, ρ is the fluid density, g is the acceleration of gravity, C_m is the specific moisture capacity, S_e the effective saturation, S is the storage coefficient, κ_s gives the hydraulic permeability, μ is the fluid dynamic viscosity, k_r denotes the relative permeability. Q_m is the fluid source (positive) or sink (negative). Thus, the fluid velocity **u** is computed by the expression

$$\boldsymbol{u} = \frac{\kappa_s}{\mu}k_r(\boldsymbol{\nabla} p + \rho g\, \boldsymbol{\nabla} D) \quad (8)$$

while the liquid volume fraction θ is given by the retention characteristic. Here, the Van Genuchten model is used :

$$\theta = \begin{cases} \theta_r + S_e\,(\theta_s - \theta_r) & H_p < 0 \\ \theta_s & H_p \geq 0 \end{cases} \qquad (9)$$

where θ_r (respectively θ_s) is the residual (respectively the saturated) liquid volume fraction, H_p is the pressure head.

$$H_p = \frac{p}{\rho\, g} \qquad (10)$$

The effective saturation is given by

$$S_e = \begin{cases} \frac{1}{\left[1+|\alpha\, H_p|^n\right]^m} & H_p < 0 \\ 1 & H_p \geq 0 \end{cases} \qquad (11)$$

where α, n are a parameters and m=1 - 1/n. The specific moisture capacity is defined by

$$C_m = \begin{cases} \frac{\alpha\, m}{1-m}\,(\theta_s - \theta_r)\, S_e^{\frac{1}{m}}\,(1 - S_e^{\frac{1}{m}})^m & H_p < 0 \\ 0 & H_p \geq 0 \end{cases} \qquad (12)$$

The relative permeability is

$$k_r = \begin{cases} S_e^{\,l}\left[1 - (1 - S_e^{\frac{1}{m}})^m\right]^2 & H_p < 0 \\ 1 & H_p \geq 0 \end{cases} \qquad (13)$$

in which, l is a parameter. The storage S can be evaluated by the linear relation

$$S = \theta_s\, \chi_f + (1 - \theta_s)\, \chi_p \qquad (14)$$

where χ_f (respectively χ_p) is the compressibility of the fluid (respectively the porous medium).

The mechanical problem is described by the equilibrium condition. In static, the governing equation is

$$\boldsymbol{\nabla}.\boldsymbol{\sigma} + \boldsymbol{F}_v = 0 \qquad (15)$$

where **σ** is the stress tensor and $\mathbf{F}_v$ is the vector of body forces. It is possible to combine the mechanical problem to fluid flux in saturated or unsaturated problem by the use of the effective stress principle due to Bishop

$$\boldsymbol{\sigma}' = (\boldsymbol{\sigma} - \boldsymbol{I}\, p_a) + \xi\, s\, \boldsymbol{I} \qquad (16)$$

in which, **σ**' is the effective stress tensor in the solid skeleton, **σ** is the total stress, **I** is the identity matrix and $\xi = \xi(S_e)$ is a parameter depending on the effective saturation, the suction s, the soil microstructure and the loading paths. The use of the effective stress allow analysis of various applications in coupled fluid-soil analysis as the consolidation problems, stability of embankments and slopes. Also it is possible to combine the mechanical problem to the diffusion one as in poroelasticity where the stress tensor is defined as

$$\boldsymbol{\sigma} = \boldsymbol{C}\,\boldsymbol{\varepsilon} - \alpha_B\, P_f\, \boldsymbol{I} \qquad (17)$$

with **C** is the elasticity matrix, **ε** the strain tensor, α_B the Biot-Willis coefficient, P_f the fluid pore pressure. In the mechanical problem, the behavior relationships other than (17) can be used to determine the solution for various applications.

4. The finite element model

The local problem is composed of two coupled partial differential equations. One for fluid diffusion through the unsaturated porous media (7) while the second is related to the mechanical equilibrium of the deformable porous media and connected structures (15). The problem is then a time dependent one, with an initial value problem and a boundary value problem.

The numerical solution is conducted by integration of the system of the partial differential equations. When the solution exists, it is obtained with the definition of the initial and the connections conditions. The local problem is transformed to a global one that describe the all concerned domain by using the integral or variation methods associated to the finite element procedure [28], [29], [30]. At the same time, the procedure performs two important transformations on the mathematical problem. First, the continuous variable becomes discrete because the unknown fields are approximated within the finite element area. For this, the finite element method use an interpolation functions related to the nodal unknowns. Second, the spatial derivation are introduced on the interpolation function while the time derivation are approximated by finite difference. So, the partial differential equations system becomes an algebraic system.

5. Applications

As example of the feasibility of the hydromechanical coupling in soil-structure interaction, we simulate the effect of a subsurface water inlet and outlet with presence of an expansive layer. The phenomena is particularly prejudicial when the soil water swings from weak to large content and inversely. To reproduce the cyclic change between moist and dry period, the incoming flux is taken with positive (pressure) or negative (suction) value. The demonstration is conducted in 2D plane strain configuration and the earth structure is assumed to be rigid (Fig. 1).

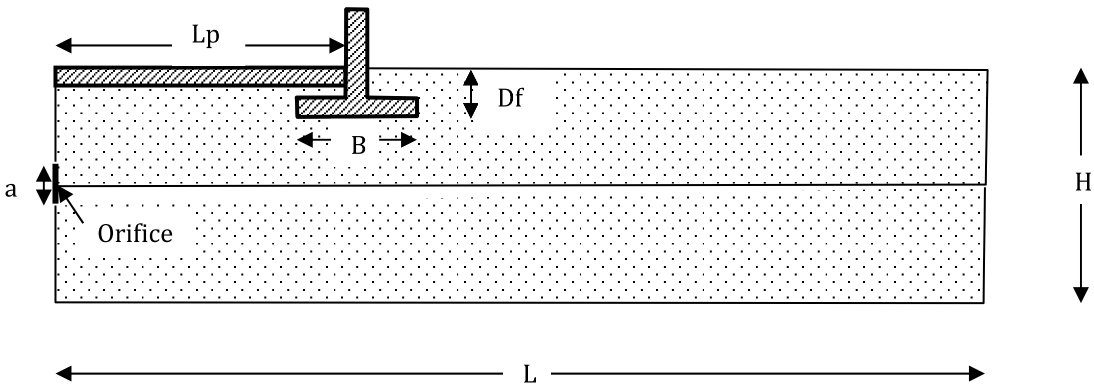

Fig. 1. The geometry.

Let consider a shallow footing attached to a floor as a reinforced concrete structure in interaction with the surrounding soil. The soil massif is composed of two layers whose the superficial one is an expansive clayey soil. The water flows across an orifice located somewhere along the massif boundaries. The principal goals in the present simulation is to show the effect of the moisture change upon the stability of the foundation. The geometry is data are L=16m is the width of the massif, H=4m is the depth of the massif, B=2m is the footing width, Lp=5m is the floor length, Df=0,8m is footing depth and a=0,8m is the orifice diameter. The mechanical boundary conditions are defined in (Fig. 2).

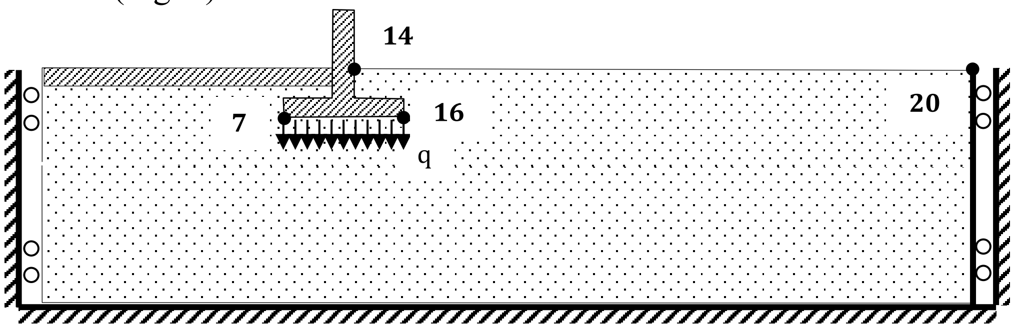

Fig. 2. The mechanical boundary conditions and the post-processing points.

All exterior boundaries are impervious except the inlet or outlet orifice. Also, (Fig. 2) shows the points used for post-processing where the nodes 7, 14 and 16 belong to the structures while the node 20 belongs to the soil. The mechanical load q transmitted by the footing is considered as a service load. The hydraulic loading is defined along a large period of 400 days (Fig. 3).

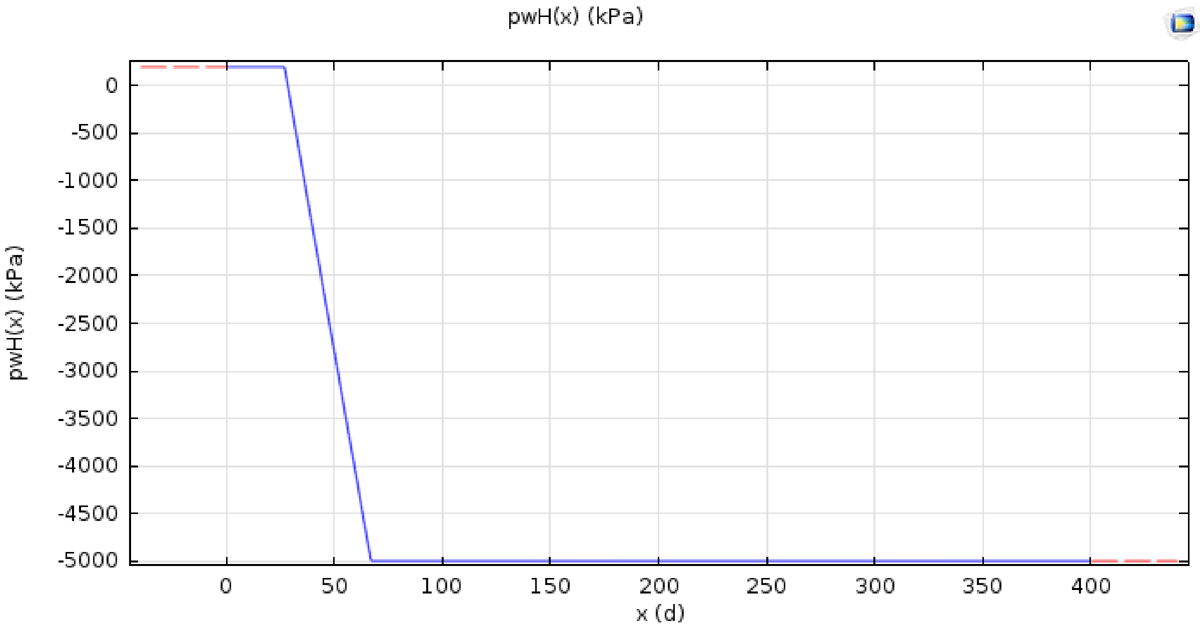

Fig. 3. The hydraulic loading

The reinforced concrete is elastic with the density ρ= 2500 kg/m^3, the Young's modulus E=50 GPa, the Poisson's ratio ν=0.2.

The massif is elastic with Mohr-Coulomb associated plasticity where the shallow expansive layer has H/2 of thickness and ρ=1800 kg/m^3, E=50 MPa, ν=0.3, the cohesion is c=50 kPa and the internal friction angle is φ= 30°.

The bottom layer has ρ=2000 kg/m^3, E=90 MPa, ν=0.3, c=50 kPa and φ= 35°. The water density is : ρ=1000 kg/m^3.

The hydraulic characteristics of the massif taken as a porous medium are : the saturated liquid volume fraction θ_s=0.4, the residual liquid volume fraction θ_r=1.e-6. The hydraulic conductivity K_s is variable with the hydraulic phase and is 0,5 m/d in Humidification and 1,5 m/d in drainage. The storage is S=5e-6 Pa^{-1}.

The van Genuchten retention model is defined with α=0.87 m^{-1}, n=1.38 and l=0.5.

The reinforced concrete hydraulic characteristics are : θ_s=0.1, θ_r=1.e-8. K_s= 2e-12 m/s, S=0.01 Pa^{-1}, α=1 m^{-1}, n=2 and l=0.5.

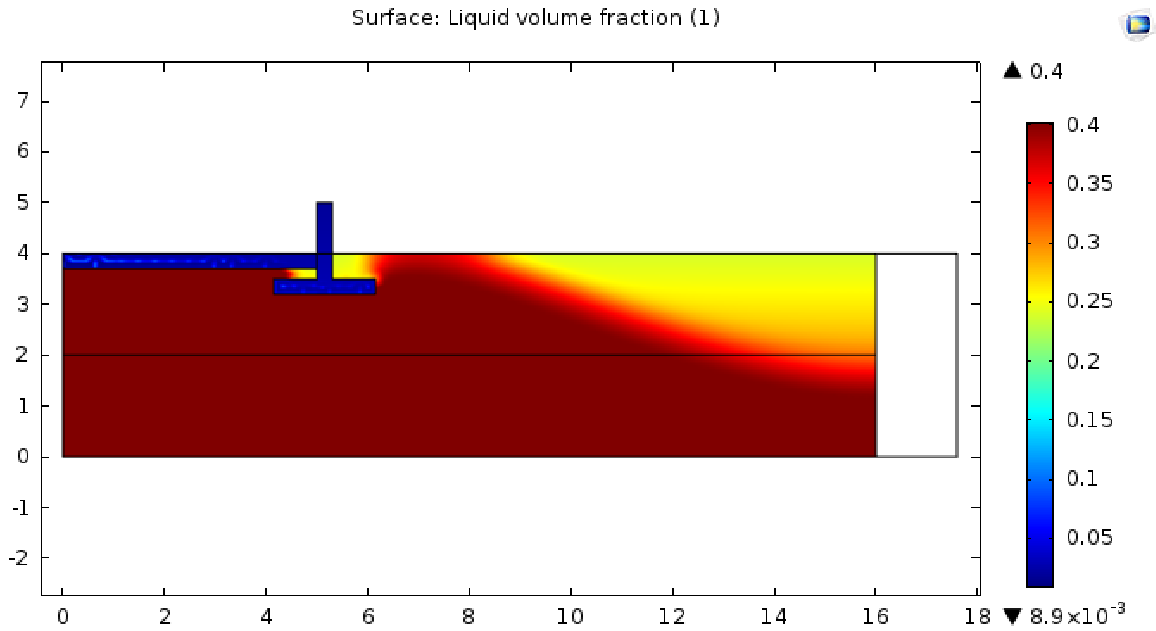

Fig. 4. profile of the liquid volume fraction at t = 7 day.

The initial stress has been estimated with the elastic plastic soil behavior. After, assuming that the service load is lower than the plastic limit load, the elastic behavior is used to simulate the hydro mechanical coupling.

Because we are interested to the reinforced concrete structure behavior, the analysis is conducted in total stresses. The simulation results are resumed as follow. The evolution of the liquid volume fraction profile is showed in (Fig. 4) at t= 7 day.

The total saturation is obtained at t=16 day. In the drainage phase, (Fig. 5) shows the liquid volume fraction at t= 360 day.

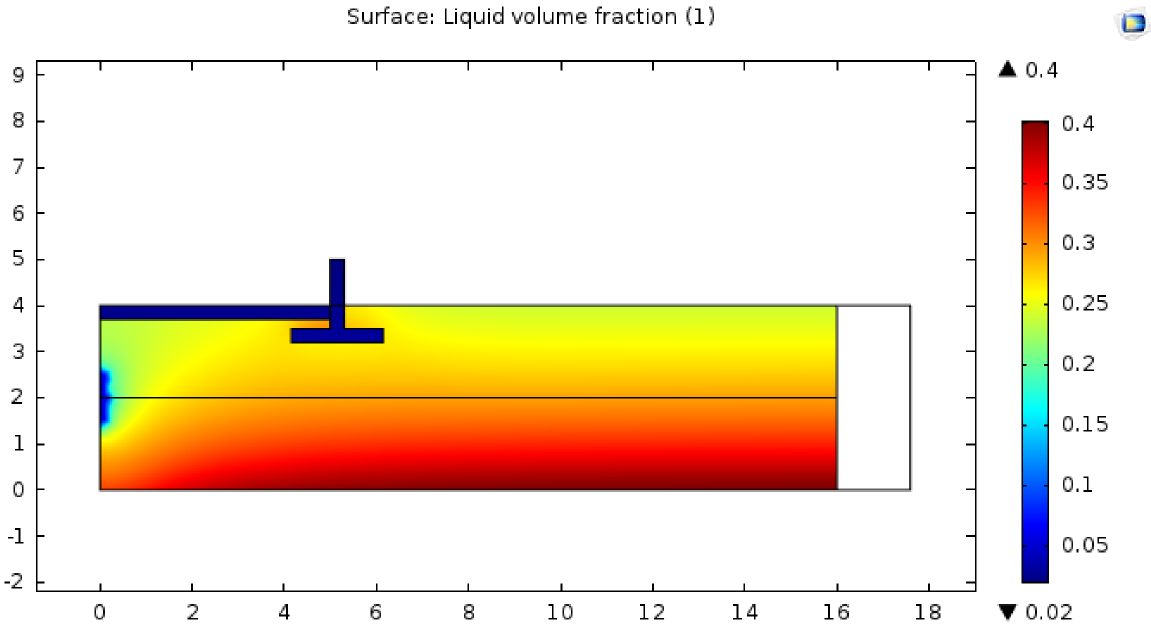

Fig. 5. The liquid volume fraction at t = 360 day.

The time evolution of the local liquid volume fraction is given in (Fig. 6).

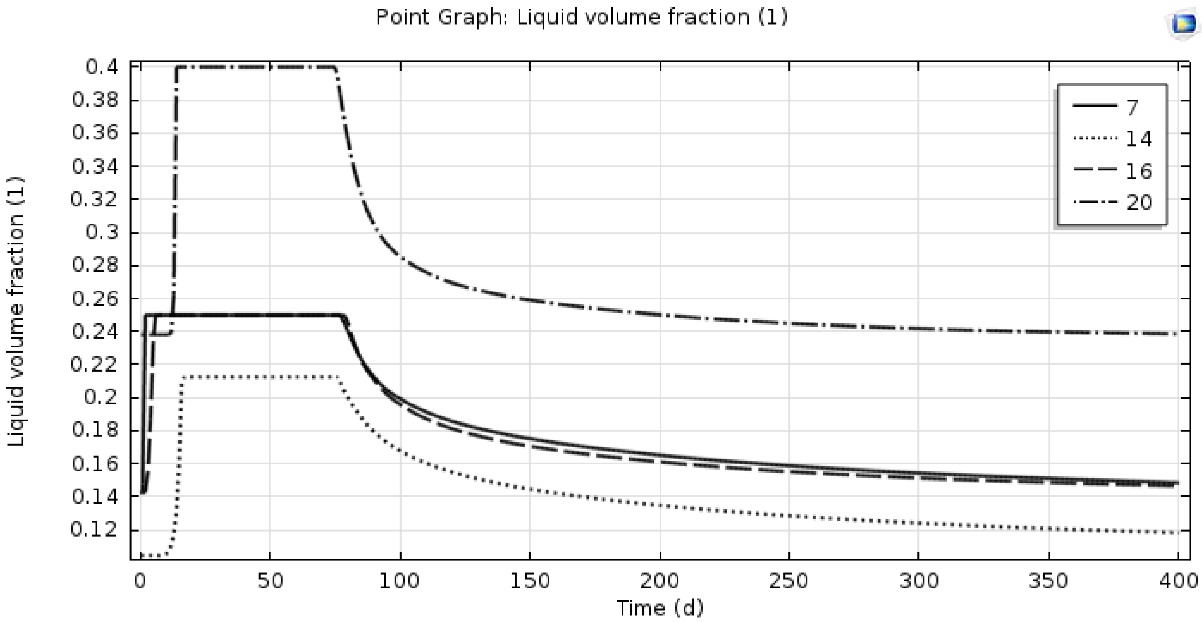

Fig. 6. The time evolution of the local liquid volume fraction.

To illustrate the distortion generated at the footing level, (Fig. 7) show vertical displacement of the footing corners.

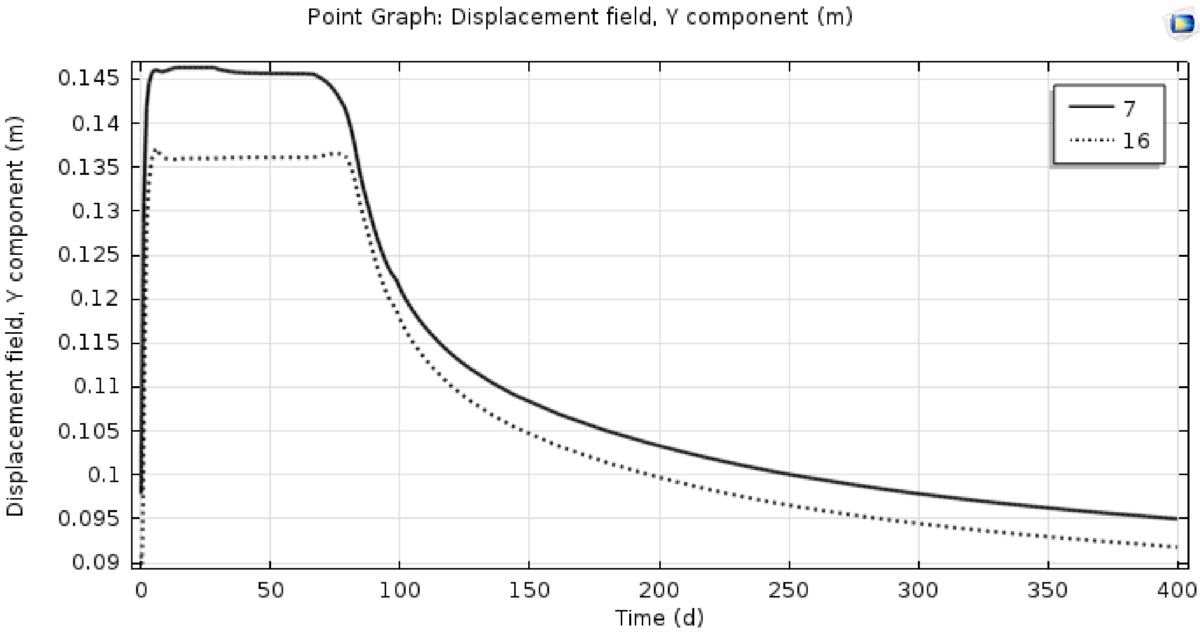

Fig. 7. The footing corners displacement . Case of rigid footing.

Also, (Fig. 8) quantify the vertical stress variation. The conclusions can be expressed here.

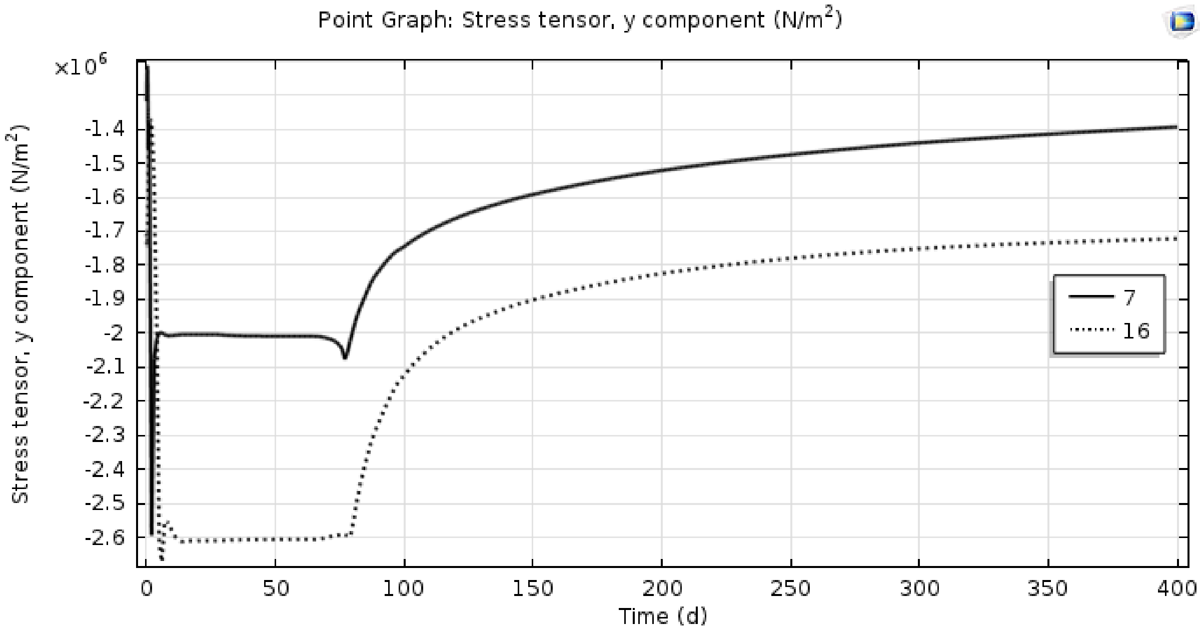

Fig. 8. The footing corners stress. Case of rigid footing.

The required time for drying is most important than for saturation as shown in (Fig. 6). One see that the nodes 7, 16 belonging to the structures, reach quickly the saturated volume fraction firstly because they are relatively near to the inlet. They are followed by the soil node 20 that is far away and for which the saturated volume fraction is greater. The node 14 reaches the saturation late because it is located beyond the glutted zone (Fig. 4). Do to the swelling stress, the distortion becomes maximum when the saturation take place (Fig. 7). In the drying phase, the distortion seems relatively constant. The same remarks as above can be formulated for the stress fields with the difference that stress distortion is always large and affect the all phases with appearance of several peaks (Fig. 8). Thus, the cyclic soil-structure-water interaction leads to cyclic distortion and stress that induce the footing incline, eccentricity towards the transmitted load and the modification of the footing base as shown in (Fig. 9, 10).

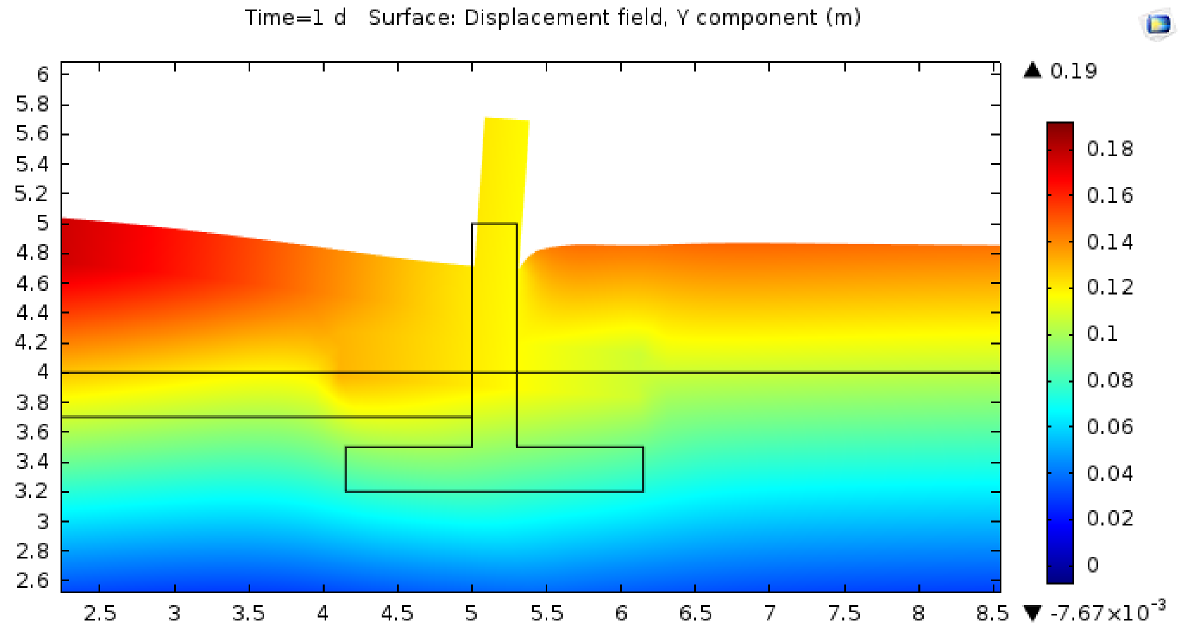

Fig. 9. The footing distortion for one cycle humidification-drainage.

Then, in addition to the reduction of the limit load, the earth structures suffer a serious warps, damages, cracking that is transmitted to the superstructures.

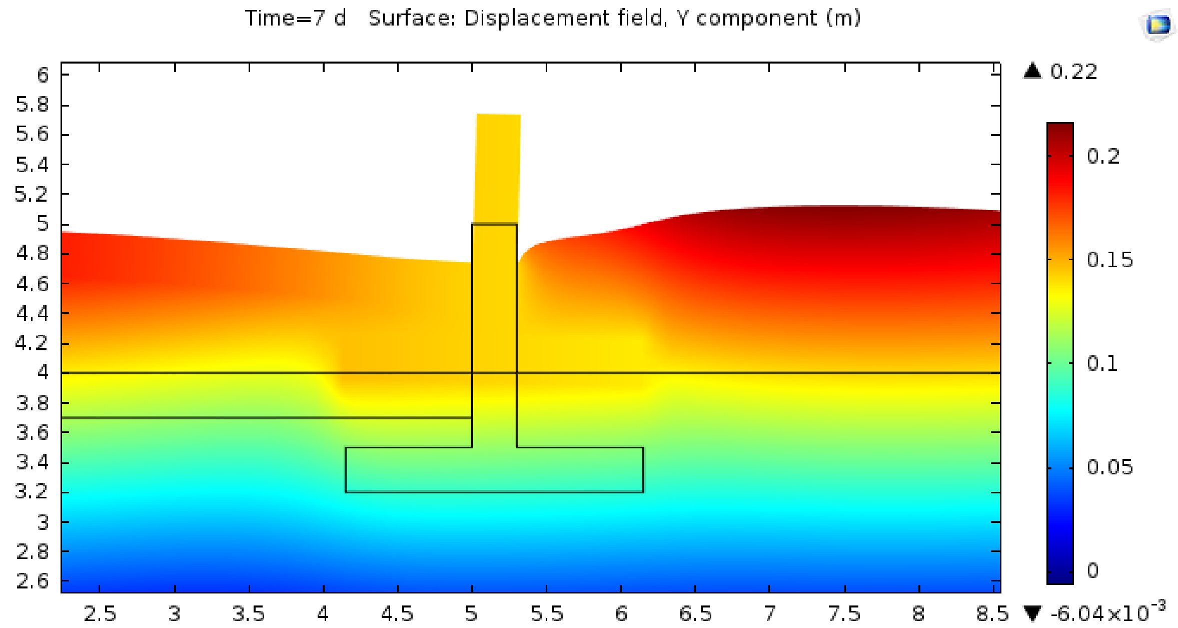

Fig. 10. The footing distortion for one cycle humidification-drainage.

6. Conclusion

The soil-structure-water interaction is the origin of rigorous problems particularly in the domain of construction . Trough this paper we have presented the practical methodology and we have shown the feasibility with an hydromechanical application. The simulation enable the quantification of damages in terms of general distortion and general stress. This conducts to loss of the load capacity and the development of a second order effects variables with the soil moisture. The soil behavior model can be satisfied with the linear laws that are simples and require less parameters or use sophisticated ones as the viscous elastic plastic laws for unsaturated soils. Also, the analysis can be generalized to take account the hydrothermal exchanges and evaporation to get a more sophisticated model and larger applications.

7. References

[1] Sakai Masaru, Jones Scott B. and Tuller Markus, 2011, Numerical evaluation of subsurface soil water evaporation derived from sensible heat balance, Water resources research, Vol. 47, W02547, doi:10.1029/2010WR009866, 2011

[2] Banimahd S.A., Zand-Parsa Sh., 2013, Simulation of evaporation, coupled liquid water, water vapor and heat transport through the soil medium, Agricultural Water Management 130 (2013) 168–177

[3] Wu C.L., Chau K.W., Huang J.S., 2007, Modelling coupled water and heat transport in a soil–mulch–plant–atmosphere continuum (SMPAC) system, Applied Mathematical Modelling 31 (2007) 152–169

[4] Xiao B., Zhao Y.-G., Shao M. -A., 2010, Characteristics and numeric simulation of soil evaporation in biological soil crusts, Journal of Arid Environments 74 (2010) 121–130

[5] Lakoud A., Curet S., Hassouna M., 2015, Modeling and Simulation of Hydration Operation of Date Palm Fruits Using COMSOL®Multiphysics, Excerpt from the Proceedings of the 2015 COMSOL Conference in Grenoble

[6] Brown Hamish, Carrick Sam, Müller Karin, Thomas Steve, Sharp Joanna, Cichota Rogerio, Holzworth Dean, Clothier Brent, 2018, Modelling soil-water dynamics in the rootzone of structured and water-repellent soils, Computers and Geosciences 113 (2018) 33-42

[7] Mahdavi Seyed Mohamad, Neyshabouri Mohammad Reza, Fujimaki Haruyuki, Heris Abolfazl Majnooni, 2017, Coupled heat and moisture transfer and evaporation in mulched soils, Catena 151 (2017) 34-48

[8] An Ni, Hemmati Sahar, Cui Yu-jun, Tang Chao-sheng, 2018, Numerical investigation of water evaporation from Fontainebleau sand in an environmental chamber, Engineering Geology 234 (2018) 55-64

[9] Pandey Vanita, Pankaj K. Pandey, 2010, Spatial and Temporal Variability of Soil Moisture, International Journal of Geosciences, 2010, 1, 87-98

[10] Daichao Sheng, 2011, Review of fundamental principles in modelling unsaturated soil behaviour, Computers and Geotechnics 38 (2011) 757–776

[11] Petitta Marco, MARIÑO Miguel A., 2010, Numerical Simulation of Pesticide Transport and Fate for Water Management in the Fucino Plain, Italy, J. Water Resource and Protection, 2010, 2, 29-41

[12] Liu Quan, Hu Rui, 2017, Simulation of Heat and Mass Transfer during Artificial Ground Freezing in Saturated Saline Groundwater, Excerpt from the Proceedings of the 2017 COMSOL Conference in Rotterdam

[13] Meot Jean-Michel, Briffaz Aurélien, Jacquin Didier, Rashidi Salim, 2015, 1D central symmetry modelling of shrinkage for non-porous materials, Excerpt from the proceedings of the 2015 COMSOL Conference in Grenoble

[14] Poirier Catherine Raymond and Courcelles Benoît, 2015, Modeling of Biocalcification in Non-saturated Conditions, Excerpt from the Proceedings of the 2015 COMSOL Conference in Boston

[15] Touati Boumediene, Lips Bernard, Benyoucef Boumediene and Virgone Joseph, 2012, Superficial evaporation in forced convection of porous medium in transitory laminates regime « Application on mint leaves drying », Energy Procedia 18 (2012) 966 – 973

[16] Sun De'an, Sun Wenjing, Xiang Li, 2010, Effect of degree of saturation on mechanical behaviour of unsaturated soils and its elastoplastic simulation, Computers and Geotechnics 37 (2010) 678–688

[17] Teng Jidong, Yasufuku Noriyuki, Zhang Sheng, He Yi, 2016, Modelling water content redistribution during evaporation from sandy soil in the presence of water table, Computers and Geotechnics 75 (2016) 210–224

[18] Castellini Mirko, Prima Simone Di, Iovino Massimo, 2018, An assessment of the BEST procedure to estimate the soil water retention curve: A comparison with the evaporation method, Geoderma 320 (2018) 82–94

[19] Johari A., Javadi A.A., Habibagahi G., 2011, Modelling the mechanical behaviour of unsaturated soils using a genetic algorithm-based neural network, Computers and Geotechnics 38 (2011) 2–13

[20] Khoei A.R., Mohammadnejad T., 2011, Numerical modeling of multiphase fluid flow in deforming porous media: A comparison between two- and three-phase models for seismic analysis of earth and rockfill dams, Computers and Geotechnics 38 (2011) 142–166

[21] Navas Pedro, López-Querol Susana, Yu Rena C. and Li Bo, 2015, B-bar based algorithm applied to meshfree numerical schemes to solve unconfined seepage problems through porous media, Int. J. Numer. Anal. Meth. Geomech. (2015)

[22] Noda T., Yamada S., 2005, Soil-water coupled elasto-plastic analysis on bearing capacity of naturally deposited clay soil, Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering, © 2005–2006 Millpress Science Publishers/IOS Press

[23] Seetharam Suresh C, and Diederik Jacques, 2013, Developments in a Coupled Thermal-Hydraulic-Chemical-Geomechanical Model for Soil and Concrete, Except from the proceedings of the 2013 Comsol Conference in Rotterdam

[24] Bien Le Binh, Predelus Dieuseul, Lassabatere Laurent, Winiarski Thierry, Angulo-Jaramillo Rafael, 2013, Combined Effect of Infiltration, Capillary Barrier and Sloping Layered Soil on Flow and Solute Transfer in a Heterogeneous Lysimeter, Open Journal of Modern Hydrology, 2013, 3, 138-153

[25] Robinet J.C., Dang K.D., Bui T.D. & Trinh Q.V., 2005, Heat and mass transfer in expansive clay. Mechanisms analysis and application to the predictive modelling of a large scale in situ experiment, Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering, © 2005–2006 Millpress Science Publishers/IOS Press.

[26] Brindt Naaran and Wallach Rony, 2017, The moving-boundary approach for modeling gravity-driven stable and unstable flow in soils, Water Resour. Res., 53, doi:10.1002/2016WR019252

[27] Montrasio Lorella, Valentino Roberto, Quintavalla Chiara, 2010, Estimation of the Degree of Saturation of Shallow Soils from Satellite Observations to Model Soil Slips Occurred in Emilia Romagna Region of Northern Italy, International Journal of Geosciences, 2010, 1, 58-65

[28] Smith I. M. and Griffiths D. V., Programming the finite element method, Second edition, John Wiley & Sons, Chichester, 1988

[29] Bathe K.J., Finite Element Procedures, Prentice−Hall, New Jersey, 1996

[30] Wood D. M., Geotechnical modelling, CRC Press, July 22, 2004