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Description of a field test involving cracking in a drying soil

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Abstract. The analysis of cracking in desiccating soils is a research topic that can be addressed by using concepts of Unsaturated Soil Mechanics. In this context, the use of physical models constitutes a promising tool to understand the mechanisms involved in this problem. In fact, previous works by the authors included the use of a laboratory environmental chamber controlling temperature and relative humidity. This paper, however, describes a field experiment consisting of a large container (3 m by 3 m and 0.5 m height) with a soil mass undergoing desiccation in an open environment near Barcelona. The container is continuously weighed to monitor the water loss evolution (or water uptake in case of rain). Basic soil variables are monitored as well: suction, water content, temperature and heat flux at different points inside the soil mass. Environmental variables, including temperature, relative humidity and wind speed close to the soil surface are also recorded. The test started early in January 2015 and the paper presents the preliminary results corresponding to the first few months. Due to the weather regime, the soil has undergone desiccation and some single rainy events. Crack patterns change dramatically when applying suction cycles to the soil.

1 Introduction

Degradation of soils due to cracking may become a serious problem in soil structures, both from the mechanical and from the hydraulic point of view. In this paper, cracking produced by desiccation is considered. Within this context, cracks appear on the soil surface and their evolution is closely related to the soil-atmosphere interaction. Some authors [1-3] have already suggested that environmental variables as wind velocity, air relative humidity or solar radiation have a strong influence on the evaporation and infiltration of water through the soil surface. Therefore, although laboratory experiments are always useful, the development of field tests has a valuable outcome in this case.

Clayey soils are particularly prone to volume changes when water content varies. During dry periods, evaporation from the soil surface takes place resulting in volume changes and eventually cracking. Further rainy events may close some cracks and create new ones having a great impact on infiltration. The analysis of drying-wetting cycles on the cracking pattern has been carried out in the laboratory in previous works and seems to be quite complex [4, 5]. Those laboratory works include environmental chambers, where Relative Humidity (RH) and/or temperature cycles can be imposed. In the experiments, a tray of initially wet soil is continuously weighed and monitored while air at a particular RH and temperature is injected into the chamber. The evolution of the tray weight along time is an indicator of the water loss/gain in the soil sample.

This paper presents an experiment that reproduces most of the features of the tests carried out in environmental chambers, but with the application of natural boundary conditions. A large tray has been installed in the field following the experience of the authors in the laboratory. The aim was to compare measurements from laboratory and field tests in order to detect if any environmental variable usually not considered in the laboratory had a significant influence on the evolution of any soil variable. Cracking was obviously a phenomenon to analyse in detail as well.

The paper describes the design and the initial installation of the field experiment. Preliminary measurements are presented, including a description of the evolution of the main variables involved as a response to environmental actions. However, a detailed interpretation of the measurements is out of the scope of this paper.

Field conditions include some variables that are usually not considered when using environmental chambers. In particular, effects of wind speed and solar radiation appear to be significant in the field and, therefore, differences between soil desiccation produced in a closed chamber or in the field could be expected. The final purpose of this field test is to identify those differences and to state their role in the context of soil desiccation and cracking. Duration of at least one year is planned for the test, with the aim of including different weather conditions from rainy to sunny periods. The test location is close to Barcelona, so a typical Mediterranean climate is expected during that period.

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2 Experimental model

A large field experiment has been designed based on the experience from environmental chambers developed in the laboratory. The soil is confined in a large tray, in order to monitor continuously its weight, as it was performed in the laboratory. Changes in weight are directly related to changes in water content within the soil mass, at least at a global scale.

The main differences of the test with respect to the laboratory experiments are basically the size of the soil sample involved and the natural environment considered (open atmosphere). The size of the sample involved plays an important role in soil cracking as shown in previous works [6], but also applying actual atmospheric conditions becomes very important when investigating real scenarios.

The experimental setup was completed with several sensors to measure soil variables and external variables. As the test represents a soil-atmosphere interaction experiment, sensors were installed both inside the soil mass and outside, to monitor atmospheric variables. A particular effort was devoted to the measurement of variables close to the soil-air interphase, where most of the hydraulic and mechanical changes are expected. This is quite often a difficult task, as the sensors themselves may constitute a preferential path for water and air flow, and a starting point for soil cracking. In order to avoid that interaction, remote sensing of some variables has been attempted as well.

2.1 Equipment

2.1.1 Overview of the field test

A high-density polyethylene (PEHD) container of 3 m by 3 m and 0.5 m of height was installed at open atmosphere in the Agrópolis open research laboratory field of UPC. The location is near Barcelona airport in an area surrounded by farms and crops. A general view of the test is shown in Figure 1, where the external sensors are highlighted.

The container may include up to 18000 Kg of soil, involving a volume of 4.5 m^3. On the upper part of the container, outdoor sensors monitoring atmospheric variables were installed. A weather station nearby (Viladecans weather station located 1.5 km away) was used as a reference. In addition to that, a reflectometer antenna developed by the RSLab from UPC (Department of Signal Theory and Communications) was also installed with the aim of measuring in a remote manner the surface water content of the soil as part of a companion research project on remote sensing leaded by that group.

The installation required the design of a steel structure to support the filled container and a shallow foundation to hold the whole system. A software controlled digital camera was used to get pictures of the soil surface every hour. All sensors installed in the soil mass or externally to the container were automatically monitored by means of a data logger Campbell CR1000. In the following sections, a detailed description of the internal and external sensors installed in the test is presented.

Figure 1. Overview of the field test. 1. Load cells; 2. Data recording system; 3. Anemometer; 4. VP-3 (Relative humidity, air temperature and vapour pressure sensors); 5. Digital camera; 6. IR-120 (infra-red remote temperature sensor); 7. RSLab reflectometer.

2.1.2 External sensors

The external sensors are not in direct contact with the soil mass. The weight of the container is monitored in order to obtain the evolution of the global gravimetric water content. This is useful when a balance of water is carried out. Internal distribution of water content can be obtained by means of internal sensors and both types of sensors are required to check the consistency of the water balance. Number #1 in Figure 1 indicates load cells used to that purpose: a total of 4 cells were used.

Environmental variables obtained from the nearby weather station include: precipitation, wind velocity (value and direction), global solar radiation, air temperature and air relative humidity. Those variables are supplied by Meteocat (Catalan Meteorological Service). In addition to that information, on top of the container, just a few centimetres above soil surface, there are two sensors VP-3 Decagon, measuring temperature, relative humidity and water vapour pressure at two different levels. There is a Davis Cup Anemometer measuring wind velocity as well (value and direction). Numbers #3 and #4 in Figure 1 indicate where they were installed.

VP-3 Decagon is an integrated sensor to measure air relative humidity (by means of a capacitance sensor) and air temperature (by using a thermistor) at the same point. A microprocessor computes the vapour pressure from temperature and relative humidity values. A small teflon sheet protects the sensor from liquid water and dust without limiting water diffusion. An additional protection against solar radiation was employed and finally, two sensors at different heights were installed.

Davis Cup anemometer records wind speed by means of bowls of wind and a magnetic switch, while the direction is measured by a weather vane and a potentiometer.

Remote measurement of temperature at the soil surface is obtained by using an IR-120 Infra-red remote temperature sensor, which detects the infra-red radiation emitted by the surface. The sensor contains a number of thermocouples connected in series which detect thermal radiation. Some of them are exposed to the source of radiation and the rest are used for reference. The output voltage is proportional to the balance of thermal energy between the exposed surface and the sensor itself. A calibrated internal thermistor measures the reference temperature and finally the processing of that information provides the surface temperature of the soil. Number #6 in Figure 1 shows the location of that sensor.

The reflectometer developed by the RSLab group attempts to measure volumetric water content of the upper part of the soil (about a few centimetres). Measurements are global but may constitute a good procedure to obtain water contents on the soil-air interphase without disturbing the soil mass.

Finally, a reflex digital camera provides with pictures of the soil surface at any convenient time and in particular, every hour. During night, an automatic lighting system is activated while taking the picture. The camera is inside a box to protect from rain and is totally software controlled.

All variables are recorded in a continuous manner (see number #2 in Figure 1).

2.1.3 Internal sensors

Internal sensors are located inside the soil mass. They were installed in the container prior to soil placement. The soil is initially poured in a liquid state, so the sensors must be fixed to a vertical bar and located at different depths, in particular, 15 cm, 25 cm and 40 cm.

This type of sensors measure volumetric water content (VWC), electric conductivity (EC), temperature, suction (Ψ) and heat flow in the soil (G). To measure VWC, EC and temperature, 3 sensors type 5TE Decagon were used. They use Frequency Domain Reflectometry (FDR) to measure VWC [7], and a thermistor to measure temperature. EC is obtained by using two small stainless steel electrodes.

Suction up to 100 MPa, according to the available range of MP-6 Decagon sensors, is measured at 8 different locations. They have a porous ceramic stone of known water retention curve that becomes in equilibrium with the surrounding soil. Using the FDR technique, indirect values of suction are obtained.

Two sensors HFP01SC are used to measure G, a useful variable to perform the energy balance. This sensor is a heat flux plate including a thermopile measuring the temperature gradient across the plate. The output voltage is proportional to the heat flux.

2.2 Material properties

The soil used in the experiment is a natural soil from the area close to the emplacement of the experiment. That zone corresponds to the Llobregat river delta (south of Barcelona) and the surficial soil has a mixture of different grain sizes, including clay particles, which may be prone to cracking when desiccated. The material was brought to the Soil Mechanics laboratory to perform standard classification tests. Preliminary experiments suggested that the material was convenient for this type of research and not very different from the Barcelona silty clay used in previous experiments by the group at UPC laboratory involving an environmental chamber [5].

The natural soil has a substantial amount of sand and silt sizes, although its geotechnical classification is a low plasticity clay (CL), likely due to almost 10% of clayey components. However, the sand and silt content is quite important. The most relevant parameters regarding soil classification are shown in Table 1.

Table 1. Basic properties of the soil tested.

Parameter	Experimental value
γ_s (unit weight of solid particles)	27.1 kN/m^3
w_L (liquid limit)	28.9%
w_P (plastic limit)	16.5%
Sand content	48.3%
Silt content	42.1%
Clay content	9.6%

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2.3 Specimen preparation

The material to be used in the experiment was selected from the indicated natural soil, sieving particles smaller than 2 mm. To facilitate the placement of the soil, enough water was added to get a liquid state. Approximately, initial water content (w_{initial}) was about 1.5 times the soil liquid limit.

The preparation of the material required a toilsome work. First, the natural soil was excavated using a tractor, then 40 mm, 20 mm, and 2 mm large sieves were used to obtain 4 m^3 of material. Particles passing the 2 mm sieve were finally used. After that, the sieved soil was mixed with water at about 45% of w_{initial} into a truck mixer, and the resulting slurry was spilled into the experimental container filling about 4.5 m^3 of total volume. A liquid consistency was very important in order to get a homogeneous mixture and to avoid any damage to the sensors already installed in the container.

Before filling the container, a pervious geotextile net was placed on its bottom, to establish a limit with a well-defined boundary condition regarding equilibration of water pressures. Figure 2a shows a particular moment when installing that geotextile. Also, a metallic wire net was installed between the bottom of the container and the geotextile, as a reference plane for the reflectometer antenna, for calibration purposes. Figure 2b shows a picture of the container just after filling with the soil, the day when the test started.

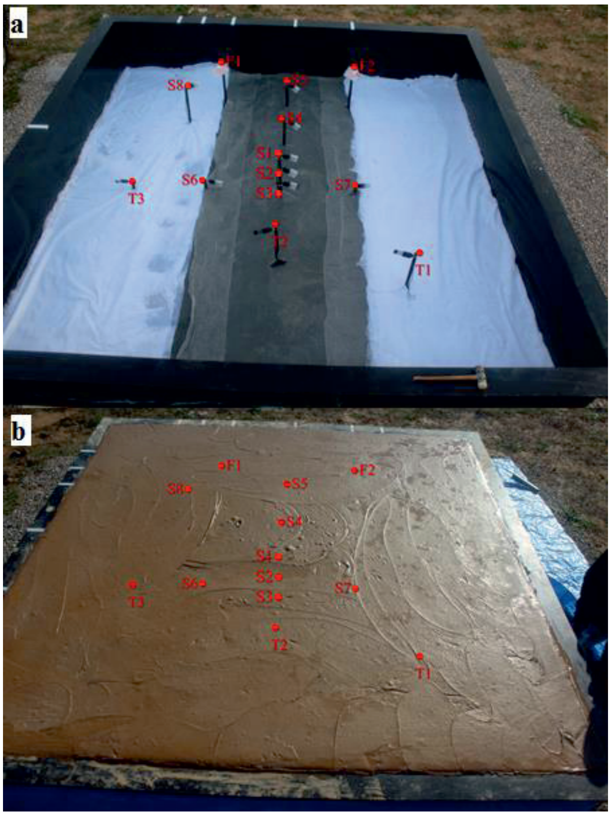

Figure 2. Distribution of the internal sensors. (S1-S8) Suction sensors; (T1-T3) VWC, temperature and EC; (F1-F2) Heat flux. **(a)** Container, geotextile & indoor sensors. **(b)** Initiation of the test.

2.4 Test program

All physical variables from the sensors are recorded and stored digitally. The system was programmed to work for at least one year. However, periodic checks were planned (every 2 - 3weeks approximately) and they were used to download the measurements to a laptop for further analysis. Also some small samples of the soil close to the surface were taken in each visit, in order to measure the water content in the laboratory to compare with in situ measurements.

It should be pointed out that some of the sensors may become out of range during such a long time period of monitoring, but still it was considered important not to change the geometry by replacing the sensors, as any defect or any odd object within the soil mass may lead to a point of crack initiation.

The construction of the setup was carried out during fall 2014, and the installation of the sensors and preparation of the soil were performed in early winter 2015. It is planned to dismantle the test after one year of recorded data. Then there are plans for further experiments changing some of the boundary conditions involved.

3 Preliminary results

Preliminary results presented here refer to the first 160 days of test, starting in winter 2015. The main trend suggests a global desiccation of the soil mass, as shown in Figure 3, where the weight of the soil mass and the precipitation are depicted as function of time.

Drying dominates the environmental action in an area with a Mediterranean climate and as a consequence of that, cracks start to form at day 22. Note that water was always lost, unless some precipitation occurred. Soil gravimetric water content when cracks initiated was about 35%. The loss of weight is almost linear at the beginning, but then slows down when cracks develop. Small rainfall events do not change significantly the global tendency of weight loss.

It has been observed, that the effects of meteorological changes (i.e., daily changes) are more sensitive in the sensors closer to the surface.

Cracking patterns change with time and may be affected by rainfall events. Figure 4 shows two pictures taken at days 30 and 150. It can be seen that the morphology of cracks is different, regarding thickness, length, area and shape of cells. Rainfall events may close some small cracks, but they may generate new ones, as stated in [5]. This is partly due to the loss of cohesion of the surficial soil layer when saturated.

Cracks after 150 days of drying are quite deep and are difficult to see in nature, at least in the area where the soil was taken. The main difference of the experiment with respect to the real scenario is the container, avoiding any water input from the ground. In actual conditions, groundwater table keeps a deep boundary condition different from the one applied in the field test.

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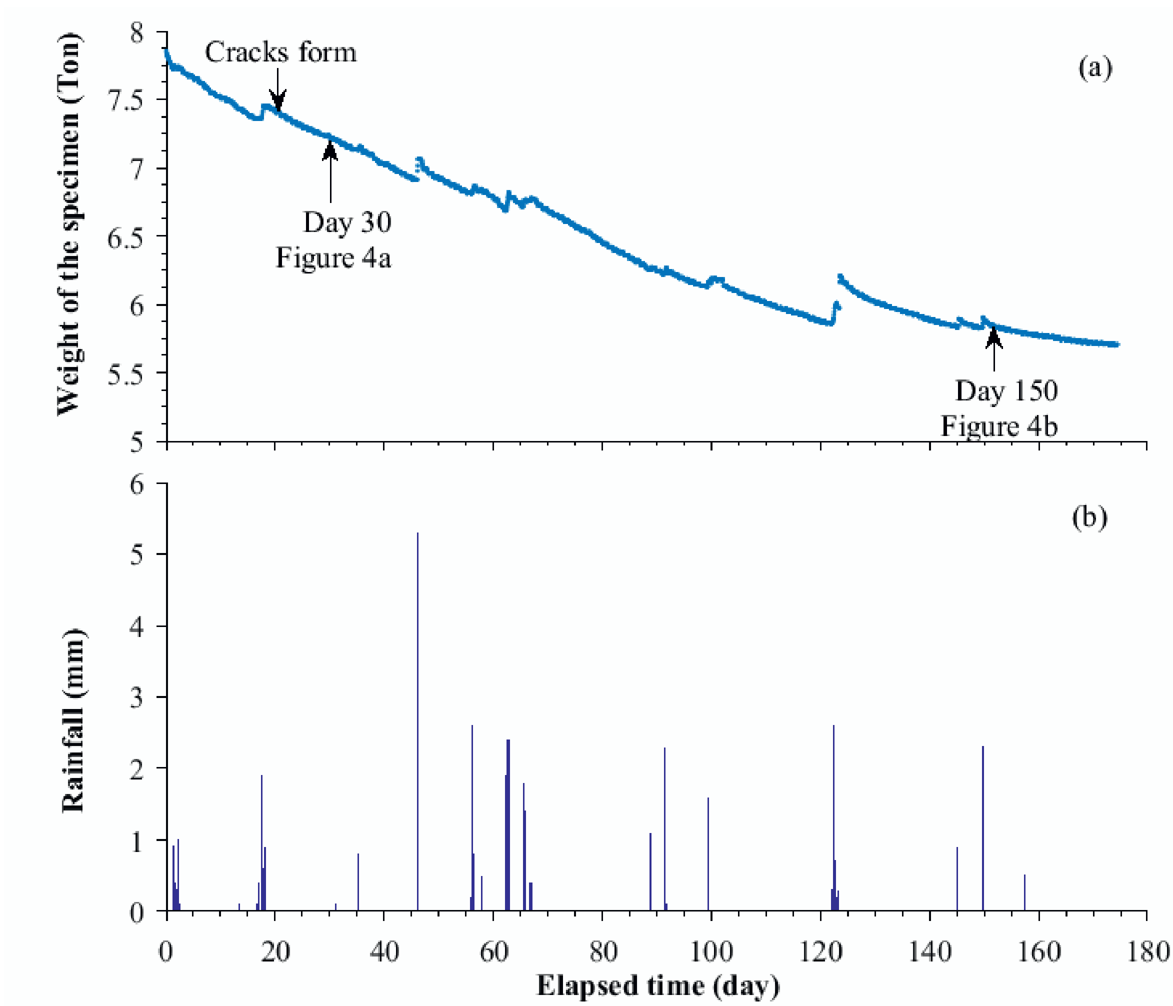

Figure 3. Natural wetting plotted against time. **(a)** Weight of the specimen evolution. **(b)** Rainfall by weather station.

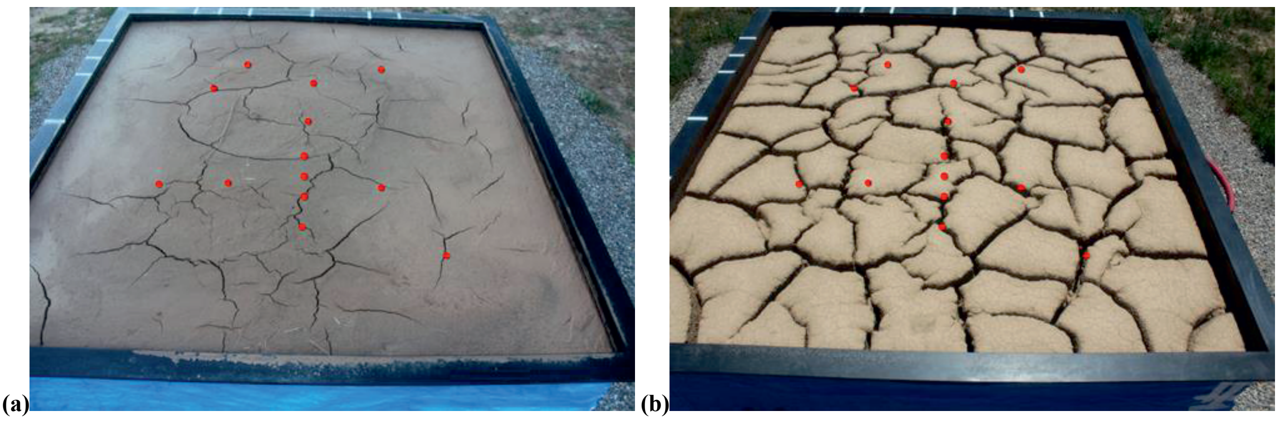

Figure 4. Crack pattern obtained during the time elapsed. **(a)** Crack pattern at day 30 and **(b)** Crack pattern at day 150.

Some of the internal sensors reached their measurement range, either due to the intensity of the evaporation rate at the beginning of summer or because they became exposed to open atmosphere due to the cracks. However, the records obtained during their measurement range will be useful in future analyses.

Cracking in desiccating soils has been described at three different levels: macro-scale continuum, meso-scale of grain and pore clusters, and micro-scale of individual pore structure or grains with liquid bridges [8]. All scales have been observed or suggested in this field test thanks to the diversity of environmental actions applied to the material and it seems that Unsaturated Soil Mechanics can be a useful tool to explain the behaviour of these processes.

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4 Conclusions

This paper describes the design and installation of a field test devoted to the analysis of cracking due to desiccating soil. The test constitutes a natural evolution of previous laboratory experiments on an environmental chamber, where soil trays were desiccated under controlled temperature and relative humidity. In those experiments, the water content evolution was recorded by weighing the soil tray and that information became an important data to analyse the whole test. The same strategy was adopted for the field test, where a large container filled with silty clay was exposed to open atmosphere conditions. The time evolution of the container weight and the main physical variables involved are automatically recorded. That includes meteorological data as well as internal variables in the soil mass, like suction, water content, temperature and heat flux. A particular effort was devoted to measure variables close to the soil surface, as large gradients of those physical variables are expected there.

Preliminary results corresponding to the first 160 days of test have been presented. The data suggest a global desiccation of the soil mass and subsequent cracking, which is consistent with the Mediterranean climate in Barcelona. Small rainfall events have not changed that global tendency. The experiment will last at least for one year and it is expected that the collected data, after interpretation, will contribute to improve the understanding of the processes involved in soil desiccation at a natural scale.

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