Development of a Large Scale Infiltration Tank for Determination of the Hydraulic Properties of Expansive Clays

Anh Minh A.M. Tang, An-Ninh Ta, Yu-Jun Cui, Jérémy Thiriat

HAL Id: hal-00425559

https://hal.science/hal-00425559

Submitted on 22 Oct 2009

Development of a Large Scale Infiltration Tank for Determination of the Hydraulic Properties of Expansive Clays

Anh-Minh TANG, An-Ninh TA, Yu-Jun CUI and Jérémy THIRIAT

Ecole des Ponts ParisTech, U.R. Navier/CERMES, 6 – 8 av. Blaise Pascal, Cité Descartes, Champs – sur – Marne, 77455 MARNE – LA – VALLEE, France

Corresponding author

Yu-Jun CUI

ENPC/CERMES
6 – 8 av. Blaise Pascal, Cité Descartes, Champs – sur – Marne
77455 Marne – la – Vallée cedex 2
France

Phone : +33 1 64 15 35 50
Fax : +33 1 64 15 35 62
Email : cui@cermes.enpc.fr

Abstract

A large-scale infiltration tank was developed to study the water transfer in compacted expansive clay. Volumetric water content sensors were buried in a soil column for water content monitoring during infiltration. In addition to water content, soil suction and temperature at various locations and the heave at the soil surface were also monitored. Emphasis was put in minimizing the effect of sensors installation on water transfer and soil deformation. The results obtained for 338-days of infiltration were presented in terms of changes of suction, volumetric water content, temperature and the soil heave. Based on the recorded data, the performance and limitation of different suction and volumetric water content sensors and the adopted test procedure were analyzed. The recorded data on soil suction and volumetric water content were finally analyzed for determining the unsaturated hydraulic properties of soil such as the water retention curve and the unsaturated hydraulic conductivity. Note also that the results constitute useful data for further physical analysis or numerical models calibration.

Key-words: Infiltration tank, expansive clay; suction; water content; monitoring; soil heave.

Introduction

The water transfer in compacted expansive soil is a key issue in geotechnical and geo-environmental engineering: in the safety assessment of geological radioactive disposal (Alonso et al., 2008) and surface waste disposal (Chapuis, 2002; Albright et al., 2006; Delage and Romero, 2008); in the analysis of the impact of seasonal changes on the behavior of embankments and dams (Ridley et al., 2003); in the analysis of soil-structure interaction caused by swell/shrinkage of expansive soils (Abduljauwad et al., 1998); in the assessment of surficial stability of compacted clay slopes (Day and Axten, 1989; Aubeny and Lytton, 2004). From an experimental point of view, the water transfer analysis requires measurement of soil suction or water content. Tarantino et al. (2008) present a review of techniques for field study on water transfer in unsaturated soils and show that several techniques are available for field measurement of suction, water content and unsaturated hydraulic conductivity. Nevertheless, as the boundary conditions in the field cannot be controlled and are difficult to be measured (Cui et al., 2005; Cui and Zornberg, 2008) additional laboratory tests are often required for field studies.

In laboratory, the unsaturated hydraulic conductivity of soil can be measured by various methods among which unsteady methods such as the instantaneous profile method (Daniel, 1982) are the most suitable for clayey soils (Benson and Gribb, 1997). After Masrouri et al. (2008), unsaturated hydraulic conductivity of expansive soils is often determined in constant-volume conditions. This condition is verified in the case of engineered clay barriers used in the geological radioactive waste disposal. Indeed, the host geological barrier constrains the swelling of engineered clay barriers upon wetting (Robinet and Rhattas, 1995; Loiseau et al., 2002; Kröhn, 2003). Nevertheless, in most cases, swelling takes place during infiltration (Kim et al., 1999; Lemaire et al., 2004). With soil swelling, the advance rate of wet front at free-swell conditions was significantly higher than at constant-volume conditions (Yong and Mohamed, 1992; Cui et al., 2008b). This shows the importance of the coupling between water transfer and soil volume change during infiltration in compacted expansive soils.

Further examination of laboratory infiltration studies reveals that, in the determination of unsaturated hydraulic conductivity by the instantaneous profile method, only the soil suction was continuously monitored (Daniel, 1982; Chiu and Shackelford, 1998; Bruckler et al., 2002; Loiseau et al., 2002), the water content evolution being deduced from the water retention curve determined separately. In the works of Robinet and Rhattas (1995) and Kröhn (2003), the infiltration test was stopped after a predefined period and the soil sample was dismantled for the direct determination of water content by oven-drying. Obviously, the number of water content profiles was limited by the number of tests performed. In the works of Kim et al. (1999) and Lemaire et al. (2004), the dual-energy gamma-ray technique was used for monitoring the variations of water content profile along the clay sample. Compared to the method employed by Robinet and Rhattas (1995) and Kröhn (2003), this method has the advantage of being non-destructive; but it needs sophisticated installation and is time consuming (Masrouri et al., 2008).

Laboratory infiltration tests with both continuous suction and water content monitoring require usually medium to large-scale equipment (Meerdink et al., 1996; Stormont and Anderson, 1999; Choo and Yanful, 2000; Yang et al., 2004) where suction is monitored by tensiometers or psychrometers while volumetric water content is monitored by TDR probes.

Note that for the suction measurement, good contact should be ensured between the sensors and the soil, and for the measurement of water content using TDR probes, full insertion of the wave guides into the soil is needed. After Yang et al. (2004), embedding the full length TDR's waveguides in the soil allows a more accurate water content measurement.

In the present work, a laboratory infiltration tank was developed for the studies on water transfer in compacted expansive clays. Compacted Romainville expansive clay was tested. During water infiltration, the measurements of suction, volumetric water content and temperature were made at various locations. The soil heave was also monitored using 15 LVDTs (linear variable differential transformers) on the soil surface. A wide range of suction (from 0 to 100 MPa) was covered by three types of sensors: (1) sensors measuring the relative humidity in air-filled pores; (2) psychrometers for the total suction; and (3) high-capacity tensiometers for the matric suction. Volumetric water content was monitored using dielectric methods. These sensors were fully buried in the soil allowing free displacement of the sensors with soil deformation. A large soil volume was considered (800 × 1000 mm section with an initial height of 1000 mm). This is mainly justified by the significant volume of the sensors; a small soil volume would lead to unrepresentative measurements because of influence of the sensors on both water transfer and soil deformation. Moreover, the large soil section allowed minimizing the effect of the friction between the sidewall of the tank and the soil on the total soil heave in the central part. An infiltration period of 338 days was performed; the results are presented in terms of variations of suction, volumetric water content, temperature, and displacement observed on the soil surface. It is worth mentioning that even though the boundary conditions of the test performed do not correspond exactly to the field conditions in the applications cited previously, the first analysis on soil suction and volumetric water content allowed determining the unsaturated hydraulic properties such as water retention curve and unsaturated hydraulic conductivity on a significant soil body. Furthermore, the data recorded can be quite useful for further theoretical and numerical analysis covering at the same time changes in suction, volumetric water content, temperature and displacement.

Experimental setup

The schematic views of the experimental setup are presented in Fig. 1 and a picture is presented in Fig. 2. The soil was compacted in an acrylic transparent tank with a 20-mm-thick wall, 800-mm internal width and 1000-mm internal length, 1550-mm height (Fig. 1*a*). The tank is constituted of four separated acrylic plates joined together by epoxy glue on the four corners. The bottom of the tank is fixed on a PVC plate (30-mm thick). On the top, an acrylic cover is used. The system is strengthened by four vertical metallic stiffeners on the four corners and confined by various lateral metallic stiffeners in order to provide a good resistance against the lateral stress developed during wetting of the soil. The joints between the plates are finally sealed by silicon glue to prevent any leakage.

The details of the sensors used are presented in Table 1 and their locations are shown in Fig. 1. The distribution of the displacement sensors (LV) is shown in Fig. 1*b*. Five ThetaProbe sensors (TP) were buried in the soil (Fig. 1*c*). On the opposite side, five ECH₂O-TE sensors (EC) were buried at the same levels. These sensors that allow the measurement of volumetric water content were installed every 200 mm along the height of the tank. Fig. 1*c* shows the 10 temperature sensors (PT) located every 100 mm along the height. The locations of high-capacity tensiometers (TS) and relative humidity sensors (RS) are indicated in Fig. 1*d* (section B-B). Each type of sensor was installed every 200 mm on both sides, allowing one

4

measurement every 100 mm along the height from each type of sensor. The RS sensor T3111 is a programmable probe that is equipped with temperature and relative humidity sensors. The RS probe contains a microprocessor-based control circuitry in a durable plastic case with connection terminals and sensors in a filter with stainless steel mesh. The same distribution pattern was used for the installation of the psychrometers (PS) as shown in Fig. 1*e* (section C-C).

The details of the plugs designed for the installation of each type of sensor are shown in Fig. 3. The supports for ThetaProbe, ECH_2O-TE and PT sensors (Fig. 3*a*) ensure the water-tightness with the passages of cables. The RS sensor measures the relative humidity in a small tank (Fig. 3*b*) communicating with the soil through a porous metallic body. As for the tensiometers (Fig. 3*c*), they were kept in direct contact with the soil.

The water flow system for the infiltration tank included the rainfall distributor and the drainage system. For the rainfall distributor, four perforated tubes with very small holes were installed on the cover of the tank. These tubes were connected to a tap of the local water system in the laboratory through a volume meter ($\pm 50 \times 10^{-6}$ m^3 of accuracy) and a flow meter ($\pm 1.5 \times 10^{-3}$ m^3/s of accuracy). Within this rainfall distributor, water can flow to the soil surface in a satisfactorily uniform pattern and at a controlled flow rate. For the drainage system, the soil was compacted on a layer of gravel (d = 2 – 5 mm) of 30-mm thick separated by a layer of geotextile of 1-mm thick. Two outlets were perforated close to the bottom of the tank for water and air drainage.

Material and experimental procedures

The Romainville clay taken from a quarry in Cormeilles - en - Parisis, 25 km north-west from Paris, was studied. A general view of the geological profile of the site was presented by Arnould (2006). Its geotechnical properties (after Audiguier et al., 2007; Laribi et al., 2008) are presented in Table 2. According to the Casagrande's classification criterion, the soil is a high plasticity clay. It belongs to CH following the USCS soil classification system.

The soil transported to the laboratory was air-dried, crushed and sieved through a 2-mm sieve. It was then stocked in a sealed box for several days in order to homogenize its water content prior to the compaction. The water content at which the clay was compacted was 5.7%. For the compaction of the soil, 56.86 kg of the air-dried soil was first poured into the tank and compacted manually to have a layer of 50-mm thick. That corresponds to a dry density of 1.35 Mg/m^3 that was similar to the in-situ dry density (Cui et al., 2006). The void ratio and the degree of saturation after compaction were 1.07 and 15.6% respectively. This procedure of compaction by layer was repeated until reaching the total height of 1000 mm. Note that this procedure allows obtaining a satisfactory homogeneity in the soil in terms of dry density.

During compaction, the installation of sensors buried in the soil was performed between the compaction of soil layers. The ECH_2O-TE and PT sensors were installed on the compacted soil layer prior to pouring the subsequent soil layer. The installation procedure of ThetaProbe is shown in Fig. 4. After the compaction of the soil layer at the defined level, a hole having similar dimension of the sensor was created manually. The sensor was then placed horizontally in the hole by inserting the 4 steel guides inside the soil. The hole was finally filled and manually compacted with a calculated quantity of soil in order to ensure the same

dry density of the soil (1.35 Mg/m^3). This procedure aimed at minimizing the effect of the sensors installation on the soil density.

The dielectric sensors (ThetaProbe and ECH$_2$O-TE) were calibrated prior to use. For this purpose, Romainville clay was compacted at various water contents to a dry density of 1.35 Mg/m^3. After the compaction, the sensors were then inserted into the compacted sample for the measurement. In Fig. 5, the volumetric water content (θ) of the compacted samples (determined using the gravimetric water contents by oven-drying and the global dry density) is plotted versus the square root of dielectric constant ($\sqrt{\varepsilon}$) provided by the ThetaProbe sensor. The following best fitted curve was found:

$$\theta = 2.5483(\sqrt{\varepsilon})^2 - 4.0981\sqrt{\varepsilon} + 0.0099 \qquad [1]$$

This equation was established based on the measurements made in the range of volumetric water content from 0 to 50%. In Fig. 6, the volumetric water content (θ) of the compacted samples (also determined using the gravimetric water contents by oven-drying and the global dry density) is plotted versus the raw value (RAW) provided by the ECH$_2$O-TE sensor. A linear relationship can be proposed:

$$\theta = 0.1049\,(RAW) - 65.47 \qquad [2]$$

Note that Decagon (2007) proposed a similar linear equation for mineral soils.

Chronologically, if the time for completion of the compaction is considered as $t = 0$, the relative humidity sensors and the displacement transducers (LV) were installed at $t = 19$ days. The system was then sealed to reach its equilibrium state for 25 days ($t = 45$ days). Infiltration was then started by rainfall on the soil surface at a rate of 0.6x10^{-3} m^3/min. The rainfall was stopped at $t = 48$ days, providing a total volume of water to the soil of 0.09 m^3. From $t = 48$ days to $t = 73$ days, no more water was added. As it was difficult to control the water level above the soil surface when fixing the rainfall intensity at 0.6x10^{-3} m^3/mn, a permanent layer of water (10 – 40 mm) was kept on the soil surface from $t = 73$ days. Subsequently, when the level of the water layer was lower than 10 mm, 0.02 m^3 of water was added, elevating the water level by 25 mm. The total volume of water added (Q_{inlet}) was plotted versus elapsed time as shown in Fig. 7a.

Experimental results

The results are presented in terms of changes in relative humidity (RH) (Fig. 7b), volumetric water content measured by ThetaProbe sensors (θ_{TP}) (Fig. 7c) and ECH$_2$O-TE sensors (θ_{EC}) (Fig. 7d) and heave at soil surface (Fig. 7e). Note that the relative humidity sensors and the displacement transducer (LV) were installed at $t = 19$ days and the system was then sealed for 25 days (until $t = 45$ days) to reach its equilibrium state. At the end of the equilibration period, the relative humidity measured was 50±1% except that measured by the RS10 sensor. For RS10 which was situated close to the soil surface, the relative humidity was equal to 56% after the installation and then decreased progressively to 53% at $t = 45$ days. Actually, during the installation of the displacement transducers (at $t = 19$ days), the cover of the tank was opened, and the soil on the surface would be humidified by the air in the laboratory. After covering the tank, the relative humidity at the soil surface decreased approaching the value at lower soil layers. The volumetric water content at the end of the equilibration period was 12±1 % for θ_{TP} and 9±1% for θ_{EC}. It was significantly higher than the global volumetric water

content (7.7%) estimated by considering a gravimetric water content of 5.7% and a dry density of 1.35 Mg/m^3.

Fig. 7b shows that after the start of infiltration at $t = 45$ days, the relative humidity measured at a depth of 50 mm (RS10) started to increase at $t = 46$ days and reached 96% after one day ($t = 47$ days). The relative humidity measured at a depth of 150 mm (RS9) started to increase at $t = 47$ days and reached 90% at $t = 50$ days. During the period $t = 48 – 73$ days where no more water was added, the relative humidity measured at these two depths remained high while that of RS8 (at 250-mm depth) and RS7 (at 350-mm depth) increased significantly. The relative humidity measured at deeper levels remained unchanged during this period. For the second phase of infiltration (from $t = 73$ days), the relative humidity measured by the other sensors increased progressively as a function of the distance from the sensor to the surface. In addition, the rate of the relative humidity increase was lower at deeper levels: for instance, 20 days were needed for RS6 (at 450-mm depth) to have the relative humidity increases from 50 to 96% ($t = 90 – 110$ days) while 150 days were needed for RS2 at 850-mm depth ($t = 150 – 300$ days).

The observations made on the changes in volumetric water content from the ThetaProbe sensors were similar to those from the relative humidity sensors (see Fig. 7c). The start of infiltration at $t = 45$ days induced a quick increase of the volumetric water content measured at 50-mm depth (TP5), from 11 to 52% after 2 days. During the period of $t = 48 – 73$ days where no more water was added, this value decreased slightly to 46% while that measured at 250-mm depth (TP4) increased progressively to 20%. For the second phase of infiltration (from $t = 73$ days), the volumetric water content measured at 50-mm depth (TP5) started first to increase quickly from 46 to 52% after 1 day. It continued to increase during the infiltration and reached 77% at $t = 300$ days. At $t = 76$ days, the volumetric water content measured at 250-mm depth (TP4) started to increase quickly (from 21%) and reached 47% after 2 days. It continued to increase and stabilized at 52% ($t = 100$ days). For the other ThetaProbe sensors, the larger the depth, the later the increase of volumetric water content. In addition, the final value of volumetric water content at a deeper sensor was lower. For instance, at $t = 300$ days, it was equal to 77% at 50-mm depth (TP5) against 47% at 650-mm depth (TP2). Note that the estimated volumetric water content at saturated state was 49% (corresponding to a density of soil particles of 2.67 Mg/m^3 and a dry density of 1.35 Mg/m^3). This high volumetric water content obtained at 50-mm depth (TP5) would be explained by a significant swelling of the soil near the surface; a volumetric water content of 77% (at saturated state) corresponds to a dry density of 0.58 Mg/m^3. On the other hand, as the ThetaProbe was calibrated only in the range of volumetric water content from 0 to 50% (Fig. 5), this high volumetric water content would be also affected by the lack of accuracy.

The ECH$_2$O-TE sensors were installed at the same levels as for the ThetaProbe sensors. Fig. 7d shows that the increase of the volumetric water content measured by the ECH$_2$O-TE sensors during infiltration was similar to that by the ThetaProbe sensors. For instance, the volumetric water content measured at 50-mm depth (EC5) increased quickly at $t = 45$ days from 9% and reached its maximum at 49% after 2 days. That was similar to the response of ThetaProbe TP5 embedded at the same level. Nevertheless, significant difference can be observed between the two types of sensors after reaching high volumetric water contents. For the ThetaProbe sensors, from $t = 73$ days (second stage of infiltration), the volumetric water content increased continuously and stabilized at about 50% (except that measured at 50-mm depth, TP5). On the contrary, for ECH$_2$O-TE sensors, the volumetric water content reached first a high value (between 60-70%) and then decreased significantly.

As far as the heaves are concerned (Fig. 7*e*), after the start of infiltration, at $t = 45$ days, it increased quickly and reached 29±1 mm after 2 days. During the period of $t = 47 – 73$ days where no more water was added, the heaves continued to increase but at a significantly lower rate until it reached 34±2 mm at $t = 73$ days. During the second phase of infiltration (from $t = 73$ days) where a layer of water was permanently maintained on the soil surface, the heaves increased quickly in the beginning and trended to stabilize at the end of infiltration. The measurement was stopped at $t = 283$ days and the final heaves measured were in the range of 105-127 mm.

For further analysis, the results presented in Fig. 7*b* were used to plot the profiles of relative humidity at various times (Fig. 8). In this figure, the elevation h was calculated from the bottom of the soil column (from the level of the geotextile). Prior to the infiltration ($t = 45$ days), the relative humidity in the soil column was equal to 50%. When water was applied to the soil surface, it increased quickly at the highest layer: at $t = 50$ days, it was higher than 90% for $h > 840$ mm. At $t = 100$ days, the relative humidity was close to 100% for $h > 640$ mm while it remained unchanged at $h < 440$ mm. This transient zone ($h = 440 – 640$ mm), where the soil started to be wetted but did not reach saturation, enlarged at higher values of time t ($h = 140 – 440$ mm at $t = 150$ days; $h = 40 – 340$ mm at $t = 200$ days). Note that in this figure, the relative humidity at the bottom was assumed to be constant at 50% which was the relative humidity of the air in the laboratory. Actually, as described previously (Fig. 1), the soil was compacted on a layer of gravel which was in contact with two air outlets. The bottom of the compacted soil column can be then assumed to be in contact with air in the laboratory. Thus both the relative humidity and the air pressure in the soil at the bottom corresponded to the conditions of the air in the laboratory.

The evolution of the volumetric water content measured by ThetaProbe sensors was plotted versus time in Fig. 9. In this figure, the elevation h corresponds to the initial position of the ThetaProbe sensors (the position would change due to soil swelling during infiltration). As mentioned previously, the volumetric water content at saturated state at a dry density of 1.35 Mg/m^3 was estimated at 49%. During infiltration, the swelling corresponded to a decrease of dry density and thus resulted in an increase of volumetric water content at saturated state. For the purpose of simplicity, in this analysis the soil was assumed to be saturated when the volumetric water content measured by ThetaProbe exceeded 49%. Fig. 9 shows that the saturated zone ($\theta_{TP} > 49\%$) was advancing from the soil surface quickly in the beginning of the infiltration, but at a decreasing rate. For instance, at $t = 100$ days, the soil was saturated for $h > 740$ mm; and then $h > 540$ mm at $t = 150$ days; $h > 340$ mm at $t = 200$ days. Note also that at $t = 300$ days the soil at $h = 140$ mm still remained unsaturated.

Based on the heave data recorded by the LV sensors (15 points, see Fig. 1*b*) and the measurements performed using a ruler (accuracy: ±1 mm) through the acrylic transparent walls of the tank, the heave of the soil surface at $t = 283$ days was plotted in a 3-D graph (Fig. 10). The maximum heave (120 – 130 mm) was observed in the central part of the surface while the minimum heave (60 – 80 mm) was observed on the four corners. The heave measured beside the walls remained lower than 100 mm.

The sensors measuring the soil suction at relatively low range (psychrometers and tensiometers) were unfortunately available only for the last months of the test. The results are presented in Fig. 11 at the same time with the data of temperature. In Fig. 11*a*, the total suctions measured by psychrometers are plotted. The total suction measured at $h = 40$ mm

(PS1) was equal to 8 MPa (higher limit for the used psychrometer) at $t = 304$ days. It decreased to 2.21 MPa at $t = 338$ days. The total suction measured at $h = 140$ mm (PS2) decreased from 0.85 MPa ($t = 285$ days) to 0.16 MPa ($t = 338$ days). The total suction measured at $h = 240$ mm (PS3) fluctuated around 0.1 MPa. At higher elevation, the total suction was lower than the lower limit of psychrometers (0.05 MPa) and no results are then available.

The results obtained from the tensiometers are presented in Fig. 11b. After the installation of tensiometers, approximately 15 days were required to reach equilibrium. At $h = 240$ mm (TS3), the matric suction was equal to 50 kPa. It is lower but in the same order of magnitude of the total suction measured by the psychrometer PS3 at the same level. Note that the total suction is the sum of matric suction and osmotic suction and this latter was not measured. Lower matric suctions were recorded at higher elevation, in concordance with advancing of the infiltration front.

The variations of temperature are presented in Fig. 11c for the PT sensors within the soil and in Fig. 11d for the RS sensors beside the walls (see also Fig. 1). It can be observed that the diurnal variation of the RS sensors (± 1°C) was more pronounced than that of PT sensors (±0.1°C except for PT10).

The suction profile at $t = 300$ days measured by the three types of sensors was plotted in Fig. 12. The total suction at $h = 0$ was assumed to be equal to that imposed by the conditions of the ambient air ($RH = 50\%$ and $T = 20°C$, corresponding to $s = 94$ MPa, see Tang and Cui, 2005). At $h = 40$ mm, $s = 18.5$ MPa corresponding to a relative humidity of 87%. At higher elevation, the relative humidity was higher than 96% ($s < 6$ MPa). In this suction range, the error of measurement by RS sensor becomes significant (see Delage et al., 1998) and for this reason, these measurements were not considered. Three values of suction are available at $t = 300$ days for the psychrometers, corresponding to $h = 40$, 140 and 240 mm. The range of the total suction measured by psychrometers was 0.05 - 8 MPa (see Table 1). For the tensiometers, the values of matric suction at $h = 240$, 340 and 440 mm are available. The results plotted in Fig. 12 show a satisfactory agreement between the measurements by the three types of sensors since all the results can be almost fitted with only one curve. To a certain extent, this also indicates that the total suction is approximately equal to the matric suction in the studied Romainville clay, the osmotic suction being negligible.

The volumetric water content (measured by the ThetaProbe) was correlated with the suction measured by the RS sensors (for $s > 6$ MPa), psychrometers (for $s = 0.05 – 8$ MPa) and tensiometers (Fig. 13). One data set (volumetric water content and suction) every 30 days was taken from the measurements at each level. A satisfactory linear correlation was obtained in a $\theta – \log(s)$ plot. This relationship, which is independent of the sensors positions and of time, correspond to the wetting path of the soil water retention curve.

The unsaturated hydraulic conductivity was determined using the instantaneous profile method which is based on the generalized Darcy's law. The hydraulic gradient (i) at a moment t and a location z was calculated as the slope of the suction profile at t and z. This suction profile was plotted from the measurement of suction changes at various depths. The volume of water passing through the section at a location z during the time period from t to $t +$ dt was calculated from the difference between the profiles of volumetric water content at t and t + dt. These profiles were plotted based on the measurements of volumetric water content at various depths. Finally, the unsaturated hydraulic conductivity (k) at the location z and at the

moment t was calculated from the corresponding water fluxes and hydraulic gradient. The calculated unsaturated hydraulic conductivity is usually plotted versus the suction s at the corresponding location z and moment t. More details about the instantaneous profile method can be found in Daniel (1982), Chiu and Shackelford (1998), Bruckler et al. (2002), Cui et al. (2008*b*).

Fig. 14 presents the variations of hydraulic conductivity versus total suction. Note that the measurements by the relative humidity sensors allowed plotting the results for the high suction range ($s = 4 – 100$ MPa) while that of psychrometers allowed plotting the results for low suction range ($s = 1 – 4$ MPa). A good agreement between the two methods was obtained. The results show that the unsaturated hydraulic conductivity was close to 10^{-14} m/s at high suction (100 MPa) and it increased to 10^{-11} m/s at low suction (1 MPa).

Discussion

In this work, an infiltration test was performed by wetting compacted Romainville clay from the top surface and monitoring the change of relative humidity, volumetric water content, suction and temperature at various locations and the heave on the soil surface. The changes in relative humidity with time (Fig. 7*b*) are similar to that obtained by Loiseau et al. (2002) when wetting a compacted expansive soil under confined conditions: the relative humidity close to the wetting end increased quickly while the rate of increase was lower at larger distances from the wetting end. This pattern is equally similar to that observed on the volumetric water content measured by ThetaProbe sensors (Fig. 7*c*) and to that obtained by Kröhn (2003).

The results of the volumetric water content measured by ThetaProbe sensors are in agreement with the results of suction. That confirms the validity of the sensor on one hand and that of the experimental procedure applied on the other hand. Actually, the performance of the ThetaProbe sensors in field conditions was confirmed in various works (Lukangu et al., 1999; Robinson et al., 1999; Verhoef et al., 2006; Smethurst et al., 2006; Zhan et al., 2007). The results obtained in this study show that the compaction procedure used allowed the sensors to be installed with negligible effect on soil density. In addition, comparing to the large dimension of the infiltration tank, the volume of the ThetaProbe sensors buried in the soil was negligible, and thus the sensors did not significantly influence the water transfer. The initial volumetric water contents measured by ThetaProbe and ECH_2O-TE sensors were similar; that confirms the homogeneity of the compacted soil in terms of both density and water content.

As shown in Fig. 7, when the volumetric water content became higher than 50%, the responses of ECH_2O-TE sensors were different from that of ThetaProbe sensors. This can be explained by the limited measurement range provided by the ECH_2O-TE sensors. Indeed, after Decagon (2007) and Kizito et al. (2008), the ECH_2O-TE sensor provides accurate measurements in the range of volumetric water content from 0 to 50%. For higher values, more calibrations are required.

The variations of heave with time recorded (Fig. 7*e*) are similar to that observed by Abduljauwad et al. (1998) and Kim et al. (1999): wetting induced a quick increase of heave and the rate decreased then progressively with time. The 3-D presentation of heave at $t = 283$ days (Fig. 10) shows a significant boundary effect: the heave measured in the middle zone of the surface (120 – 130 mm) was twice of that on the corners (60 – 80 mm). The significant

boundary effect can be attributed to the friction between the walls of the infiltration tank and the soil; this friction decreased the soil swelling as the vertical stress does in oedometer condition. Indeed, most works have showed that the maximum swelling strain recorded on expansive soils upon wetting in oedometer decreased drastically when the vertical stress increased. As a consequence, the measurements provided by the suction sensors near the edge of the tank affected by the edge friction and corresponding constraint on the porosity, and do not represent the suction changes in the central part of the tank.

The boundary effect can be also observed on the temperature measurement (Fig. 11): the diurnal variation of T measured within the soil column (± 0.1 °C) was significantly lower than that measured on the walls (± 1°C). In addition, T measured close to the soil surface (PT10) fluctuated with higher amplitude than other PT sensors.

The time needed to reach suction equilibrium was quite long for the tensiometers: 15 days (see Fig. 11). This long time is related to the low permeability of compacted expansive soils (Singh and Kuriyan, 2003; Oliveira and Marinho, 2008). In addition to the limited range of suction for the tensiometers (lower than 1.5 MPa), this long equilibrium time is another drawback of the tensiometers when used to monitor the soil suction in expansive soils. This is probably the reason why tensiometers have been not commonly used in the studies on expansive soils. In addition, as stated by Cui et al. (2008*a*), the high-capacity tensiometer is slightly sensitive to temperature changes (the pressure given increases with the temperature rise at a rate of 1 kPa/°C). For this reason, the accuracy of the tensiometers used in the conditions of the present test can be estimated at 1 kPa. That corresponds equally to the level of positive pore water pressure in the flooding condition (100 mm of water). Obviously, this water level can not be monitored by the high-capacity tensiometers used.

Besides the instantaneous profile method used for determining the unsaturated hydraulic conductivity, there are other methods for analyzing such experimental data. In the work of Robinet and Rhattas (1995), the unsaturated hydraulic conductivity was evaluated using a simple theoretical approach considering the presence of water in two forms, adsorbed and capillary. Water pressure and gas pressure were used as variables. Kim et al. (1999) used a one-dimensional numerical model to analyze the soil deformation and unsaturated transient water flow in swelling soil based on a laboratory infiltration test. The Wind's (Wind, 1968) method, previously described to estimate soil hydraulic properties under evaporation conditions, was applied to infiltration conditions by Bruckler et al. (2002). Lemaire et al. (2004) analyzed the water transport in expansive clay (from an infiltration test) using the common diffusion equation involving Boltzmann variable. A parameter of hydraulic diffusivity was deduced using the Matano's (Pel et al., 1996) method. After Lemaire et al. (2004), two fluid transport mechanisms were involved in the test performed: imbibition of the microporosity in the scale of clay grains and capillary imbibition in the mesoporosity around the clay grains.

The results of unsaturated hydraulic conductivity are in agreement with that obtained in previous works (Daniel, 1982; Chiu and Shackelford, 1998; Bruckler et al., 2002; Cui et al. 2008*b*): the unsaturated hydraulic conductivity increased with infiltration. After Cui et al. (2008*b*), similar trend is usually observed on low-plasticity soils. For compacted expansive clays, Cui et al. (2008*b*) obtained also an increase in hydraulic conductivity with suction decrease when wetting the soil under free swell conditions whereas an inverse trend was observed at constant-volume conditions due to pore clogging by clay exfoliation.

The results obtained in this study are in agreement with existing data, confirming that the size of the tank is large enough for neglecting the effect of embedded sensors on the water transfer and soil swelling. On the other hand, the large size of the section allows developing studies on the soil-atmosphere interaction when rainfall, solar radiation, air circulation with controlled relative humidity are applied on the soil surface. The development of such a system can be based on the works reported by several authors as Kohsiek (1981), van de Griend and Owe (1994), Aluwihare and Watanabe (2003). Note however that most studies on soil-atmosphere interaction are usually conducted with soil and/or climate monitoring in field condition (Tsaparas et al., 2003; Fityus et al., 2004; Smethurst et al., 2006; Zhan et al., 2007; Cui and Zornberg, 2008).

Conclusion

A large-scale infiltration tank was developed in order to study the water infiltration in compacted expansive Romainville clay. The soil sample was instrumented by various suction sensors (high capacity tensiometer, psychrometer, and relative humidity sensor), volumetric water content sensors (ThetaProbe and ECH_2O-TE), temperature sensors and displacement sensors. A specific installation was adopted for each type of sensor. Emphasis was put in minimizing the effect of sensors installation on water transfer and soil deformation. An infiltration test was performed with monitoring for 338 days. The following conclusions can be drawn.

- Monitoring total suction changes by measurement of relative humidity at various locations allowed tracking the water transfer in the soil. As these measurements are only valid for the high suction range they should be completed with the measurements by other types of sensors for lower range of suction (psychrometer, tensiometer). The results obtained show a good agreement between the three types of suction sensors. Note however that long equilibrium time was required when using high-capacity tensiometers for suction monitoring in expansive soils as Romainville clay.

- Sensors for monitoring the volumetric water content were buried inside the soil column, which allowed the free displacement of the sensors with the soil during infiltration. The good agreement between water content measurement and suction measurement confirms that the dimensions of the soil sample were large enough to minimize the effect of the sensors on water transfer.

- Heave measured at various locations on the soil surface showed a significant effect of the tank-soil friction on the soil swelling, the heave measured in the middle of the surface being twice that on the corners.

- With the experimental procedure applied, the response of the ThetaProbe sensor has been found to be in agreement with that of suction measurement while the response of the ECH_2O-TE showed some anomalies.

- The variations of hydraulic conductivity versus total suction were determined from the suction and volumetric water content measurements. The results were in good agreement with other works on compacted expansive soils: the hydraulic conductivity was increasing with suction decreases. For the studied Romainville clay, the unsaturated hydraulic conductivity was close to 10^{-14} m/s at high suction (100 MPa) and it increased to 10^{-11} m/s at low suction (1 MPa).

Acknowledgments

References

Abduljauwad, S. N., Al-Sulaimani, G. J., Basunbul, I. A., and Al-Buraim, I., 1998, "Laboratory and field studies of response of structures to heave of expansive clay," *Géotechnique*, Vol. 48, No. 1, pp. 103-121.

Alonso, E. E., Springman, S. M., and Ng, C. W. W., 2008, "Monitoring Large-Scale Tests for Nuclear Waste Disposal," *Geotechnical and Geological Engineering,* Vol. 26, No. 6, pp. 817 – 826.

Albright, W. H., Benson, C. H., Gee, G. W., Abichou, T., McDonal, E. V., Tyler, S. W., and Rock, S. A., 2006, "Field performance of a compacted clay landfill final cover at a humid site," *Journal of Geotechnical and Geoenvironmental Engineering,* Vol. 132, No. 11, pp. 1393 – 1403.

Aluwihare, S., and Watanabe, K., 2003, "Measurement of evaporation on bare soil and estimating surface resistance," *Journal of Environmental Engineering-ASCE*, Vol. 129, No. 12, pp. 1157-1168.

Arnould, M., 2006, "Discontinuity networks in mudstones: A geological approach," *Bulletin of Engineering Geology and the Environment*, Vol. 65, No. 4, pp. 413-422.

Aubeny, C. P., and Lytton, R. L., 2004, "Shallow slides in compacted high plasticity clay slopes," *Journal of Geotechnical and Geoenvironmenal Engineering*, Vol. 130, No. 7, pp. 717 – 727.

Audiguier, M., Geremew, Z., Laribi, S., Cojean, R., 2007, "Caractérisation au laboratoire de la sensibilité au retrai-gonflement des sols argileux," *Revue Française de Géotechnique,* No. 120 – 121, pp. 67 – 82.

Benson, C. H., and Gribb, M. M., 1997, "Measuring unsaturated hydraulic conductivity in the laboratory and field," *Unsaturated Soil Engineering Practice*, New York: ASCE, Geotechnical Special Publication No. 68, pp. 113-168.

Bruckler, L., Bertuzzi, P., Angulo-Jaramillo, R., and Ruy, S., 2002, "Testing an infiltration method for estimating soil hydraulic properties in the laboratory," *Soil Science Society of America Journal*, Vol. 66, No. 2, pp. 384-395.

Chapuis, R. P., 2002, "The 2000 R.M. Hardy Lecture: Full-scale hydraulic performance of soil-bentonite and compacted clay liners," *Canadian Geotechnical Journal*, Vol. 39, No. 2, pp. 417-439.

Chiu, T.-F., and Shackelford, C. D., 1998, "Unsaturated hydraulic conductivity of compacted sand-kaolin mixtures," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 124, No. 2, pp. 160-170.

Choo, L.-P., and Yanful, E. K., 2000, "Water flow through cover soils using modeling and experimental methods," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 126, No. 4, pp. 324-334.

Comet, 2008, "*T3111 Transmitters: Programmable transmitter of temperature, relative humidity and other derived humidity values with 4-20 mA outputs. Instruction Manual*." 8 pages.

Correge, 2008, "*Thermosonde à câble à résistance platine*," www.correge.fr/thermosonde-cable.

Cui, Y.J., Lu, Y.F., Delage, P and Riffard, M. 2005, "Field simulation of in-situ water content and temperature changes due to ground-atmospheric conditions," *Géotechnique*, Vol.55, No. 7, pp. 557-567.

Cui, Y.-J., Mantho, A.-T., Cui, K., and Audiguier, M., 2006, "Water retention properties and volume change behaviour of natural Romainville clay," *Proc. 4th Int. Conf. on Unsaturated Soils (UNSAT' 2006)*, Carefree, AZ, Vol 1., pp. 873-882.

Cui, Y.J., and Zornberg, J., 2008, "Water Balance and Evapotranspiration Monitoring in Geotechnical and Geoenvironmental Engineering," *Geotechnical and Geological Engineering*, Vol. 26, No. 6, pp. 783 – 798.

Cui, Y. J., Tang, A. M., Mantho, A. T., and De Laure, E., 2008*a*, "Monitoring field soil suction using a miniature tensiometer," *Geotechnical Testing Journal,* Vol. 31, No. 1, pp. 95-100.

Cui, Y.J., Tang, A.M., Loiseau, C., Delage, P., 2008*b*, "Determining the unsaturated hydraulic conductivity of a compacted sand-bentonite under constant-volume and free-swell conditions," *Physics and Chemistry of the Earth*, Vol. 33, Supplement 1, pp. S462 – S471.

Daniel, D. E., 1982, "Measurement of hydraulic conductivity of unsaturated soils with thermocouple psychrometers," *Soil Science Society of America Journal*, Vol. 46, No. 6, pp. 1125-1129.

Day, R. W., and Axten, G. W., 1988, "Surficial stability of compacted clays slopes," *Journal of Geotechnical Engineering,* Vol. 115, No. 4, pp. 577 – 580.

Decagon, 2007, "*ECH2O-TE/EC-TM Water Content, EC and Temperature Sensors*," Pullman, WA 99163 USA.

Delage, P., Howat, M.D., and Cui, Y.J., 1998. "The relationship between suction and swelling properties in a heavily compacted unsaturated clay". *Engineering Geoglogy*, Vol. 50, Nos 1 -2, pp. 31 – 48.

Delage, P., and Romero, E., 2008, "Geoenvironmental Testing," *Geotechnical and Geological Engineering*, Vol. 26, No. 6, pp. 729 – 749.

Delta-T, 1999, "*ThetaProbe Soil Moisture Sensor _ type ML2x _ User Manual*," Cambridge CB5 0EJ, England.

FGP, 2004, "*Modèle DX20EL Capteur de déplacement LVDT*," www.fgp-instrumentation.com.

Fityus, S. G., Smith, D. W., and Allman, M. A., 2004, "Expansive soil test site near Newcastle," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 130, No. 7, pp. 686-695.

Kim, D.J., Angulo Jaramillo, R., Vauclin, M., Feyen, J., Choi, S.I., 1999, "Modelling of soil deformation and water flow in a swelling soil," *Geoderma*, Vol. 92, pp. 217 – 238.

Kizito, F., Campbell, C. S., Campbell, G. S., Cobos, D. R., Teare, B. L., Carter, B., and Hopmans, J. W., 2008, "Frequency, electrical conductivity and temperature analysis of a low-cost capacitance soil moisture sensor," *Journal of Hydrology*, Vol. 352, No. 3-4, pp. 367-378.

Kohsiek, W., 1981, "A Rapid-Circulation Evaporation Tank for Measuring Bulk Stomatal-Resistance," *Journal of Applied Meteorology*, Vol. 20, No. 1, pp. 42-52.

Kröhn, K.P., 2003, "Results and interpretation of bentonite resaturation experiments with liquid water and water vapour," *Proc. Int. Conf. From Experimental Evidence towards Numerical Modeling of Unsaturated Soils*, Weimar, Germany, (ed. T. Schanz), Berlin: Springer, Vol. 1, pp. 257 – 272.

Laribi, S., Audiguier, M., and Cojean, R., 2008, "Assessing shrink/swell properties of two argillaceous soils from the Paris Basin: A comparison of cation exchange determination methods," *Bulletin of Engineering Geology and the Environment*, Vol. 67, No. 3, pp. 415-424.

Lemaire, T., Moyne, C., and Stemmelen, D., 2004, "Imbibition test in a clay powder (MX-80 bentonite)," *Applied Clay Science*, Vol. 26, No. 1-4, pp. 235-248.

Loiseau, C., Cui, Y.J., and Delage, P., 2002 "The gradient effect on the water flow through a compacted swelling soil," *Proc. 3rd Int. Conf. on Unsaturated Soils (UNSAT 2002)*, Recife, Brazil (ed. Jucá, J.F.T., de Campos, T.M.P. and Marinho, F.A.M.), Lisse: Swets & Zeitlinger, Vol. 1, pp. 395-400.

Lukangu, G., Savage, M. J., and Johnston, M. A., 1999, "Use of sub-hourly soil water content measured with a frequency-domain reflectometer to schedule irrigation of cabbages," *Irrigation Science*, Vol. 19, No. 1, pp. 7-13.

Masrouri, F., Bicalho, K., and Kawai, K., 2008, "Laboratory Hydraulic Testing in Unsaturated Soils," *Geotechnical and Geological Engineering*, Vol. 26, No. 6, pp. $691 - 704$.

Meerdink, J. S., Benson, C. H., and Khire, M. V., 1996, "Unsaturated hydraulic conductivity of two compacted barrier soils," *Journal of Geotechnical Engineering-Asce*, Vol. 122, No. 7, pp. 565-576.

Oliveira, O. M., and Marinho, F. A. M., 2008, "Suction equilibration time for a high capacity tensiometer," *Geotechnical Testing Journal*, Vol. 31, No. 1, pp. 101-105.

Pel, L., Brocken, H., and Kopinga, K., 1996, "Determination of moisture diffusivity in porous media using moisture concentration profiles", *Int. J. Heat and Mass*, vol. 39, pp. 1273-1280.

Ridley, A. M., Dineen, K., Burland, J. B., and Vaughan, P. R., 2003, "Soil matrix suction: Some examples of its measurement and application in geotechnical engineering," *Géotechnique*, Vol. 53, No. 2, pp. 241-253.

Robinet, J. C., and Rhattas, M., 1995, "Détermination de la perméabilité non saturée des matériaux argileux a faible porosité," *Canadian Geotechnical Journal*, Vol. 32, No. 6, pp. 1035-1043.

Robinson, D. A., Gardner, C. M. K., and Cooper, J. D., 1999, "Measurement of relative permittivity in sandy soils using TDR, capacitance and theta probes: comparison, including the effects of bulk soil electrical conductivity," *Journal of Hydrology*, Vol. 223, No. 3-4, pp. 198-211.

Singh, D. N., and Kuriyan, S. J., 2003, "Estimation of unsaturated hydraulic conductivity using soil suction measurements obtained by an insertion tensiometer," *Canadian Geotechnical Journal*, Vol. 40, No. 2, pp. 476-483.

Smethurst, J. A., Clarke, D., and Powrie, W., 2006, "Seasonal changes in pore water pressure in a grass-covered cut slope in London Clay," *Géotechnique*, Vol. 56, No. 8, pp. 523-537.

Stormont, J. C., and Anderson, C. E., 1999, "Capillary barrier effect from underlying coarser soil layer," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 125, No. 8, pp. 641-648.

Tang, A. M., and Cui, Y. J., 2005, "Controlling suction by the vapour equilibrium technique at different temperatures and its application in determining the water retention properties of MX80 clay," *Canadian Geotechnical Journal*, Vol. 42, No. 1, pp. 287-296.

Tarantino, A., Ridley, A. M., and Toll; D. G., 2008, " Field Measurement of Suction, Water Content, and Water Permeability," *Geotechnical and Geological Engineering*, Vol. 26, No. 6, pp. $751 - 782$.

Tsaparas, I., Rahardjo, H., Toll, D. G., and Leong, E.-C., 2003, "Infiltration characteristics of two instrumented residual soil slopes," *Canadian Geotechnical Journal*, Vol. 40, No. 5, pp. 1012-1032.

Van de Griend, A. A., and Owe, M., 1994, "Bare Soil Surface-Resistance to Evaporation by Vapor Diffusion under Semiarid Conditions," *Water Resources Research*, Vol. 30, No. 2, pp. 181-188.

Verhoef, A., Fernandez-Galvez, J., Diaz-Espejo, A., Main, B. E., and El-Bishti, M., 2006, "The diurnal course of soil moisture as measured by various dielectric sensors: Effects of soil temperature and the implications for evaporation estimates," *Journal of Hydrology*, Vol. 321, No. 1-4, pp. 147-162.

Wescor, 2004, "*PSYPRO Water Potential System _ Users Manual*," Wescor, Logan, UT 84321-5294 USA.

Wind, G.P., 1968. Capillary conductivity data estimating by a simple method. *In* P.E. Rijtema and H. Wassink (ed.) Water in the unsaturated zone, vol. 1, Proc. Wagenigen Symp., June 1966. Int. Assoc.Scientific Hydrol., Gentbrugge, Belgium.

Yang, H., Rahardjo, H., Wibawa, B., and Leong, E.-C., 2004, "A soil column apparatus for laboratory infiltration study," *Geotechnical Testing Journal*, Vol. 27, No. 4, pp. 347-355.

Yong, R. N., and Mohamed, A. M. O., 1992, "A Study of Particle Interaction Energies in Wetting of Unsaturated Expansive Clays," *Canadian Geotechnical Journal*, Vol. 29, No. 6, pp. 1060-1070.

Zhan, T. L. T., Ng, C. W. W., and Fredlund, D. G., 2007, "Instrumentation of an unsaturated expansive soil slope," *Geotechnical Testing Journal*, Vol. 30, No. 2, pp. 113-123.

Table 1. Sensors used

Name	Type	Manufacturer	Model	Parameter measured	Range	Accuracy	Number	Position	Reference
TS	High-capacity tensiometer	ENPC		Matric suction	0 – 1500 kPa	_	6	Wall	Cui et al. (2008*a*)
PS	Psychrometer	Wescor	PST-55	Total suction	0.05 – 8 MPa	± 0.03 MPa	8	Wall	Wescor (2004)
RS	Transmitter	Elcowa	T3111	- Relative humidity	0 – 100%	±2.5%	10	Wall	Comet (2008)
				- Temperature	-30°C to +150°C	±0.4°C			
TP	ThetaProbe	Delta-T	ML2x	Volumetric water content	0 – 100%	±1.0%	5	Soil	Delta-T (1999)
EC	Capacity	Decagon	ECH$_2$O-TE	-Volumetric water content	0 – 100%	±3.0%	5	Soil	Decagon (2007)
				- Electrical conductivity	0 – 50 dS/m	±10.0%			
				- Temperature	-40 to +50°C	±1.0°C			
PT	Resistance temperature detectors	Correge	PT1000	Temperature	0 – 100 °C	±0.3°C	10	Soil	Correge (2008)
LV	Linear variable differential transformer	FGP	DX20EL	Displacement	0-50 mm	±0.125 mm	15	Surface	FGP (2004)

Table 2. Geotechnical properties of Romainville green clay (after Audiguier et al., 2007; Laribi et al., 2008)

Property	Romainville green clay
Carbonate content (%)	15-20
Organic matter content (%)	0.12
Specific surface area (m^2/g)	98
Blue methylene value	6.5
Liquid limit (%)	75
Plastic limit (%)	40
Plasticity index (%)	35
< 2 μm (%)	84
Specific gravity	2.67

(a) 3-D View   (b) View from the top

(c) Section A - A   (d) Section B - B   (e) Section C - C
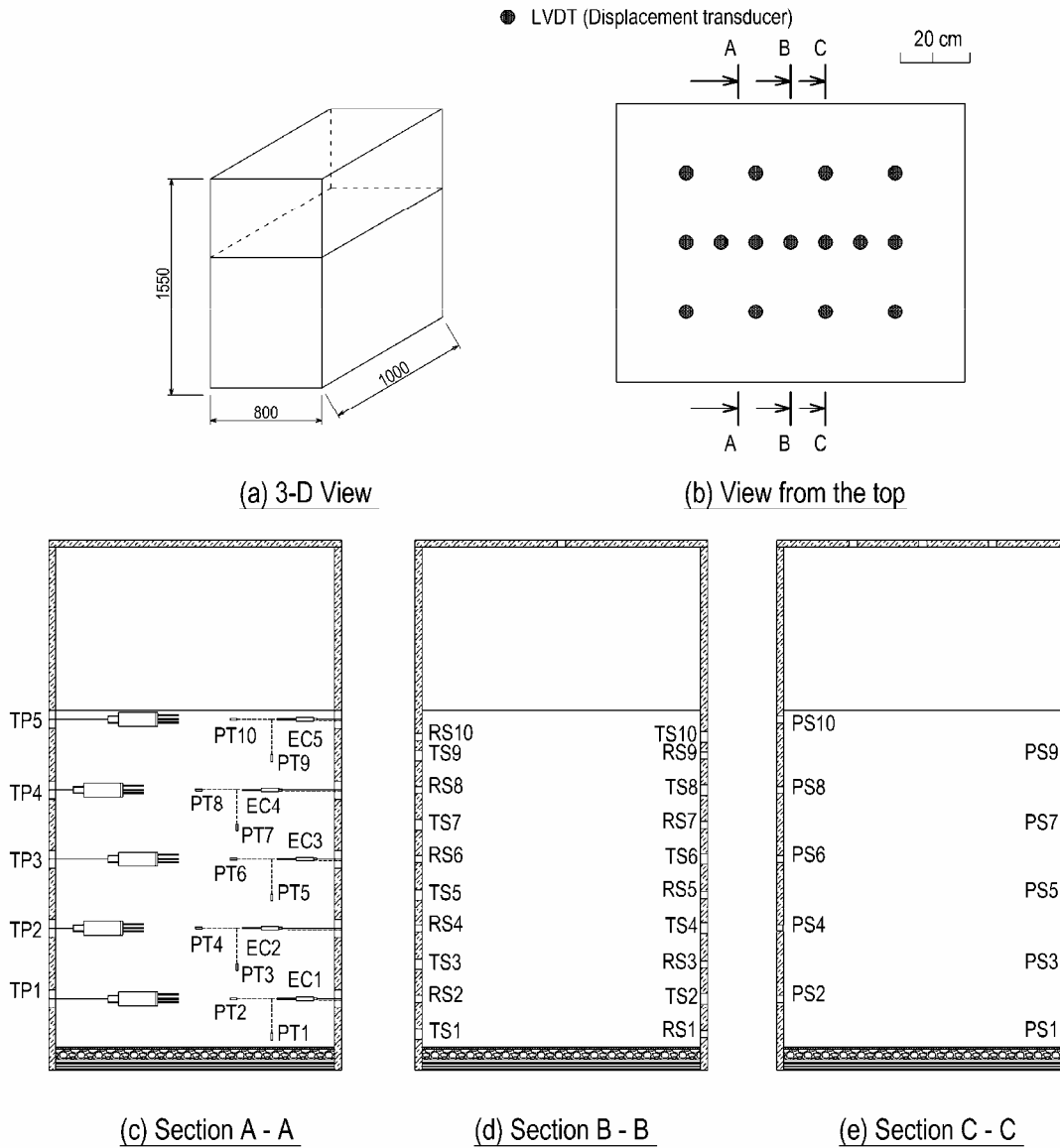
TP: Volumetric water content sensor (ThetaProbe)
PT: Temperature sensor
EC: Volumetric water content sensor (ECH2O-TE)
TS: Matric suction sensor (Tensiometer)
RS: Relative hudimity sensor
PS: Total suction sensor (Psychrometer)

Fig. 1. Schematic views of the experimental setup

Fig. 2. Picture of the experimental setup
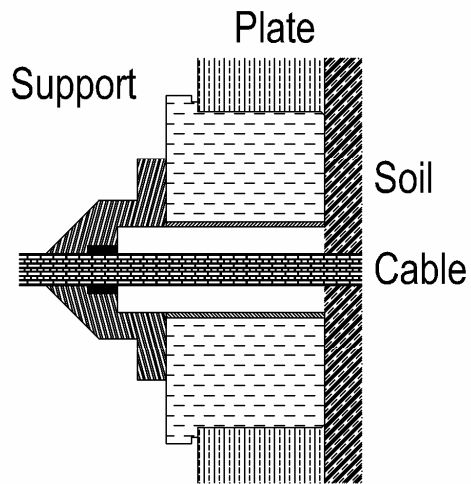
a) ThetaProbe, ECH2O-TE, PT
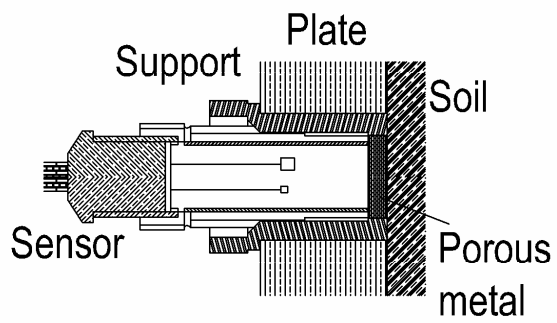
b) RS (Relative humidity and temperature)
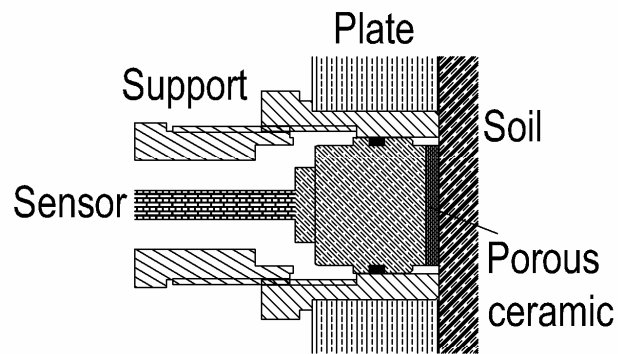
c) TS (Tensiometer)

Fig. 3. Details of the sensors used
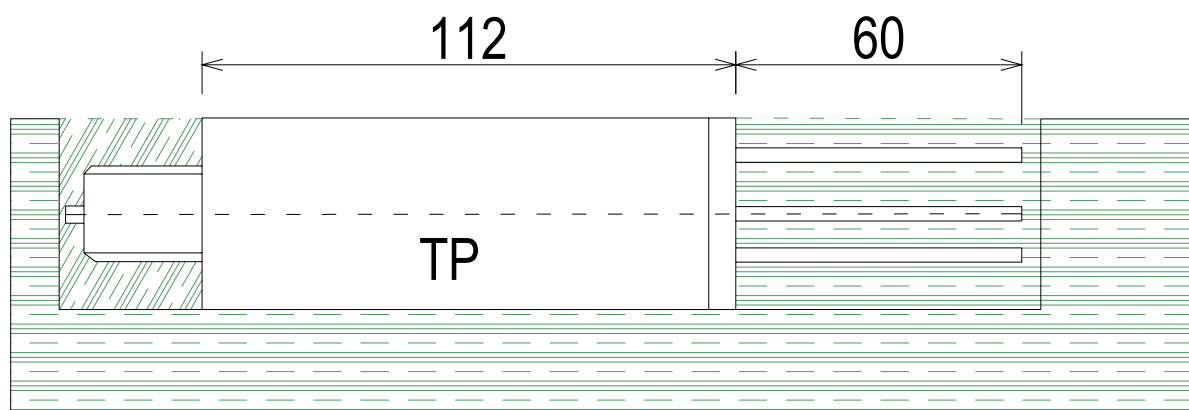
Fig. 4. Installation of the ThetaProbe (TP) sensors

$$y = 2.5483x^2 - 4.0981x + 0.0099$$
$$R^2 = 0.9719$$
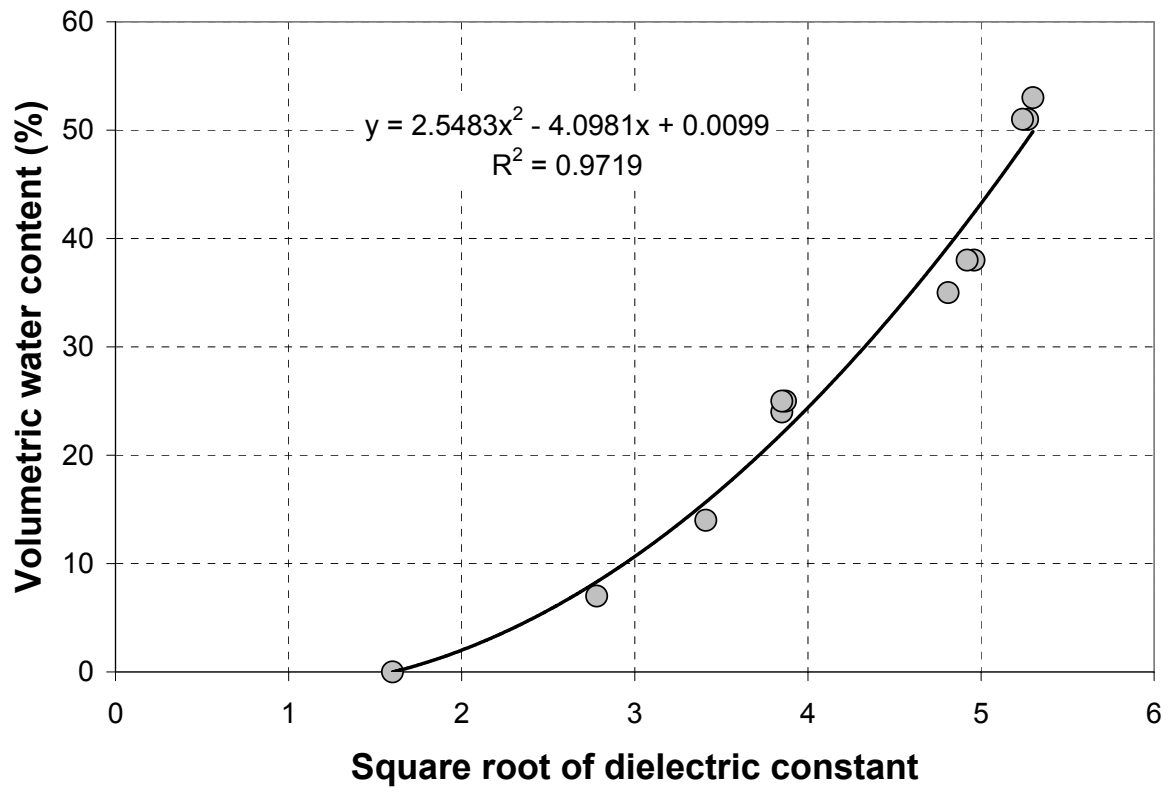
Fig. 5. Calibration of ThetaProbe.
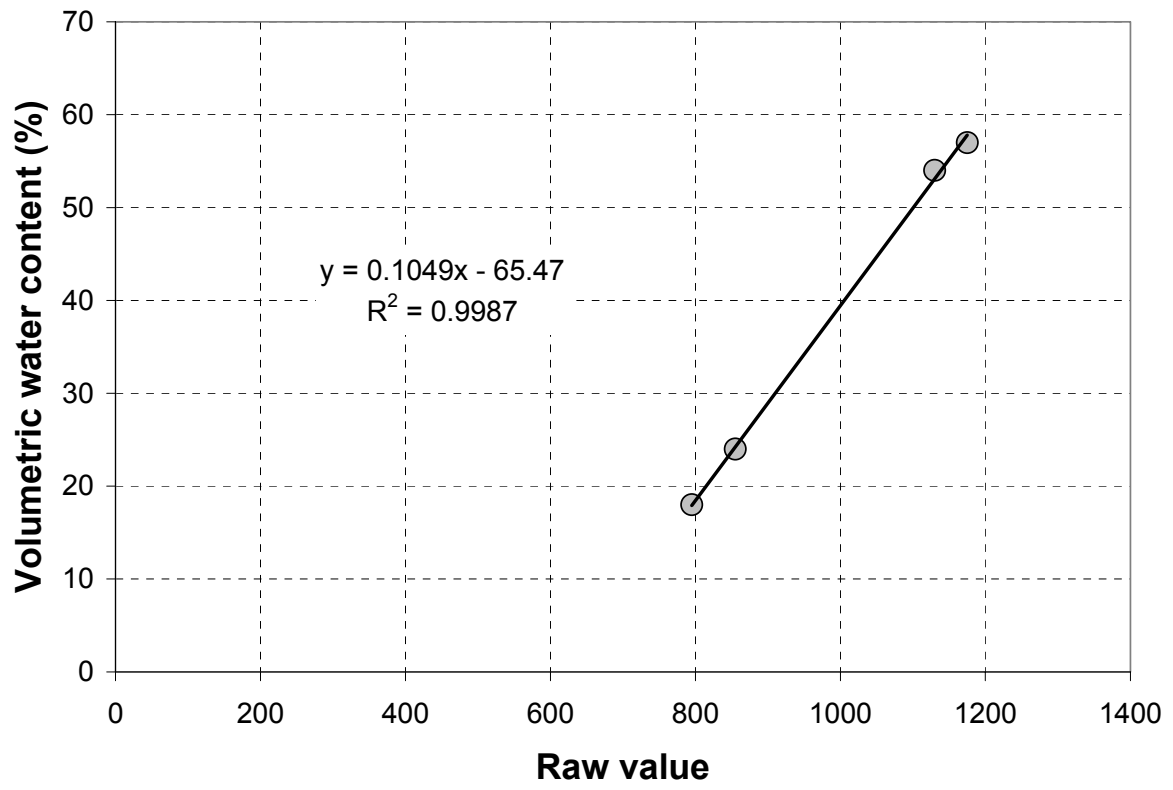
Fig. 6. Calibration of ECH$_2$O-TE
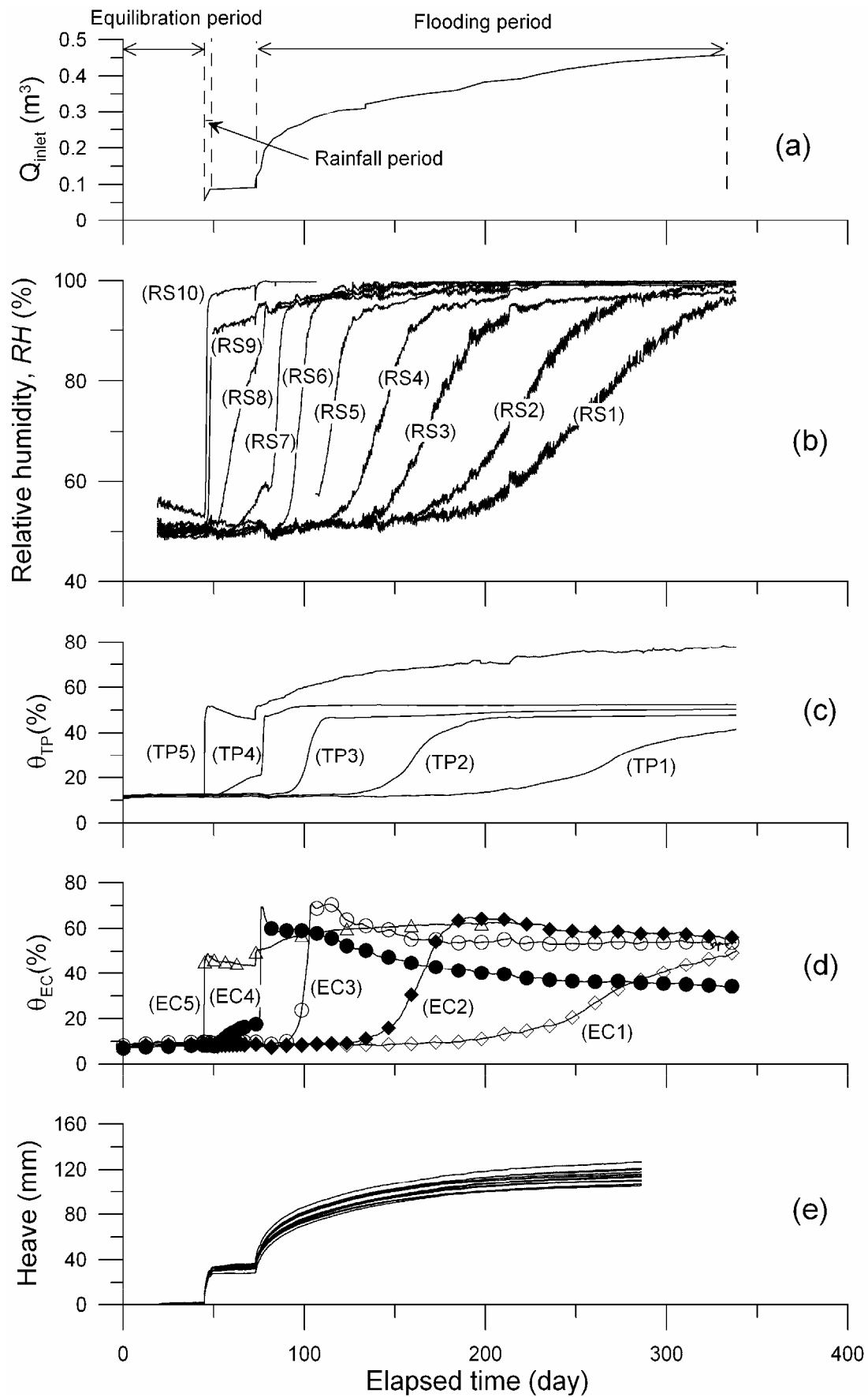
Fig. 7. Data monitored versus time (part 1)
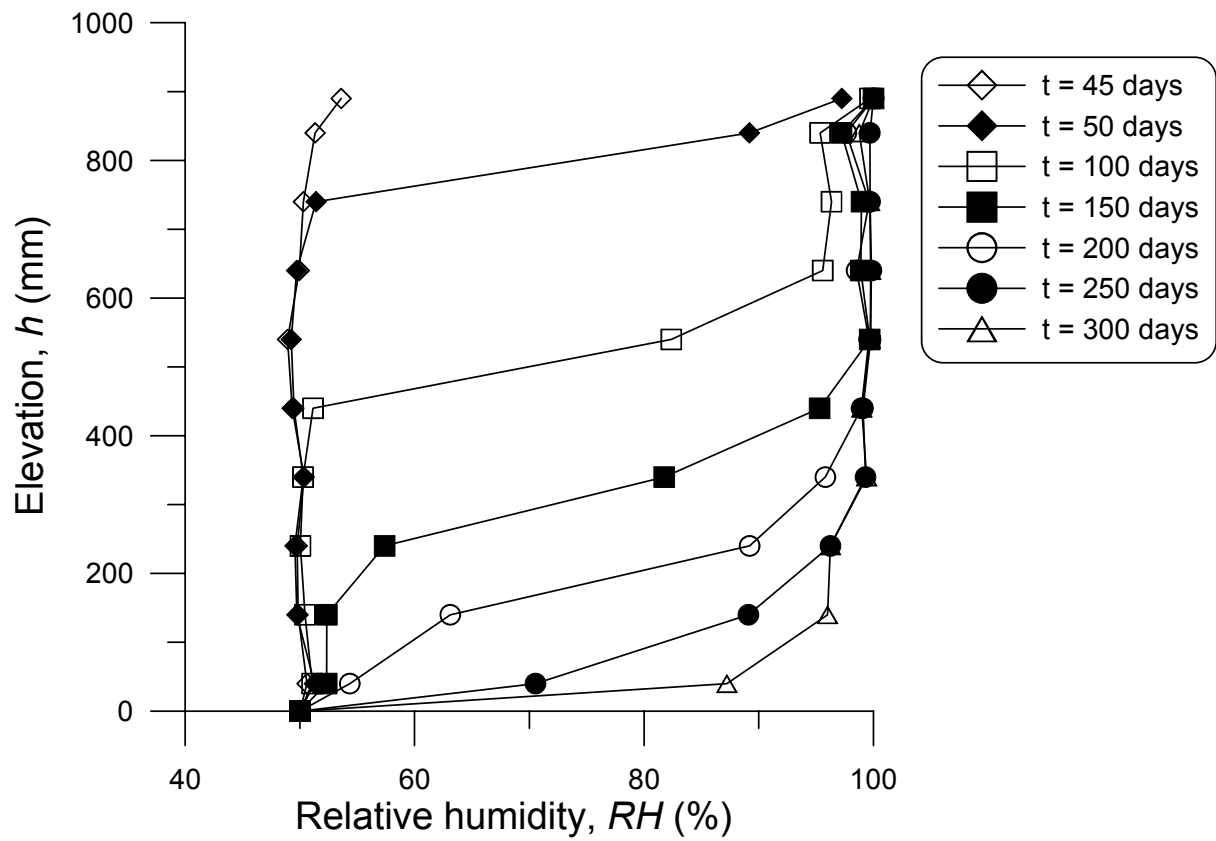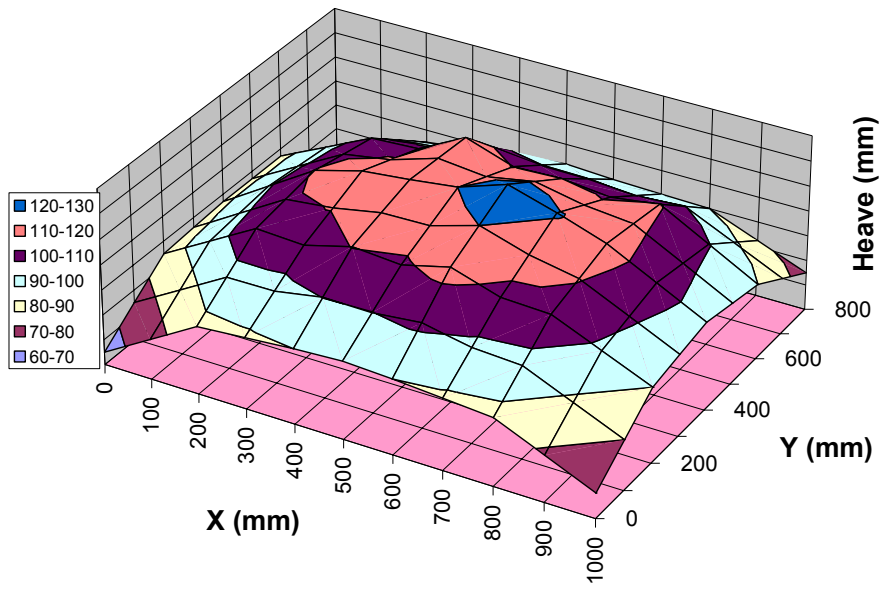
Fig. 8. Relative humidity profiles at various times
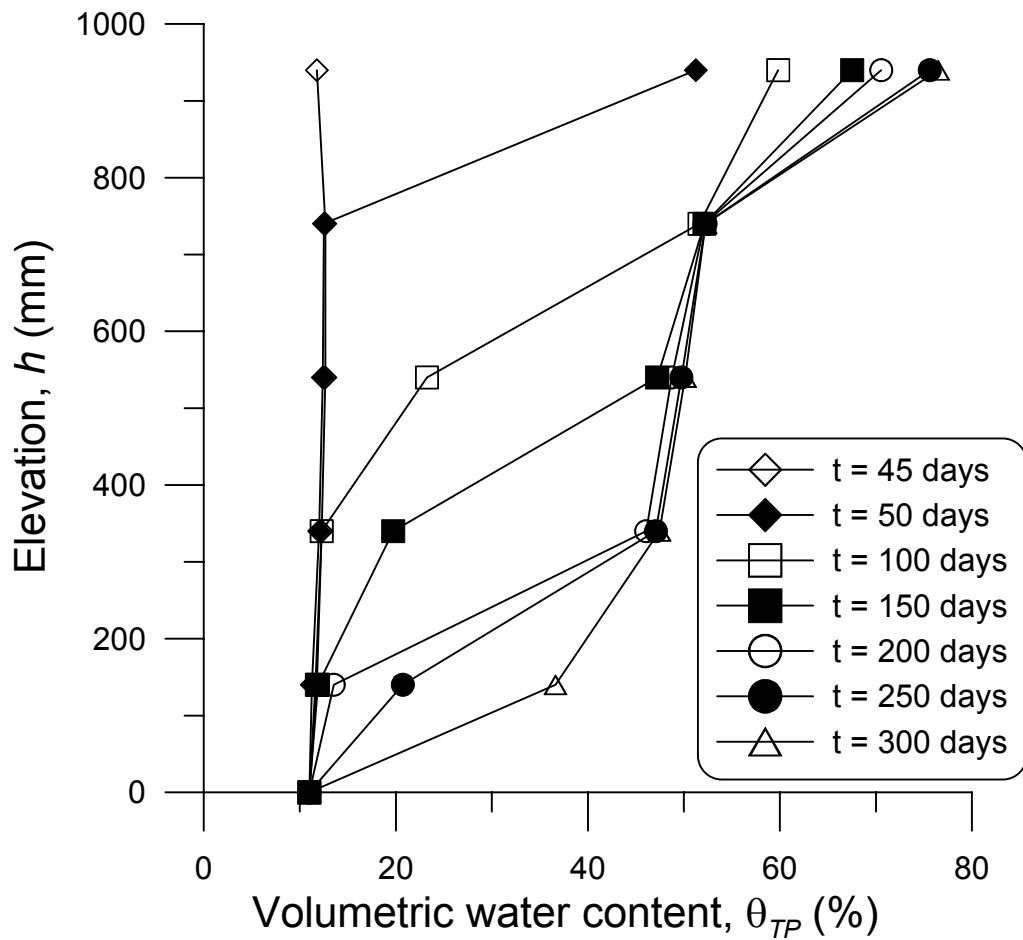
Fig. 9. Profiles of volumetric water content measured by TP sensors at various times

Fig. 10. 3-D presentation of heave at t = 283 days
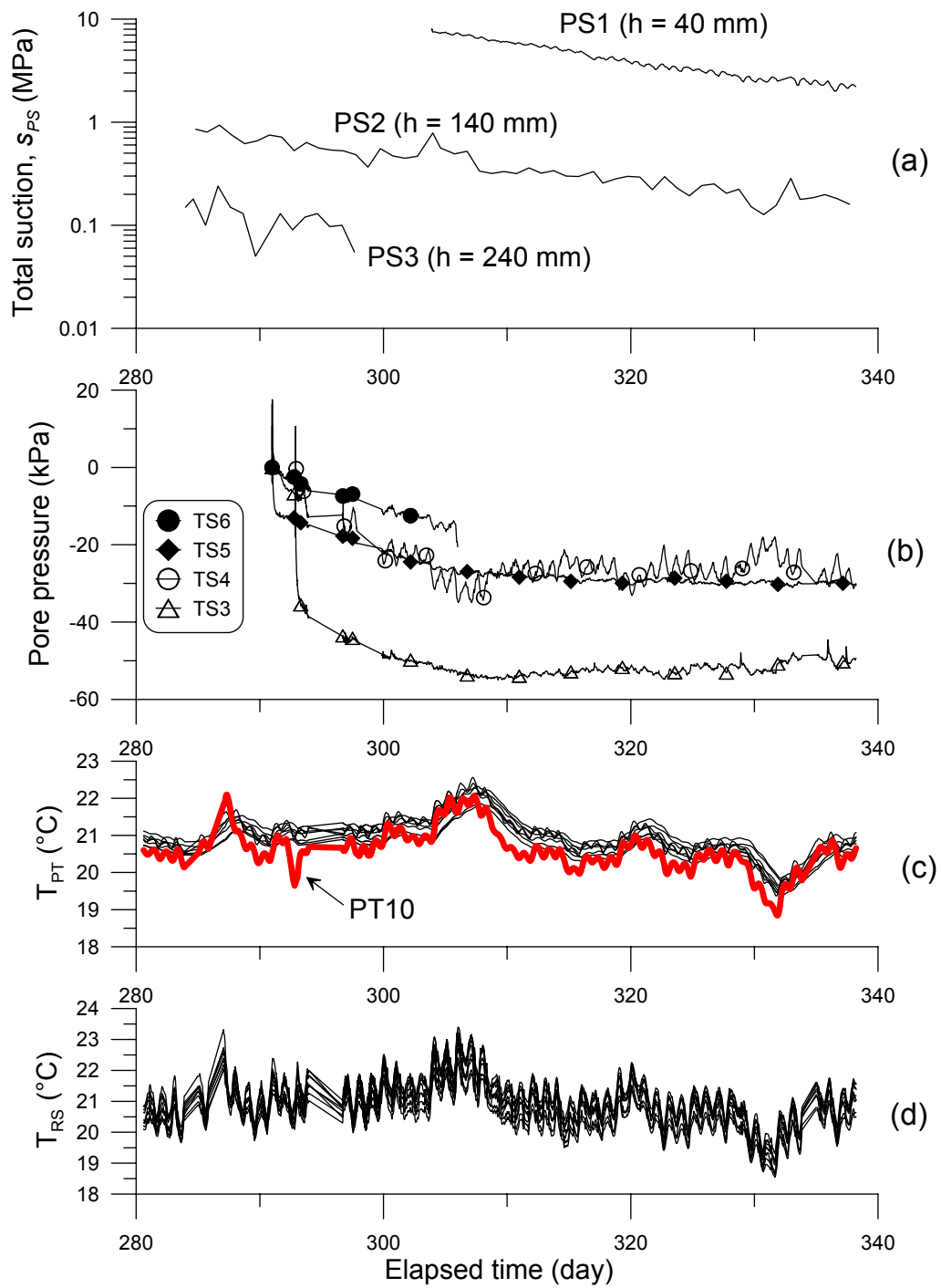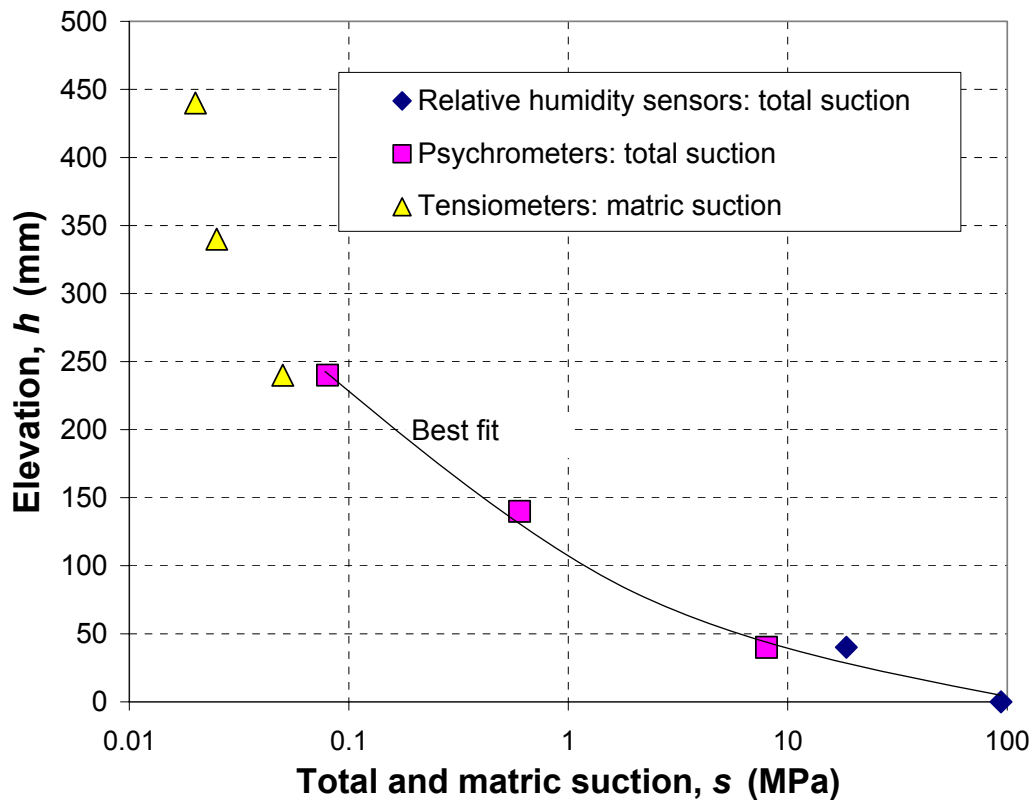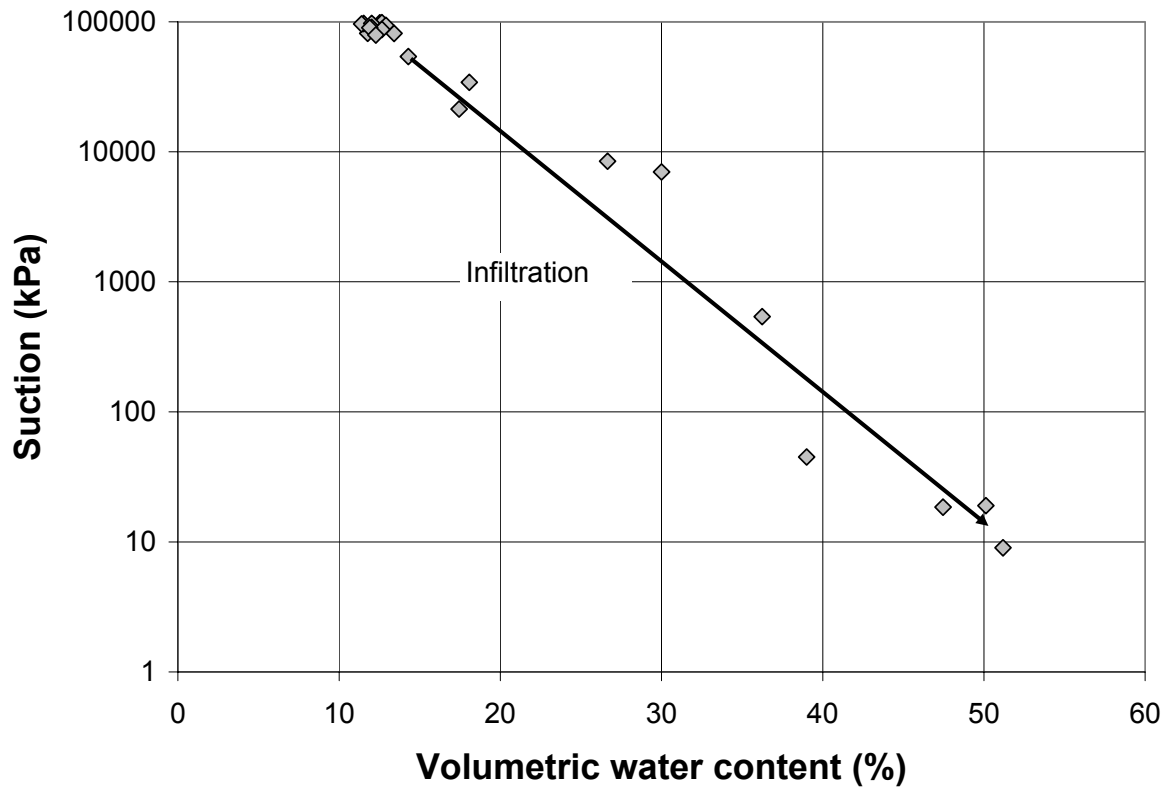
Fig. 11. Data monitored (part 2)

Fig. 12. Suction profile at t = 300 days measured with three types of sensor

Fig. 13. Suction measured by RS sensors, psychrometers and tensiometers versus volumetric water content measured by ThetaProbe sensors
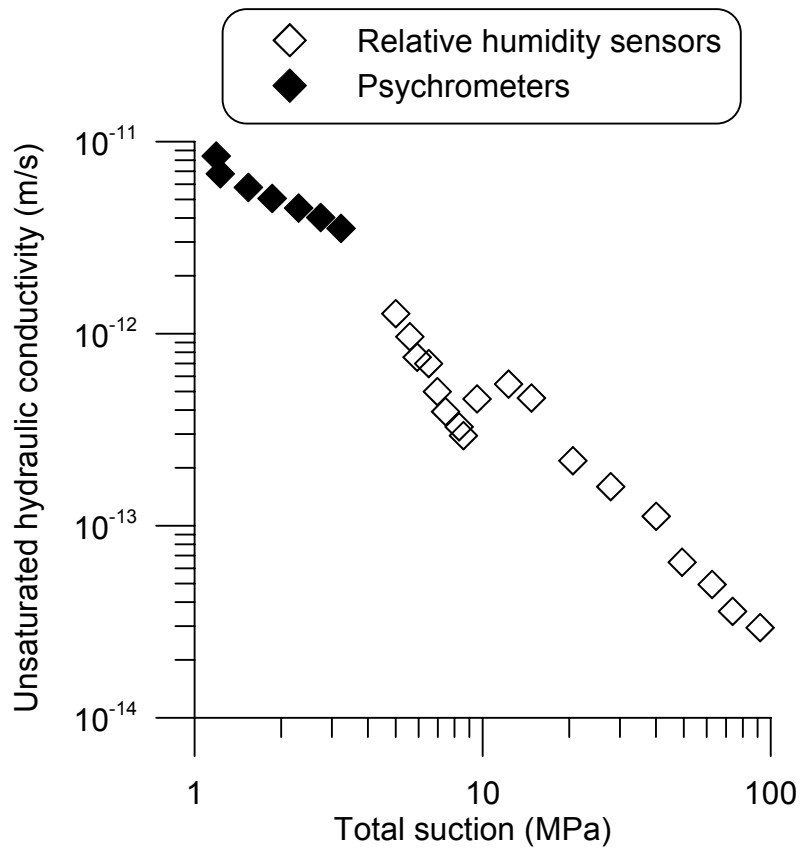
Fig. 14. Unsaturated hydraulic conductivity versus total suction