INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

SIMSG   ISSMGE

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Soil surface boundary condition in desiccating soils
Condition aux limites de la surface de sol dans les sols dessicants

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ABSTRACT: Soils undergoing desiccation exhibit shrinkage and eventually cracking. That may become an environmental problem in practical applications. From a Geotechnical perspective, it is possible to solve the corresponding Thermo-Hydro-Mechanical (THM) equations involved in the problem applied to the soil mass. When this is attempted, the challenge of defining the surface boundary condition arises. The paper presents an analysis of the soil-atmosphere interaction problem in the context of desiccating soils considering experiments and numerical analyses solving the TH equations using an "in house" Finite Element code. A comparison between measurements and calculations highlights the main variables dominating the evaporation from soil surfaces. The boundary condition applied on the soil surface is discussed in detail and becomes the key aspect in this kind of simulations.

RÉSUMÉ: Les sols en cours de dessiccation présentent un retrait et éventuellement une fissuration. Cela peut devenir un problème environnemental dans les applications pratiques. D'un point de vue géotechnique, il est possible de résoudre les équations Thermo-Hydro-Mécaniques (THM) correspondantes impliquées dans le problème appliqué à la masse du sol. Lorsque cela est tenté, une difficulté majeure réside dans la définition des conditions aux limites à la surface du sol. Le document présente une analyse du problème de l'interaction sol-atmosphère dans le contexte de la dessiccation des sols, en tenant compte des expériences et des analyses numériques résolvant les équations TH à l'aide d'un code «interne» éléments finis. Une comparaison entre les mesures et les calculs met en évidence les principales variables dominant l'évaporation à la surface du sol. La condition à la limite appliquée à la surface du sol est discutée en détail et apparait être l'aspect essentiel de ce type de simulations.

Keywords: Desiccating soils; Soil-atmosphere interaction; Evaporation; TH analysis

1 INTRODUCTION

Desiccation of soils induces shrinkage because of the water loss due to evaporation. Eventually and particularly if the deformation is not homogeneous, cracks develop on soil surface and maybe in the soil mass as well. This is indeed an environmental problem with important consequences from a Geotechnical perspective (Blight, 1997). On the one hand, cracked soils have large permeabilities and preferential flow paths which can be a serious drawback in liners or clay barriers for water containment or for waste isolation purposes. On the other hand, cracked soil has reduced mechanical properties, i.e., bearing capacity may decrease from $(2+\pi)$ S_u to $2S_u$, being S_u the undrained shear strength.

Despite the importance of this process in practical applications, the analysis of soil desiccation is still far from being a routine. The classical approach in Soil Mechanics and Geotechnical Engineering involves the solution

of the unsaturated flow equation in a geometry applying a boundary condition to the ground surface. The definition of the surface boundary condition becomes then a fundamental issue. It is accepted that temperature plays an important role in the evaporation process and most of the analyses performed nowadays are Thermo-Hydraulic (TH) simulations. Recent developments include a mechanical constitutive law in the analyses (Levatti et al, 2018).

When laboratory experiments involving evaporation processes are simulated using the unsaturated flow equation, the classical boundary condition may be expressed in terms of a prescribed suction at soil surface. That suction is related to the relative humidity of the laboratory atmosphere. However, when the experiments are conducted in the field, evaporation is mainly controlled by other factors, such as temperature and wind velocity. In this case the boundary condition must be defined in terms of an energy balance at the soil surface (Cuadrado, 2019).

In this paper a simulation of evaporation processes in soils using a TH formulation is presented and applied to laboratory experiments. The extension to field conditions is also indicated. Some laboratory experiments are described first and then the TH formulation and the corresponding simulations are presented. The boundary condition at the soil surface controls the evaporation rate and therefore, its correct definition becomes fundamental in the simulations. A sensitivity analysis is carried out to check the effect on the evaporation process. Final remarks about the effect of cracking on evaporation are also included.

2 EVAPORATION EXPERIMENTS

Several trays filled with saturated sand, saturated soft clay and water were exposed to a laboratory atmosphere with controlled temperature and relative humidity (22ºC ± 2ºC and 60% ± 5%). The weight of trays was measured by using a scale, to check the rate of water loss. Several trays were installed simultaneously on a table, but it was found out that evaporation was different depending on the relative position of the trays. It became evident that evaporation was very sensitive to local conditions in the laboratory (small local wind, local heterogeneities of air relative humidity, etc). Only a few selected trays, considered representative, will be shown in this paper.

2.1 Materials and methods

The sand used in the experiments was taken from Castelldefels beach, south of Barcelona. It is a uniform sand (SP, Universal Soil Classification) with most particles in the range 0.2 – 0.4 mm and solid grains density of 2.65 g/cm^3.

The clay was obtained from the "Agropolis" site, an area close to Barcelona Airport used by UPC for field experiments. It is in fact a clayey sand (SC, Universal Soil Classification) with solid particles density of 2.70 g/cm^3, but only the fine fraction (size < 0.40 mm) was used in the experiments. Liquid limit is 28%, plastic limit 16% and Plasticity Index is 12%.

Several plastic trays were filled with sand, clay or just water. Sand and clay were mixed initially with water to form a saturated material with liquid consistency in order to get a homogeneous mixture, easy to pour on the trays. Then the trays were exposed to a controlled laboratory atmosphere as mentioned above. Figure 1 shows the evolution of a clay tray, showing the desiccation process and cracking. Cracks were not observed in the sandy trays.

Many trays were exposed to that atmosphere in order to check repeatability. From all the experiments carried out, a list of selected trays is presented in Table 1, indicating the type of material and the amount of water loss due to evaporation.
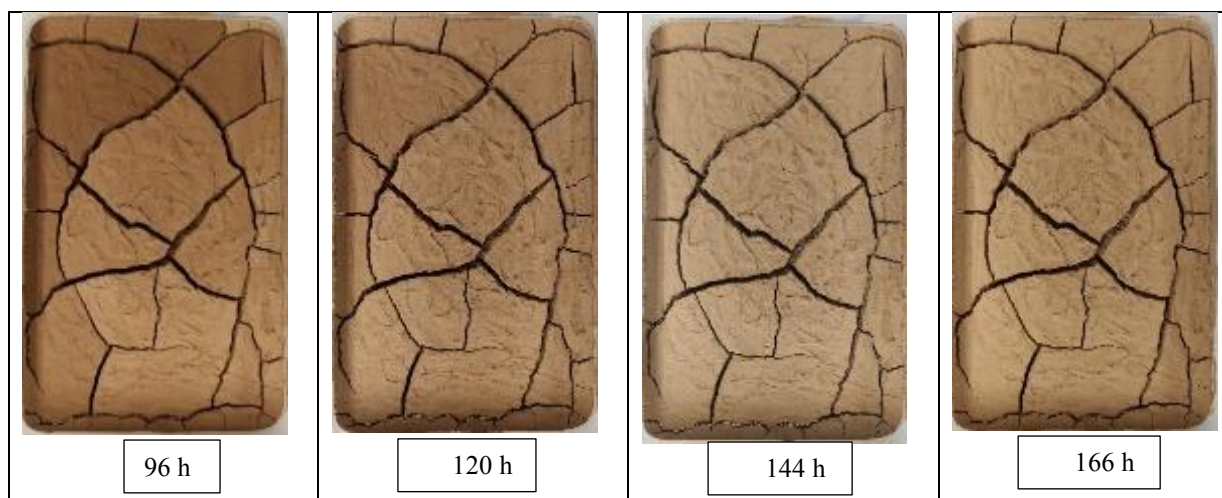
Figure 1. Pictures obtained at different times (in hours) during desiccation of a typical clayey tray (test E2)

Table 1. Selected list of trays including saturated sand or clay, desiccated under controlled conditions.
("e"=soil thickness)

Tray	Mater.	Initial weight (g)	Initial water (g)	Final water (g)
A4	Sand e=17mm	1666.30	312.4	0.5
B4	Sand e=17mm	1659.62	312.6	0.5
C2	Sand e=30mm	2401.07	448.7	0.2
C4	Sand e=17mm	1662.95	310.6	0.5
D1	Sand e=17mm	1648.8	308.3	4.2
D2	Sand e=17mm	1646.74	303.0	0.8
D4	Sand e=17mm	1658.15	311.5	0.5
E1	Clay e=22mm	1805.0	446.4	27.8
E2	Clay e=22mm	1976.48	492.9	28.0
E4	Sand e=17mm	1663.07	311.7	0.5

2.2 Trays with water

As a reference, trays filled with demineralized water were exposed to the same laboratory atmosphere and the water loss due to evaporation recorded at different times. Table 2 presents the properties of the trays with water. Figure 2 presents the evolution of water loss along time. The rate of water loss is apparently constant, with small differences between trays that may be explained because environmental conditions may not be exactly the same above all trays. It becomes evident that evaporation is very sensitive to small local variations of boundary conditions, even in an "apparent" controlled environment.

Table 2. Characteristics of the trays with water only

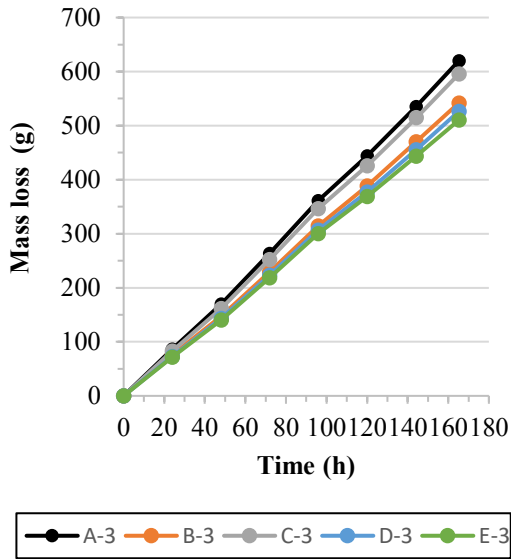| Tray	Mater.	Initial weight (g)	Final weight (g)
A3	Water	1754.8	1134.6
B3	Water	1749.7	1207.5
C3	Water	1760.8	1165.1
D3	Water	1760.1	1233.5
E3	Water	1743.5	1233.2

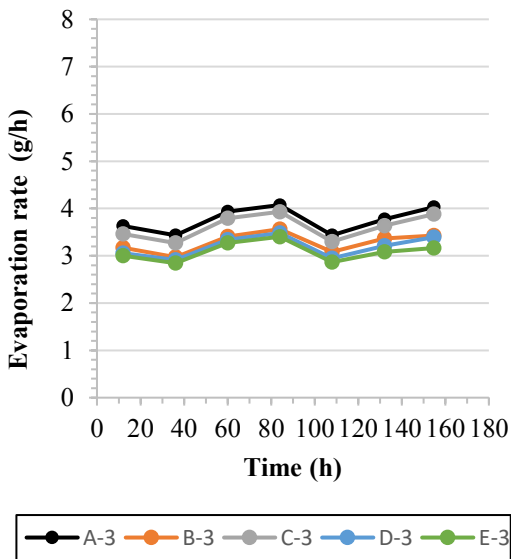*Figure 2. Loss of water over time for the trays with water only*

Figure 3. Rate of evaporation for trays with water only

Figure 3 shows the rate of water loss obtained from Figure 2. Rates are always between 3 and 4 g/h.

2.3 Trays with soil

The evolution of the weight loss along time for trays with clay and with sand is represented in Figure 4. Note that there is a constant final weight of the trays suggesting a limit in the evaporation process. That constant limit depends on the characteristics of the tray (thickness of the soil and type of soil – clay/sand).

Figure 5 presents the evaporation rate for the trays over time. Note that there are 3 stages well defined in this evolution, as indicated by other authors (Shokri et al., 2010; Zhang et al, 2015, Wilson et al., 1997). The first stage in which the rate is constant, basically controlled by the environment, although its duration depends on soil properties. The second stage where the rate decreases gradually, controlled basically by soil hydraulic properties. A final third stage with a very low rate of evaporation and vapour diffusion as main mechanism of water flow. This final rate could be zero if the water is totally evaporated as in closed systems like the trays.
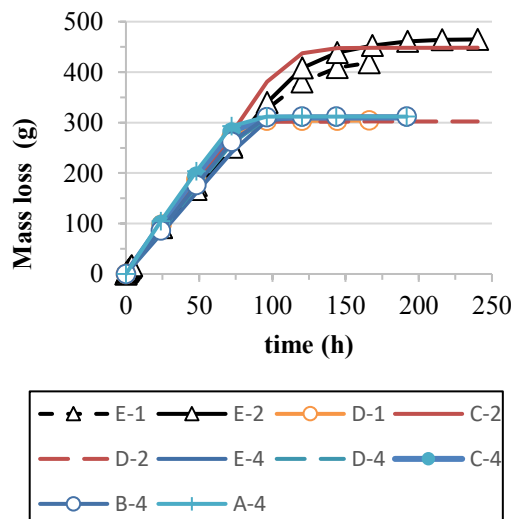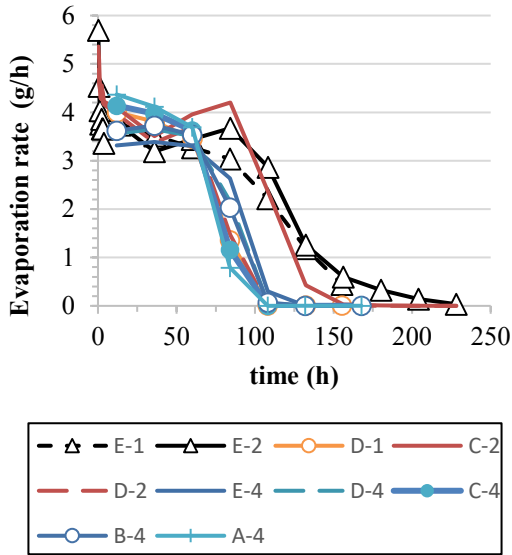

Figure 4. Mass loss over time for the trays with soil

Figure 5. Rate of evaporation for the trays with soil

2.4 Discussion of results

It is convenient to compare evaporation rates at the beginning of the desiccation process, where environmental conditions dominate the process. Note that initial evaporation rate is about 3 to 4 g/h for sand and clay, similar to the value measured in trays with water. In some cases, however, a greater value has been measured at the initial time.

When analysing evaporation rates, it is common to refer the values measured on soil surfaces (actual evaporation) to the values measured on pure water (potential evaporation). This ratio is assumed to be always less than one, that is, evaporation from water is assumed to be the maximum value.

Figure 6 presents the ratio Actual Evaporation over Potential Evaporation for some selected trays. Note that values above 1 at the beginning of the desiccation were measured in some cases. It becomes evident that measurements are very sensitive to boundary conditions (temperature and relative humidity).
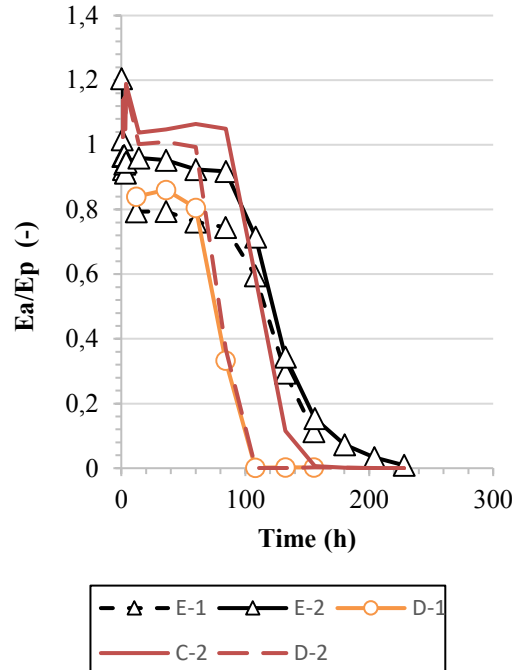

Figure 6. Ratio of Actual Evaporation over Potential Evaporation for selected trays.

Results are not totally conclusive to suggest that Actual Evaporation may be greater than Potential Evaporation in some cases. This is a controversial issue, as it is not clear if in any case evaporation from soil surfaces may be greater than from water (Tollenaar et al., 2018, Encalada, 2018).

Another effect observed in the experiments is the fact that cracking does not change substantially the evaporation rate, as observed in other experiments (Lakshmikantha, 2009, Cuadrado, 2019).

3 NUMERICAL SIMULATIONS

3.1 Main assumptions

An in house Thermo-Hydro-Mechanical Finite Element Code ("Code_Bright") has been used to simulate the evaporation process observed

in the trays. A detailed description of the equations and the formulation is presented in Olivella et al. (1996). The program solves the balance equations for mass (solid, water and gas) and energy in a porous medium. In addition to that, appropriate constitutive equations are considered. This includes mechanical constitutive equation (if Mechanical problem is considered), Darc's law (for advection of water and gas), Fick's law (for diffusion) and Fourier's law (heat conduction). Kelvin equation considers that phase change is instantaneous and Henry's law defines the amount of air dissolved in liquid water. Usually the gas pressure is assumed to be constant (the atmospheric pressure) in this type of problems and this assumption has been considered in the examples below. Additionally, the mechanical problem has not been solved in these cases.

3.2 Boundary conditions

The boundary conditions at the soil surface define the evaporation rate in a boundary value problem. The flux of vapour, j_g^w, at the soil surface is specified as:

$$j_g^w = (\omega_g^w)^0 j_g^0 + \beta_g \left((\rho_g \omega_g^w)^0 - (\rho_g \omega_g^w) \right) \tag{1}$$

where subscript indicates phase (g: gas) and superscript species (w: water), ω is the mass fraction, ρ is density, P_g is gas pressure, and the superscript ^{0} refers to a prescribed value. β_g is a parameter controlling the boundary condition. If $\beta_g = 0$, then a fixed flow is imposed, but if β_g is large, difussion of vapour prevails.

The boundary condition in terms of energy is defined by imposing the flux of energy, j_e :

$$j_e = j_e^0 + \gamma_e (T^0 - T) + E_g^w j_g^w + E_g^a j_g^a + \\ + E_l^w j_l^w + E_l^a j_l^a \tag{2}$$

where the first term is a prescribed flux of energy, second term is used to prescribe a fixed temperature (by using a large value of γ_e) and the rest of terms are energy fluxes. E is the internal energy for each component: water vapour and air in gas phase and water and dissolved air in the liquid phase.

In practical applications, defining β_g and γ_e are fundamental, as they control how fast boundary conditions are applied to the soil mass in contact to the atmosphere. They can be obtained by calibration if measurements are available. In desiccating soils at laboratory environmental conditions, evaporation is controlled by relative humidity and temperature. However, under field conditions, wind velocity and radiation play a fundamental role in the evaporation rate (Blight, 1997). In that case it is possible to relate β_g and γ_e with wind velocity and atmospheric physical properties, but this is out of the scope of this paper (Cuadrado, 2019).

3.3 Numerical results

Experiments involving trays with water, clay and sand were simulated. Water was represented as a material with a high porosity (0.99), high intrinsic permeability (10^{-7} m^2) and a water retention curve with low suction. Figure 7 shows the liquid permeability depending on saturation ratio, S_l, and Figure 8 presents the water retention curves.

A 2D geometry was considered in the simulations. Lateral boundaries were assumed to be impervious to any phase and to heat, whereas the bottom boundary was impervious to gas and water, but allowed the transfer of energy. For the sake of simplicity, the same parameter γ_e was used for the upper and lower boundaries.

The area of the models (for 1 m) corresponds to the area of the trays, as evaporation occurs on the tray surface. The thickness of the model was the same as in the experiments.
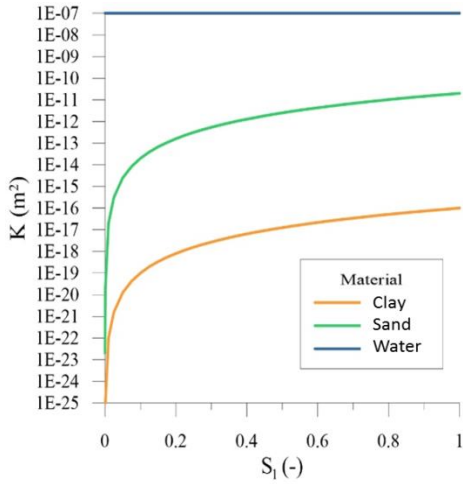
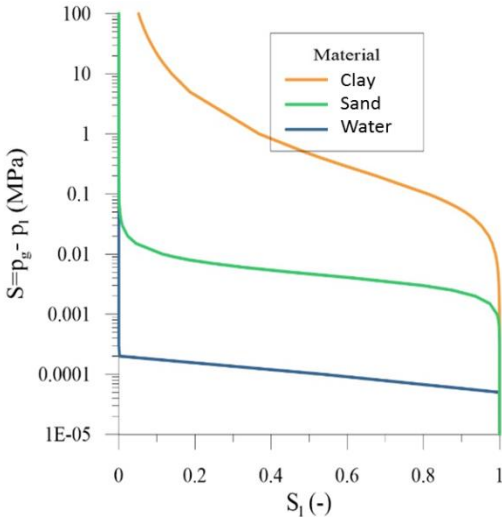*Figure 7. Intrinsic permeability considered in the simulations*

Table 3. Boundary conditions used in the simulations

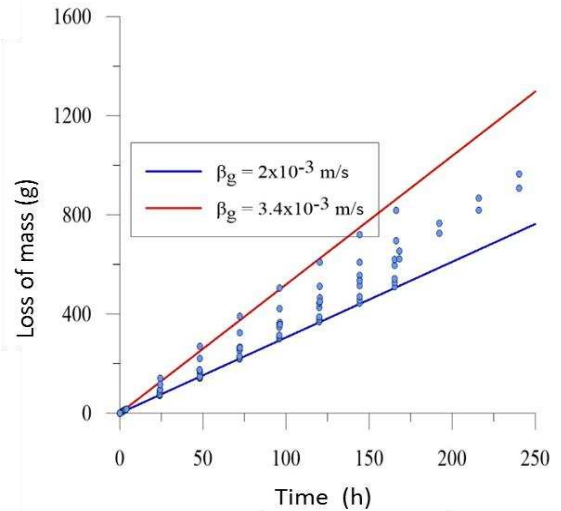| Material	Water	Clay	Sand
ρ_a^0 (kg m^{-3})	1.2102		
ρ_v^0 (kg m^{-3})	0.0117		
ω_g^0 (kg kg^{-1})	0.0096		
β_g (m s^{-1})	$2 \cdot 10^{-3}$ to $3.4 \cdot 10^{-3}$	$2.5 \cdot 10^{-3}$	$2.1 \cdot 10^{-3}$ to $2.7 \cdot 10^{-3}$
γ_e (J s^{-1}°C^{-1})	10^5 to 10		

Figure 9. Evaporation from water trays. Comparison between measurements (dots) and simulations (lines) using two different values of β_g

Figure 8. Soil water characteristic curves used in the simulations (suction vs saturation ratio)

Temperature in the laboratory was 22°C and Relative Humidity 60%. Table 3 presents the specifications used in the boundary conditions. Figure 9 shows the results of two simulations for water trays in terms of loss of mass of water against time. Each simulation corresponds to a different value of β_g and the same value of $\gamma_e = 10^5$ (which implies a quick equilibrium of temperature in the medium and outside).

Figures 10 and 11 present the comparison between measurements and simulations for clayey and sandy trays respectively. In all cases simulations reproduce reasonably the tendency of measurements, particularly at the beginning of the evaporation process (stage 1), when environmental conditions dominate. However, they are very sensitive to the parameter β_g. In general this parameter should be calibrated to reproduce actual measurements as there is not a consistent routine to define this value in advance. Parameter γ_e controls temperature evolution, but this will be discussed elsewhere.
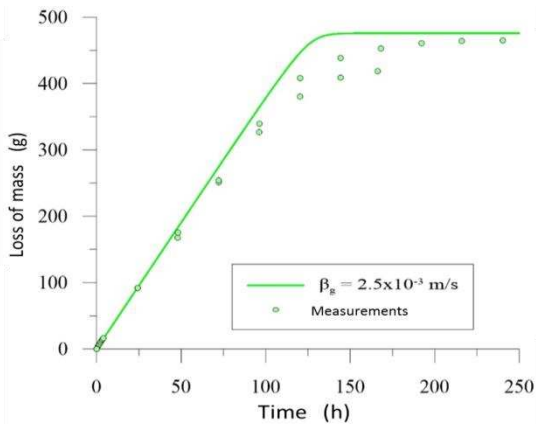
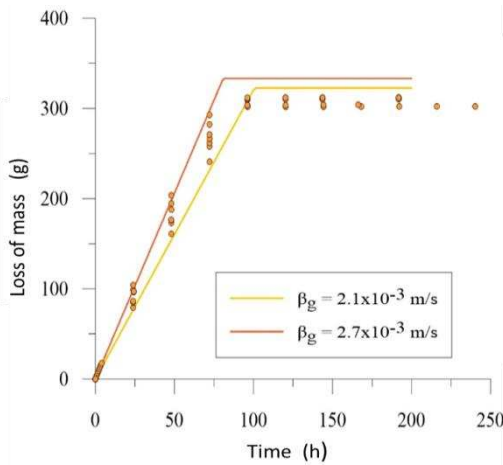Figure 10. Evaporation from clayey trays

Figure 11. Evaporation from sandy trays. Measurements (dots) and simulations (lines)

4 CONCLUSIONS

The paper presents a set of experiments involving desiccation of soil trays (clay and sand). Because of evaporation is the main driving process, trays with water only have been used for reference as well. TH numerical simulations reproduce reasonably the loss of water along time at the begining of the processs, when environmental conditions dominate. A discussion about the boundary conditions used is presented. It has been observed that cracking does not change the rate of evaporation in clayey samples.

5 ACKNOWLEDGEMENTS

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