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Experimental and numerical investigation of soil-atmosphere interaction

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ABSTRACT

The soil-atmosphere interaction was investigated by conducting physical model test in the laboratory and by performing numerical analysis using data from an experimental site.

For the physical model test, a large scale environmental chamber was developed. This chamber was instrumented by various sensors allowing the soil suction, volumetric water content, and temperature to be monitored at various depths. In the zone occupied by air, temperature, relative humidity and air rate (wind speed) were monitored. The soil surface temperature was also measured by an infrared thermometer. The soil sample was prepared by compaction and wetted from the soil surface before being dried under controlled conditions of relative humidity, temperature and flow rate of air. A camera fixed above the chamber allowed monitoring the development of cracks. The evaporation rate was calculated based on the temperature and relative humidity data at the inlet and the outlet of the chamber, allowing assessment of the performance of the chamber to simulate the evaporation phenomena. The results show that evaporation is a heat consuming process: in the test condition, both air and soil were cooled by the evaporation process. Cracks developed during soil drying. Analysis of the 'cracking surface ratio' and 'weighted width' showed that the evolutions of these two parameters are similar: thus, in practice, only one is needed for evaporation analysis.

For the numerical analysis, a two-dimensional model of soil-atmosphere interaction was developed and implemented in a fully coupled thermo-hydro-mechanical (THM) code. The soil surface boundary conditions were determined from meteorological data using water balance and energy balance equations. The settlement due to soil-atmosphere interaction in an experimental site was simulated. Comparison between calculation and measurement showed that the THM codes can satisfactorily predict the soil settlement, provided that appropriate evapotranspiration models are implemented.

1. Introduction

The soil–atmosphere interaction has been widely studied in the fields of agronomy, hydrology and climatology. It has been well recognised that soil water evaporation rate depends on various factors such as net solar flux, air conditions, soil surface properties and soil properties (Chanzy et al., 1995; Kobayashi et al., 1998; Qiu et al., 1998; Baruah and Hasegawa, 2001; Grifoll et al., 2005; Verhoef et al., 2006; Romano and Giudici, 2009). Recently, this issue has also received much attention in the field of geotechnical and environmental engineering (Zornberg and Caldwell, 1998, 2003, Cui et al., 2005; Cui and Zornberg, 2008; Blight, 2009; Cui et al., 2010) for applications on waste management and stability analysis of geotechnical structures.

For the experimental study, different devices have been developed for the measurement of soil water evaporation: the evaporation pan (Blight, 1997; Singh and Xu, 1997; Wilson et al., 1997); the lysimeter (Stroosnijder, 1987; Wallace, 1991; Kondo et al., 1992; Plauborg, 1995; Herbst et al., 1996; Wilson et al., 1997; Qiu et al., 1998; Wythers et al., 1999; Kuhn and Zornberg, 2006; Young et al., 2007); the system of wind-tunnel (Yamanaka et al., 1997; Yuge et al., 2005); the environmental chamber (Kohsiek, 1981; van de Griend and Owe, 1994; Aluwihare and Watanabe, 2003). Comparison between the different methods shows that the environmental chamber is one of the best devices for studying soil water evaporation because it can provide full set of data involving both air and soil, at a relatively low cost. However, examination of the existing environmental chambers shows that most of them only analyse the air conditions, the soil being few instrumented and studied (Kohsiek, 1981; van de Griend and Owe, 1994; Aluwihare and Watanabe, 2003).

In terms of numerical analyses, several models have been developed to calculate the actual evapotranspiration. Most of these models consider non-coupled heat and water transfer equations (Belmans et al., 1983). Some models calculate the actual evapotranspiration by solving coupled heat and mass transfer equations, including liquid and vapour phase transfers (Braud et al., 1993). However, all these models only deal with thermo-hydraulic aspect and completely neglect the mechanical aspect,

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despite the fact that in some geotechnical applications such as the assessment of buildings damage due to drought effects, it is important to evaluate the soil settlement due to soil water evaporation.

This paper shows two examples of investigating soil-atmosphere interaction, one, experimental, uses a well instrumented environmental chamber, while the other, numerical, is based on an evapotranspiration model implemented in an existing thermo-hydro-mechanical code, θ-stock (Gatmiri et al., 1999), for unsaturated soils. In the experimental work emphasis is put on the soil cracking effects, while in the numerical part of the research the adopted approach is validated by the comparison of soil settlement prediction based on parameters determined from laboratory tests and measurement at an experimental site.

2. Experimental investigation

2.1. Experimental set-up, materials and methods

The environmental chamber used is an acrylic transparent tank 800 mm wide, 1000 mm long and 1550 mm high. The 1550 mm height is occupied by soil (1000 mm) and air (550 mm). Several sensors were installed in the soil through two opposite walls of the chamber: at one side, 5 ThetaProbe sensors (TP) for the measurement of volumetric water content were buried every 200 mm; 10 relative humidity sensors (RS), 10 high-capacity tensiometers (TS) and 8 psychrometers (PS) for the measurement of suction in the full suction range were installed every 200 mm; the same number of sensors were installed in the opposite side wall, allowing one measurement every 100 mm along the height of the soil column for each type of sensor. The same sensor disposition was adopted for 10 PT1000 sensors that measured the soil temperature. The general layout of the environmental chamber is shown in Fig. 1. The temperature and relative humidity outside the chamber were also monitored.

For the air conditioning, flow rate controlled air from a compressed air source was measured by a flowmeter (±2% accuracy over the working range of 500 L/min). Thanks to a heating tube, air was then heated. The maximum temperature was about 250 °C (the air temperature in the chamber was much lower as it will be observed later through the results). The heated air was then monitored by one RS sensor giving the actual temperature and relative humidity of air before being diffused into the chamber through 8 holes of an air distributor. At the outlet of the chamber, the air was gathered in an air collector where temperature and relative humidity were again measured. Note also that monitoring the temperature at the soil surface was ensured by an infrared thermometer.

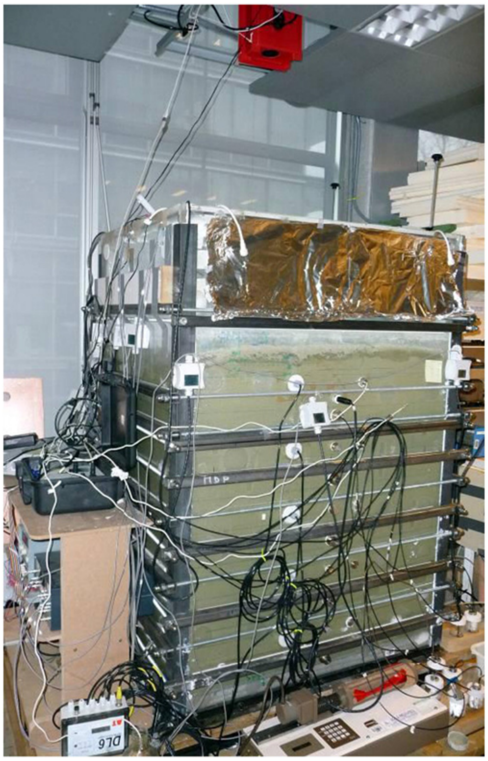

Fig. 1. Picture of the environmental chamber.

In order to monitor cracks at the soil surface during the drying process, a high definition camera with specific lens was fixed over the chamber. Furthermore, various resistance temperature sensors and RS sensors were installed inside the chamber in the zone occupied by air in order to obtain data useful to establish the temperature and humidity profiles through the entire height of the environmental chamber.

The Romainville clay taken from the eastern region of Paris was used for this study. Its basic geotechnical properties were investigated by Audiguier et al. (2007) and Laribi et al. (2008), and are shown in Table 1. From the relatively high values of Atterberg's limits (liquid limit of 75%; plastic limit of 40% and plasticity index of 35), large fraction of clay fraction (<2 μm, 84%) and large specific surface (98 m^2/g), it can be deduced that this soil is of expansive nature.

The soil taken from the site was air dried in the laboratory to reach a gravimetric water content of 5.7% and then crushed and sieved at 2 mm. The soil column in the environmental chamber was prepared by compaction in layers of 50 mm to a dry density of 1.35 Mg/m^3, similar to the in-situ dry density (Cui et al., 2006). All the sensors buried in the soil were installed during the compaction.

The compacted soil was first wetted from the surface during 338 days. The recorded data showed a good performance of all sensors installed in the soil (see Tang et al., 2009). In particular, the measured suctions and volumetric water contents allowed plotting the water retention curve as shown in Fig. 2. A linear relationship was identified in a semi-logarithmic plane. Note that at the end of the wetting phase, most of the soil column was saturated at a volumetric water content of nearly 50%, the volumetric water content of the first 50 mm from the surface being much higher (77% at 50 mm depth) because of the large soil swelling in this zone.

2.2. Experimental procedures and data processing

For the soil drying, 1.67×10^{-3} m^3/s (100 L/min) of air were passed through the heating tube having a temperature of 150°C (as mentioned before, the temperature in the environmental chamber was much lower and in the range encountered in normal summer reason in many regions). The test took 30 days. A water layer of about 20 mm was put on the soil surface at the beginning of the test. The wind speed was measured using an anemometer placed 50 mm above the soil surface and moved to several positions inside the chamber, registering an average value of 0.4 m/s. This value is relatively low compared to that of some sites in France (2.0 m/s, Cui et al., 2005) and to those reported in literature (1.0 m/s, in Yamanaka

Table 1
Geotechnical properties of Romainville clay (after Audiguier et al., 2007; Laribi et al., 2008).

Property	Romainville clay
Carbonate content	15–20%
Organic matter content	0.12%
Specific surface surface	98 m^2/g
Liquid limit	75%
Plastic limit	40%
Plasticity index	35%
<2 μm	84%
Specific gravity	2.67