

Experimental Investigation of Soil-Atmosphere Interaction in an Instrumented Embankment Constructed with Two Treated Clays

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Abstract. This paper discusses the field monitoring of an experimental embankment divided into two symmetrical instrumented sections constructed with two clays treated with lime and/or cement in the northeast of France. The soil-atmosphere interaction is investigated in the monitored embankment. The field instrumentation included spatial and temporal changes of the soil suction, moisture, and temperature at predefined locations within the embankment, as well as measurements of meteorological data, collected from April to November 2011. The data show similarities in the suction daily variations trend in the two treated clays. Maximum changes in suction occur near ground surface. Even at the location of -0.75 m from the slope face the interchange of water between the atmosphere and the ground was observed in the daily soil suction measurements. No significant hydrologic response of the soils to rainfall was observed during the period of water deficit. The rainfall events showed a significant effect on the soil suction changes in the initial period of water surplus after a long period of water deficit. The comparison of the period of water deficit observed in the responses of the mean monthly suction and moisture measurements in the treated soils and the one estimated by simple water balance models based on standard meteorological observations in the region indicate that there is an overall qualitative agreement between the modelling and observational results.

Keywords: field monitoring, suction, temperature, moisture, evaporation, soil- atmosphere interaction.

1. Introduction

Compacted soils are widely used for the construction of earth embankments or earth fills, but the behavior of these soils is not fully understood, mainly because of their unsaturated state. Compacted soils are unsaturated during the construction stage; subsequently the degree of saturation is either increased (*e.g.*, infiltration or loading) or decreased (*e.g.*, evaporation), and the soil properties may change considerably. Understanding these changes in the soil properties, especially the changes in the pore-water pressure, is crucial in optimizing the design of earthen land-fill covers and in controlling their long-term performance (Bicalho et al., 2000).

Negative pore-water pressures (or suctions) contribute to increasing the strength of the unsaturated soil, and changes in weather conditions might lead to changes in suctions and in the strength of the soil making it more susceptible to failure. When the water table is at significant depth, soil suction changes are likely to be directly controlled by atmospheric conditions (Toll et al., 2011). In

consequence of that, suction should be viewed as an environmental variable (Gens, 2010), and field monitoring results can help engineers to understand the impact of soil surface conditions and soil moisture and temperature on the soil suction profiles.

The interactions between the atmosphere and the soil surface have not been potently addressed by civil engineers, and particularly by geotechnical engineers, even though, it has already been the topic of several publications (Blight, 1997, 2013; Wilson et al., 1997; Cui et al., 2005, 2010; Gens, 2010; Hemmati et al., 2012). Soil suctions can be changed under two principal mechanisms: infiltration or evapotranspiration. The amount of rainfall infiltration into the soil mass depends on external factors as well as intrinsic soil parameters, and the effect of rainfall infiltration on soil instabilities has been studied and published by many researchers (Brand, 1981, Wolle & Hachich, 1989; Lim et al., 1996; Rahardjo et al., 2001, 2005; Springman et al., 2003; and Huang et al., 2009). Evapo-transpiration from soil, on the other hand, is a significantly more complex mechanism,

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occurring in the form of combined liquid and vapor transport both at the depth and ground surface.

Under field conditions it is not possible to separate evaporation from transpiration totally, and the term of actual evapotranspiration is used to describe the amount of evapotranspiration that occurs under field conditions, or the total water loss. Evaporation from the bare soil surface is controlled by atmospheric and soil conditions. When available soil moisture is depleted, the actual evaporation will be limited by the monthly precipitation (lower limit) and the potential evaporation (upper limit). In months when the potential evaporation is less than the rainfall, the actual evapotranspiration is closer to the potential value (Fetter, 1994). In this case, the potential evaporation can be used to estimate the actual evaporation. However, there are some uncertainty regard to the potential evaporation value, which depends on the model structure and input data, to be investigated.

The investigation of soil-atmosphere interactions is a multidisciplinary complex research field, and, results of *in situ* monitoring of soil-atmosphere interactions have improved understanding and modelling descriptions of coupled heat, water vapour, and liquid water fluxes in unsaturated soils (Cui *et al.*, 2005, 2010). Accurate instrumentation of the soil surface in a large-scale and long-term is required for improving hydro-thermal soil profiles predictions especially in different fine-grained soils exposed to the same meteorological conditions.

This paper presents and discusses the on-going field monitoring of a large-scale experimental embankment divided into two symmetrical instrumented sections constructed with two different treated clays in the northeast of France. The objective of the study was to investigate the influence of weather changes on the treated soil responses (*i.e.*, suction, volumetric water content and temperature) to provide an understanding of soil-atmosphere flux in the embankment system over time. The study highlights some features of soil-atmosphere interactions, in particular, the impact of the duration and intensity of rainfall on low permeable soils during dry and wet periods, and examines the use of simple water balance models based on standard meteorological observations to assess soil suction and moisture conditions.

2. Materials and Methods

2.1. Site description and materials used in the experimental embankment

The experimental embankment was constructed at Hericourt, in the Haute-Saone department (Franche-Comte region) in the northeast of France. It is exposed to a continental climate, with oceanic influences. The embankment dimensions are 107 m long by about 5 m high with side slopes of 1 on 2 (Vertical: Horizontal). The embankment was divided into two symmetrical sections, constructed

with two different fine-grained soils to represent two types of constructions: a road and a railway embankment. The soils used in the embankment were treated with cement and/or lime in different percentages.

In the experimental program, the *in situ* testing, soil sampling and laboratory testing were undertaken to help characterize the used materials. According to the unified soil classification system, the two natural soils were classified as: CL, an inorganic clay with low plasticity, and CH, an inorganic clay with high plasticity. The French Soil Classification System classifies these soils into A2 and A4 groups, respectively. The same soils were classified by the AASHTO soil classification system as A-2 and A-7, respectively. The soils in this group are fine grained soils and quite common in occurrence in the region. The soils classified as CH group often have an affinity for water. If the compaction is not sufficient or the treatment is not adequate, they may shrink or swell and lose much of their stability (Lund & Ramsey, 1959; Croft 1967; Bell 1996). The grain/particle size distribution, Atterberg limits, and Methylene blue (VBS) mean values of the two natural soils are summarized in Table 1. The specific surface (m^2/g) is about $24 \times VBS$ (Cui *et al.*, 2010).

Figure 1 presents one cross section of the embankment. The section constructed with the silty clay (CL) treated with cement and/or lime (*i.e.*, CEM and/or CaO) in different percentages represents a railway embankment. The top layer consists of a railway-type structure with 0.25 m of gravel, underlain by a layer called CDF of 0.30 m of CL + 1% CaO + 5% CEM. The section below called PST consists of three layers of 0.30 m and the natural soil was treated with cement (CL + 3% CEM). The fill of the central area consists of a layer of 0.40 m and eleven layers of 0.30 m of the natural soil treated with lime (CL + 2% CaO). The section constructed with a treated high plasticity clay (CH) represents a road embankment and the top layer consists of a road-type structure with 0.25 m of silt with lime and cement (1% CaO + 5% CEM), underlain by a subsequent layer called CDF of 0.30 m of CH + 2% CaO + 3% CEM. The section below called PST consist of three layers of 0.30 m of CH + 2% CaO + 3% CEM. The fill of the embankment consists of a layer of 0.40 m and eleven layers of 0.30 m and the natural soil was treated with lime (CH + 4% CaO). The locations of the instrumentation (SUC and TDR) discussed in this paper are also shown in Fig. 1.

Tests conducted at IFSTTAR (the French Institute for Transports, Development and Networks, formerly LCPC) of Nantes showed that the mineralogical composition of the CH soil contains mainly micas, montmorillonite and quartz. Only one of the four tested samples showed the presence of carbonates (calcite and dolomite). No phase sulphate (gypsum or anhydrite) or sulphide (pyrite or pyrrhotite) have been observed. The swelling volume of the CH samples treated with 5% lime after immersion for 7

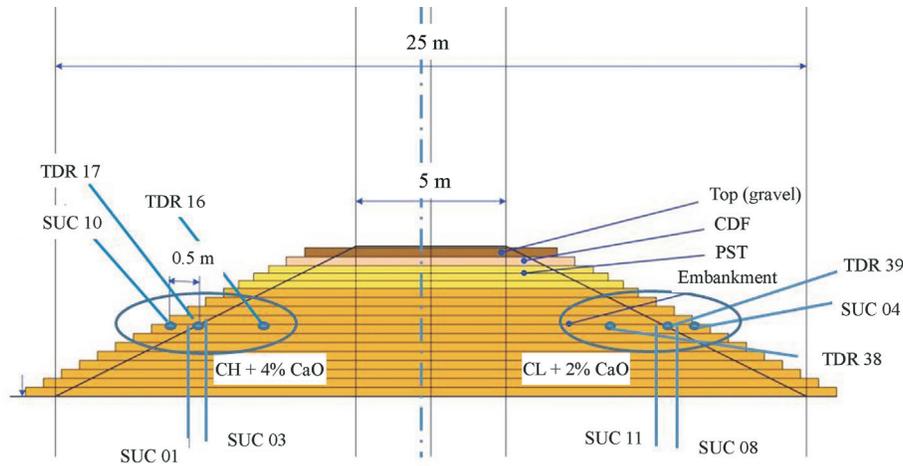


Figure 1 - A cross section of the experimental embankment constructed with two clays treated with lime and/or cement.

days at 40 °C varied from 1% to 6% for which the presence of carbonates was detected (Froumentin, 2012).

A series of laboratory tests of the natural and treated soils were conducted to evaluate the relevance of the chosen treatment formulation and the batching. Standard Proctor compaction tests results show that the addition of lime (CaO) to the soil increases quickly the optimum water content (w_{opt} , standard Proctor test) and decreases the corresponding dry density (γ_{dmax}), and the influence of lime treatment is accentuated in the CH soil (Table 2). The addition of cement (CEM > 3%) provokes the same phenomena but its influence is less than of the influence of lime. For a given water content, the addition of CEM and/or CaO reduces the swelling potential, liquid limit, and plasticity index of the soil, and increases its shrinkage limit (Croft, 1967; Bell, 1996; Le Runigo, 2008; Okyay & Dias, 2010). This is due to the flocculation and cementation of soil particles.

2.2. Field instrumentation program

In the construction of the embankment, 5280 m³ of silty clay (CL), 4710 m³ of high plasticity clay (CH), 320 t of lime and 162 t of cement were used. Soil and meteorological conditions on the test plots at the embankment have been monitored since the construction was completed in 2010. The field instrumentation program consists of detailed monitoring of matric suction, volumetric water content, and soil temperature at predefined locations over time within the embankment.

The instrumentation layout was symmetrical for the two sections of the experimental embankment constructed with the two fine-grained soils treated with lime and/or cement. The embankment consists of 17 layers made of the two fill materials compacted to optimum water contents (Standard Proctor tests). The optimum water contents were determined by the intercept of the compaction curve with the degree of saturation line corresponding to 85%. At each layer, the gravimetric water content and soil density were measured at various positions before and after construction, and the measurement variations were quite small. No leachate of lime or cement with rainfall was observed in the monitored area.

A layer of the slope, approximately at mid-slope, was selected for the investigations and analyses in this paper. The selected layer, located at about 1,8 m from the embankment base, is instrumented with sensors, for measuring suction (SUC) and water content (TDR), located close to allow estimation of the *in situ* soil water retention curves (Fig. 1).

Table 2 - Compaction tests results of the two natural and treated soils used in the investigated embankment sections.

Soils	w_{opt} (%)	γ_{dmax} (kN/m ³)
CL	17.9	17.60
CL+2%CaO	20.3	16.80
CH	26.4	15.00
CH+5%CaO	40.0	11.97

Table 1 - Characterization of the two natural soils used in the embankment.

Soils	Grain size distribution		Liquid limit (w_L)	Plasticity index (I_p)	Methylene blue value (VBS)
	≤ 0.075 mm	≤ 0.002 mm			
CL (A2)	50% - 60%	25% - 30%	40	18	2.19
CH (A4)	90%	80% - 85%	79	45	4.2 - 6.3

The field instrumentation program generated a large amount of data; therefore, this paper summarizes some of this data in graphical form from April 2011 to November 2011.

The embankment was also equipped with a site-specific meteorology station on the top surface to record the meteorological data every 30 min, including solar radiation, precipitation, atmospheric pressure, wind speed and direction, and air temperature and relative humidity at 0.5 m and 1.5 m above ground level. The soil surface temperature and atmospheric pressure were also monitored. All components were supplied by Delta-T devices Ltd.

Time Domain Reflectometry (TDR) method, a measurement technique for electrical properties (*i.e.*, dielectric constant and electrical conductivity), is used to monitor the volumetric soil water content changes at the investigated embankment. The used sensors are TRIME-PICO 64, of IMKO Micro GmbH, in Germany, which are capable of simultaneously measuring soil temperature and inferring the volumetric water content. A total of 44 called Quasi-TDR based TRIME Pico 64 was used in the embankment in two symmetrical sections. The probes installed were linked to a control panel and data acquisition system, which allowed regular measurements. The readings frequency was usually once every 3 h.

TDR is a relatively accurate and automated method for determining the water content and electrical conductivity of porous media. The water content is derived from the dielectric permittivity of the medium, while the electrical conductivity is inferred from the TDR signal attenuation. Empirical and dielectric mixing models are used to relate water content to measured dielectric permittivity. The success of TDR technique for soil water content measurement originated from the Topp *et al.* (1980)'s universal calibration in which several soils were tested and an empirical equation was obtained by regression for the relationship between apparent dielectric constant and volumetric water content. TRIME measuring system operates with a factory calibration (Topp *et al.*, 1980) for mineral soils as a standard. Material-specific calibration is recommended if one needs accuracy to the last digit.

A total of 24 Watermark soil suction sensors connected to a data acquisition system was used to monitor the matric suction changes over time at the investigated embankment. The readings frequency was usually a value every 24 h. The used sensor is an indirect, calibrated method of measuring soil suction. It is an electrical resistance type sensor. These "Granular Matrix Sensors" electronically read the amount of moisture absorbed through a special "granular matrix", or mix of precisely composed materials. This special mix buffers the sensor against the effects of different salinities and ensures a lifetime much longer than the traditional "gypsum blocks". The readings were calibrated to reflect the same values that would be generated by a Tensiometer. All conversion equations take into account

the soil temperature, because as temperature increases resistance decreases (Spaans & Baker, 1992). Variations in soil temperature can affect water potential readings by 1 to 3% per degree Celsius (Irrometer, 2005; Spaans & Baker, 1992). Shock *et al.* (1998) found that as the soil dries, the temperature effect increases. The measurement range of the used Watermark sensor is 0-200 kPa. The Watermark soil suction sensor is a product of the Irrometer Company, Inc.

2.3. Estimation of potential evaporation (ET)

The estimation of the potential evaporation (*i.e.*, the maximum evaporation rate in the case of water availability) of the investigated region is an important component of the hydrological cycle and essential for understanding soil-atmosphere fluxes in the embankment system performance over time. Several methods have been proposed to estimate ET from standard meteorological observations (Xu & Singh, 2001). In this study, the ET was estimated using two methods applied in the year 2011 when the weather data were directly measured in the investigated slope. The used methods, a temperature based equation (Thornthwaite, 1948) and a combination of temperature and air relative humidity based equation (Romanenko, 1961) are briefly summarized here and the cited references are suggested for a more detailed discussion

The empirical Thornthwaite (1948) method is highly used in several publications, even though the method is not recommended for use in areas that are not climatically similar to the developed area, in the eastern region of USA, where sufficient moisture water was available to maintain active transpiration. Moreover one should be aware that the soil temperature fluctuates daily and yearly affected mainly by changes in air temperature and solar radiation. Fetter (1994) reported that the amount of evaporated water is the greatest near the equator where solar radiation is more intense.

Often one chooses a model to estimate ET based on the available data to calculate the model. Thornthwaite (1948) formula is evaluated in this paper due to the advantage that the temperature based method offers in calculating ET by using only temperature. The method for monthly ET (mm/month) is:

$$ET \text{ (mm/month)} = 16 d (10T/I)^a; \text{ for } 0 \leq T \leq 26 \text{ }^\circ\text{C} \quad (1)$$

$$a = 0.000000675 I^3 - 0.0000771 I^2 + 0.0179 I + 0.492$$

where T is the mean temperature for the month (in $^\circ\text{C}$), I is the annual thermal index, *i.e.* the sum of monthly indices $[i = (T/5)^{1.514}]$, d is a correction factor which depends on latitude and month. In this paper, d is defined equal to 1 (Xu & Singh, 2001).

Romanenko (1961) derived an evaporation equation based on the relationship using mean monthly temperature, T (in $^\circ\text{C}$), and air relative humidity, R_h (in %):

$$ET \text{ (mm/month)} = 0.0018 (25 + T)^2 (100 - R_h) \quad (2)$$

The air relative humidity is the ratio of the absolute humidity to the saturation humidity for the air temperature. The saturation humidity is directly proportional to the air temperature, and the evaporation ceases when the air relative humidity approaches to 100%. Xu & Singh (2001) proposed an equation to calculate R_v , but, in this study, the mean monthly relative humidity values measured at the instrumented area are adopted.

Soil moisture at a location varies depending on the amount of precipitation (rain or snow) and evaporation. The atmospheric water balance (B), at a particular locality, can be written as (Blight, 1997):

$$B = P - ET \tag{3}$$

where P is the precipitation, and ET is the potential evaporation. During the period of excess water (B positive), there is moisture available for ground-water recharge and runoff. The uncertainties regard to the potential evaporation value, which depends on the model structure and input data, might result in different B values.

3. Results and Discussion

3.1. Meteorological data

The year of 2011 had a cumulative precipitation (rainfall) of 773 mm recorded by a French weather station at Luxeuil-les-Bains (located about 50 km from the site-specific meteorological station) compared with the average annual precipitation of 619 mm in France. It is observed some difference in the daily total rainfall measurements between these two places due to the great distance between them (see Fig. 2), especially in the months of April, June, August and September 2011 (Table 3). The results demonstrate that meteorological data measured by a site-specific meteorological station is important. The site-specific meteorological data are used in the investigations and analysis in this paper.

Table 3 - Comparison between the monthly rainfall values recorded at Luxeuil-les-Bains (site1) and those recorded at the site-specific meteorological station (site2).

Month (2011)	Monthly rainfall recorded at site 1 (mm/month)	Monthly rainfall recorded at site 2 (mm/month)
April (A)	11.2	0.6
May (M)	37.4	37.2
June (J)	147	85.8
July (J)	149.8	120.4
August (A)	68.2	118.6
September (S)	31.1	72.2
October (O)	71	64
November (N)	7.2	9.8

Storms with heavy rainfall exceeding 50 mm/h were not recorded in 2011 in the investigated site. Some rainy periods of heavy rain (10-50 mm/h) were observed from May to July 2011: one on May, 4 (18.6 mm/ 30 min), two events on June 8 (17.8 mm/30 min and 11 mm/30 min), two events on June 15 (9.6 mm/30 min and 7 mm/30 min), one on June 17 (6.6 mm/30 min), and the other on July 12 (13 mm/30 min). A total of 34 rainfall events of moderate rain (2.5-10 mm/h) was recorded in July 2011, the month with the highest monthly precipitation in 2011. A total of 13 rainfall events of moderate rain (2.5 -10 mm/h) was recorded in June 2011, and only one moderate rainfall event was recorded in May (*i.e.*, May 05, 3 mm/30 min). Cumulative total rainfall in May, June and July were 37.2 mm/month, 85.8 mm/month, and 120.4 mm/month respectively. Figure 2 also presents the total daily rainfall collected from April to November 2011 by the site-specific meteorological station. The largest daily rainfall

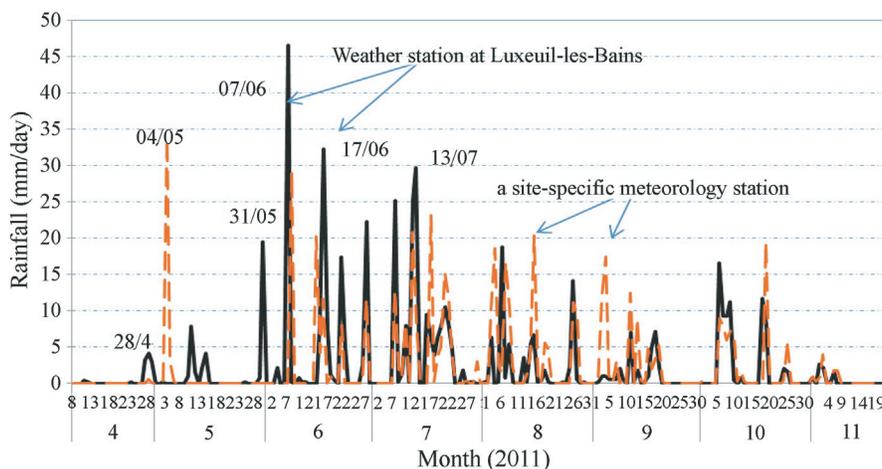


Figure 2 - Comparison between the mean daily rainfall values recorded by a French weather station at Luxeuil-les-Bains and those recorded by the site-specific meteorological station.

totals (34 mm/day) was on May 4, 2011, corresponding to circa of 92% of the month rainfall totals recorded in May, 2011.

The air temperature and relative humidity were recorded at 0.5 m and 1.5 m above the soil surface, which had an average air temperature of 16.3 °C (at soil surface), 13.8 °C (at 1.5 m) and 13.5 °C (at 0.5 m) in 2011. The air temperature varied between -4.3 °C and 34.5 °C and 4.1 °C and 34.3 °C, at 0.5 m and 1.5 m above the soil surface, respectively. At the soil surface, the air temperature varied between -3.6 °C and 44.6 °C. June and August, 2011 were the hottest months and November 2011 was the coldest, with the mean monthly temperatures near soil surface equal to 20.05 °C, 20.49 °C, and 7.24 °C, respectively (see Table 4).

Blight (1997) stated that air temperature and relative humidity gradients are generally not constant with the height above the soil surface, but they are approximately constant at heights of 0.5-2 m above the surface. The results show that the air temperatures are approximately constant at heights of 0.5 m and 1.5 m above the surface. A small difference of about 5-10% was observed in the air relative humidity recorded at 0.5 m (RH1) and 1.5 m (RH2) above the surface. The air close to the soil surface is warmer than it is higher up (at 0.5 m and 1.5 m above the soil surface) from April to August in 2011. The same trend is not observed in the months with lower temperatures (October and November 2011). Wind speeds between 0 and 5.5 m/s were recorded in 2011. The mean monthly wind speed was about 1.0 m/s for the entire monitoring period. Wind speed is important because stronger winds cause more evapotranspiration (Strunk, 2009).

Table 4 - Variation of the soil surface temperatures (Maximum, Minimum and Mean Monthly) recorded every 30min from April to November 2011.

Month (2011)	Maximum temperature soil surface (°C)	Minimum temperature soil surface (°C)	Mean monthly temperature soil surface (°C)
April (A)	33.99	-0.36	14.91
May (M)	44.64	4.89	19.10
June (J)	44.32	6.04	20.05
July (J)	41.12	4.24	17.92
August (A)	41.68	5.09	20.49
September (S)	38.17	2.6	17.21
October (O)	32.77	-1.99	10.93
November (N)	24.95	-3.63	7.24

3.2. Estimation of atmospheric water balance (B values)

Figure 3 presents the estimation of B values for the investigated region in 2011 based on the recorded rainfall (P) and computed potential evaporation values: ET_T (Thornthwaite, 1948) and ET_{R1} (using measured RH1) and ET_{R2} (using measured RH2) estimated by Romanenko (1961). The difference (5-10%) observed in the air relative humidity recorded at 0.5 m (RH1) and 1.5 m (RH2) above the ground surface resulted in variation (over 20 mm in June 2011) in the ET_{R1} and ET_{R2} values calculated by Eq. 2 (Romanenko, 1961). Fluctuations in the calculated ET_T were generally consistent with the measured air temperatures in the region during 2011. According to the ET methods used in this paper, the months of water deficit (B negative) were April and

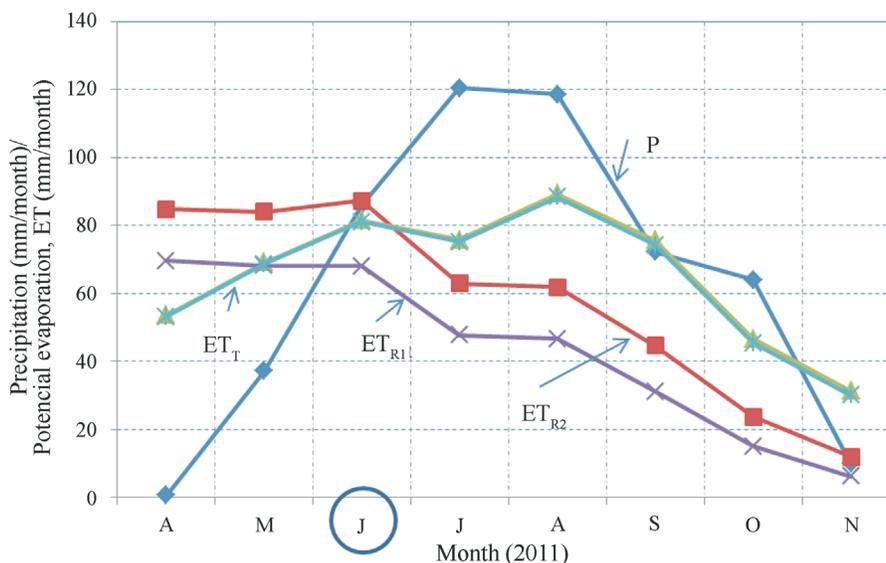


Figure 3 - Comparison among estimated monthly potential evaporation values (ET_{R1} , ET_{R2} , ET_T) and measured precipitation (P) at the site from April (A) to November (N) in 2011.

May. The period of water surplus (B positive) was from July to October. In June 2011, B varies from 0 (i.e., ET_{R2}) to +20 mm (i.e., ET_{R1}), and in November 2011, B values may be negative or positive depend on the adopted ET method.

The difference observed in the two methods can be attributed to variations of measured air relative humidity during 2011. Thornthwaite (1948) considered only the air temperature as input data while Romanenko (1961) considered the air temperature and relative humidity as input data. The mean monthly solar radiation and wind speed measured values in the region remained essentially unchanged during the evaluation period; therefore, it may be reasonable the assumption of no influence of the solar radiation and wind speed on the evaporation considered by the used methods for the region in 2011. The results, presented in Fig. 3, indicate that ET_T is lower than ET_{R1} and ET_{R2} during the period of water deficit (B negative) and higher than ET_R during the period of water surplus (B positive). Even though, Blight (1997) showed that the Thornthwaite (1948) equation consistently underestimates the measured evapotranspiration; Chen *et al.* (2005) suggested that the

Thornthwaite (1948) method overestimates ET where climate is relatively humid, while for arid and semiarid parts of China it produces an underestimation.

3.3. Responses of soil suction, moisture and temperature to meteorological changes

The layer of the slope located at about 1.8 m from the embankment base, approximately at mid-slope, was selected for the investigations and analysis because it is symmetrically instrumented with sensors for measuring suction and water content, located close to allow the estimation of the *in situ* soil water retention curves for the two treated soils.

The *in situ* soil water retention curves (SWRC) obtained from April to July 2011 for the two investigated treated soils, CL + 2% CaO and CH + 4% CaO, are presented in Figs. 4a and 4b, respectively. The relationships between soil suction and degree of saturation for the two soils were obtained considering no volume changes, and the soil porosity value of about 53% for the lime treated CH soil and 43% for the lime treated CL soil. A small variation

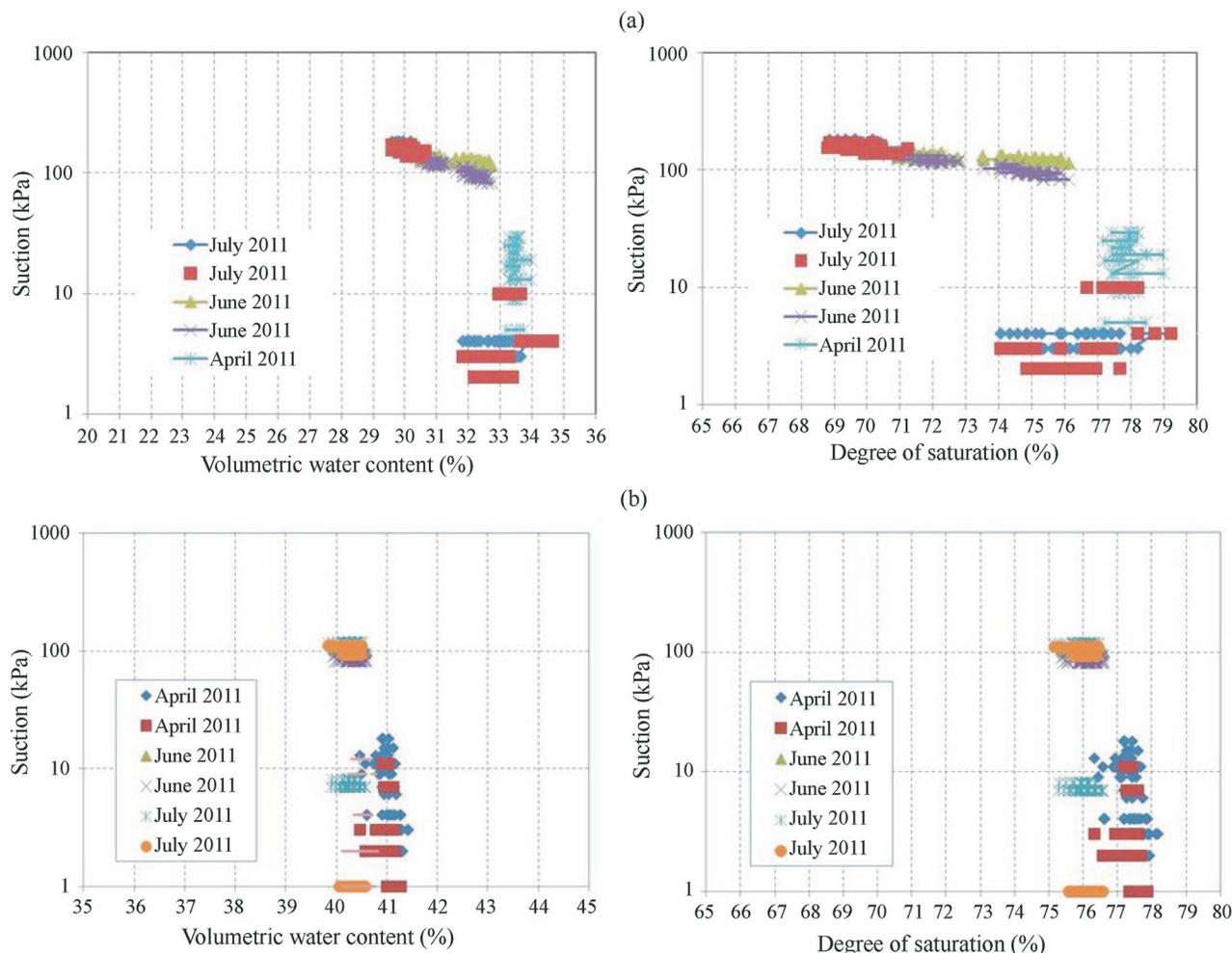


Figure 4 - The *in situ* soil water retention curves obtained from April to July 2011 for: (a) CL + 2% CaO soil and (b) CH + 4% CaO soil.

was observed in the volumetric water content and corresponding soil suctions in the two treated soils during the investigated period.

The laboratory soil water retention curves (SWRC) of the used soils have not yet been measured. It is well known that SWRC is hysteretic, with bounding curves defining the wetting and drying processes. Consequently, it very difficult to estimate the *in situ* relationship between water content and soil suction from laboratory measurements. The lime treated CL shows a more pronounced variation in the

degree of saturation from April to July 2011. No appreciable degree of saturation difference (< 2%) was observed in the investigated layer in the CH + 4% CaO section.

Figures 5 and 6 summarize the *in situ* soil suction, volumetric water content and rainfall measurements collected daily from April (month 04) to November (month 11) in 2011. Figures 5a and 6a show the *in situ* soil suction measurements for the two groups of three sensors symmetrically installed at the same layer along the face of each section of the embankment constructed with the lime treated

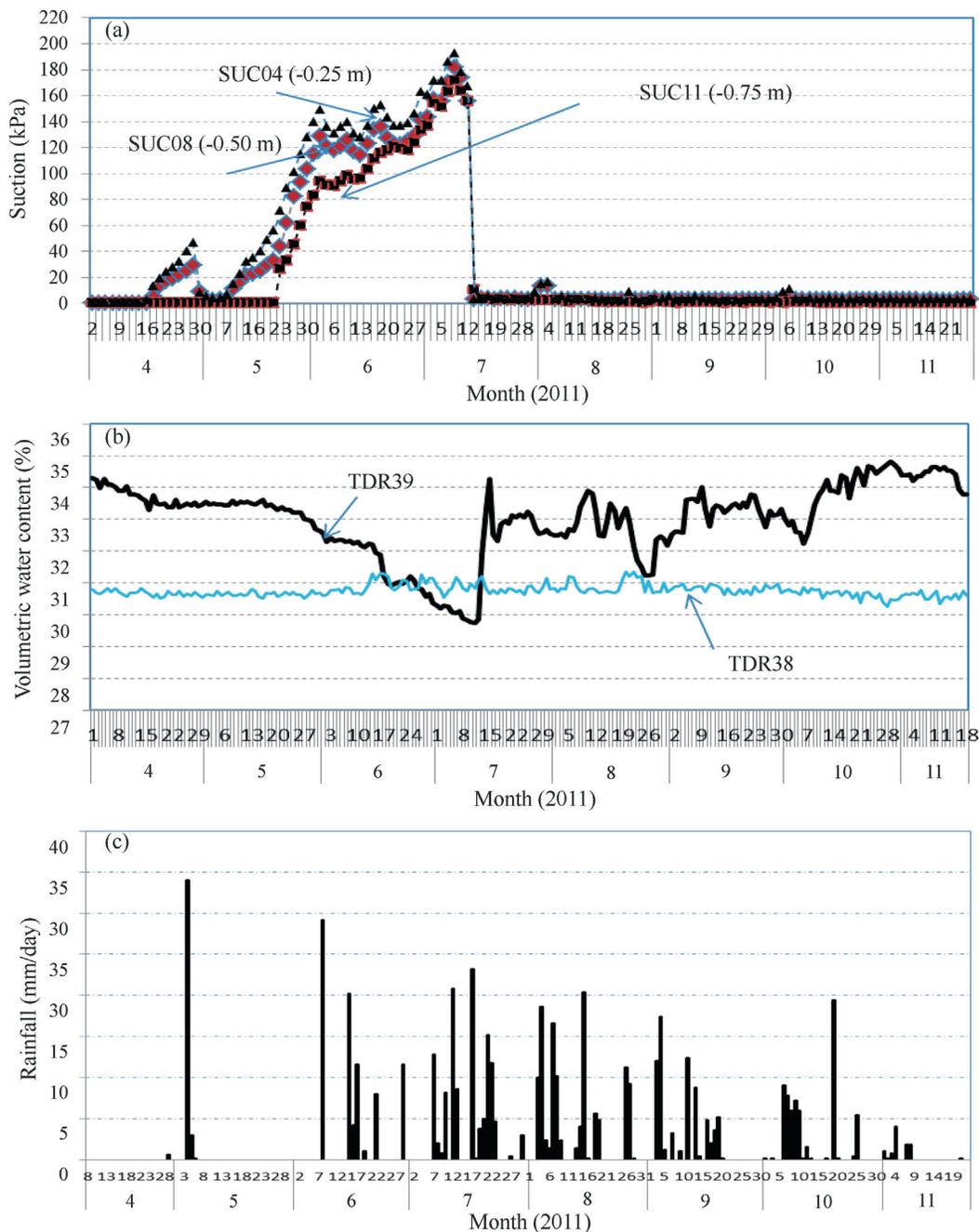


Figure 5 - The daily measured (a) soil suctions, (b) volumetric water contents, and (c) rainfall, in different locations from slope face (mid-slope, CL+ 2% CaO section) from April to November, 2011.

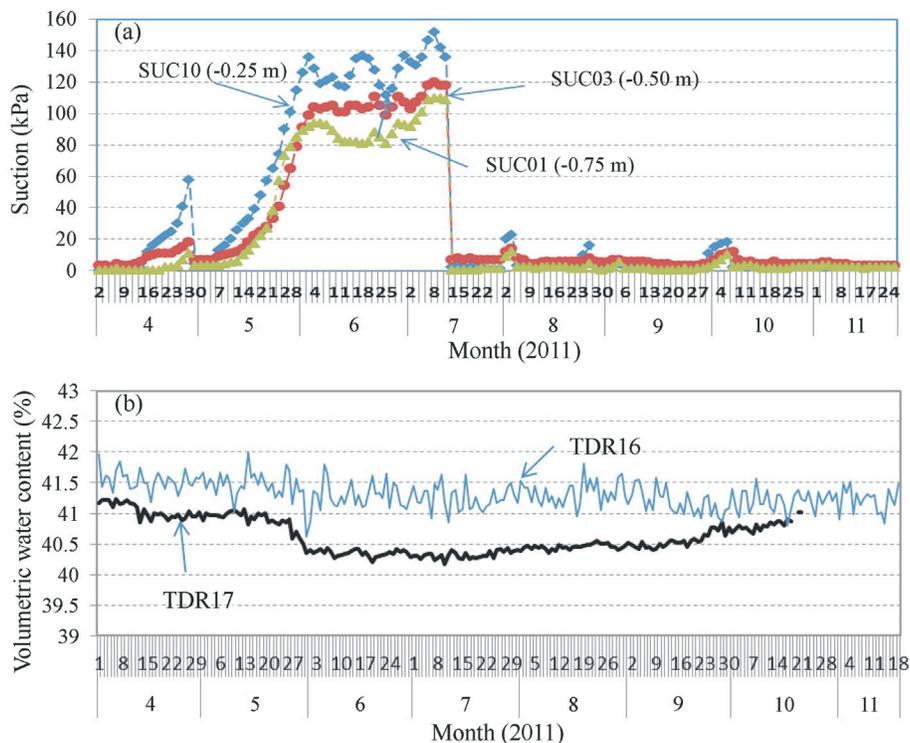


Figure 6 - The daily measured (a) soil suctions, (b) volumetric water contents, in different locations from slope face (mid-slope, CH+ 4% CaO section) from April to November, 2011.

clays, CL +2% CaO and CH + 4% CaO, respectively. As can be seen, suction is usually less than 200 kPa, and the pressure limit can be determined by the soil suction sensor. At each section of the slope the three Watermark soil suction sensors were placed at 0.25 m, 0.5 m, and 0.75 m from the ground surface (mid-slope face) as shown in Fig. 1. The results show similarities in the daily variations trend of suctions in the two treated fine-grained soils. The suction values are high near the ground surface, sensors placed at -0.25 m of the slope face, during the period of water deficit (*i.e.*, from April to June 2011) in the two investigated soils, and the fluctuation of the suction measurements generally decrease with depth.

The suction values observed in the CH + 4% CaO soil are generally lower than those at the corresponding points in the CL + 2% CaO soil, mainly due to the difference in the magnitude of the corresponding measured volumetric water content values: 39-43% (lime treated CH) and 29-35% (lime treated CL). The maximum volumetric water content of a given soil volum is the saturated volumetric water content or the soil porosity. Considering the soil porosity value of about 53% for the lime treated CH and 43% for the lime treated CL, the degrees of saturation change from 74% to 81% in the investigated layer in the CH +4% CaO section and from 68 to 81% in the investigated layer in the CL +2% CaO section.

The data presented in Figs. 5a and 6a show that the daily suctions are recovered gradually in response to the pe-

riod of water deficit from April to June 2011 in the two treated clays. Even at the location of -0.75 m (soil suction sensors SUC11, CL + 2% CaO and SUC01, CH+ 4% CaO) from the mid-slope face the effect of evaporation was observed in the daily suction and moisture measurements in the two treated soils. The soil moisture responses observed in the TDR 39 (located between the soil suction sensors SUC08 and SUC11) in the soil CL + 2% CaO are consistent with the soil suction measurements: the volumetric water content gradually decreased as the water moved down into the soil or evaporated from April to June 2011. The soil moisture responses observed in the TDR 38 (located at a greater depth, about -0.875 m from TDR39 and -1.5 m from the ground surface or the slope face) remained almost constant in the lime treated CL soil (Fig. 5b).

The same soil moisture response was not observed in the lime treated CH soil, in general, very small changes in the soil moisture were observed at the corresponding location. This may be explained by the differences in the hydraulic conductivity and water retention curves of the two treated soils presented in Fig. 4. Blight (1997) reported that the rate of infiltration is affected by the hydraulic conductivity of the soil, its surface gradient and its water content or suction. Taibi *et al.* (2009) present experimental results on two fine-grained soils showing that the relative hydraulic conductivity, k_r , which is defined as the ratio of the effective hydraulic conductivity at a given saturation to the saturated hydraulic conductivity, has a small value (≈ 0.05)

while the degree of saturation, S_r , is relatively high ($\approx 80\%$). These results are consistent with the measured k_r values presented in previous studies (Taibi, 1994; Bicalho, 1999) for fine-grained soils.

The field monitoring has also shown, in general, no significant hydrologic response of the soils to some rainy periods of heavy rain (10-50 mm/h) observed during the period of water deficit (*i.e.*, no rainfall infiltration is observed from April to June 2011). The rainfall events showed a significant effect on the soil suction changes (dramatic drop of suction) in the initial period of rainy season (July 2011) after a long period of water deficit in the two treated soils (see Figs. 5a and 6a).

Figure 7 presents a comparison among mean monthly measured soil suction (*i.e.*, soil suction sensors SUC10 and SUC04) and volumetric water content (*i.e.*, TDR 17 and TDR 39) values, at mid-slope (about -0.25 m from slope face) in the two treated soil sections from April to November 2011. Figure 7c show that the mean monthly degrees of saturation change from about 73% to 80% in the investigated layer in the CL + 2% CaO section. No appreciable degree of saturation difference ($< 2\%$) was observed in the investigated layer in the CH + 4% CaO section. The soil porosity of the lime treated CH and CL were 53% and 43%, respectively.

The simplified atmospheric water balance based on mean monthly potential evaporation calculated using stan-

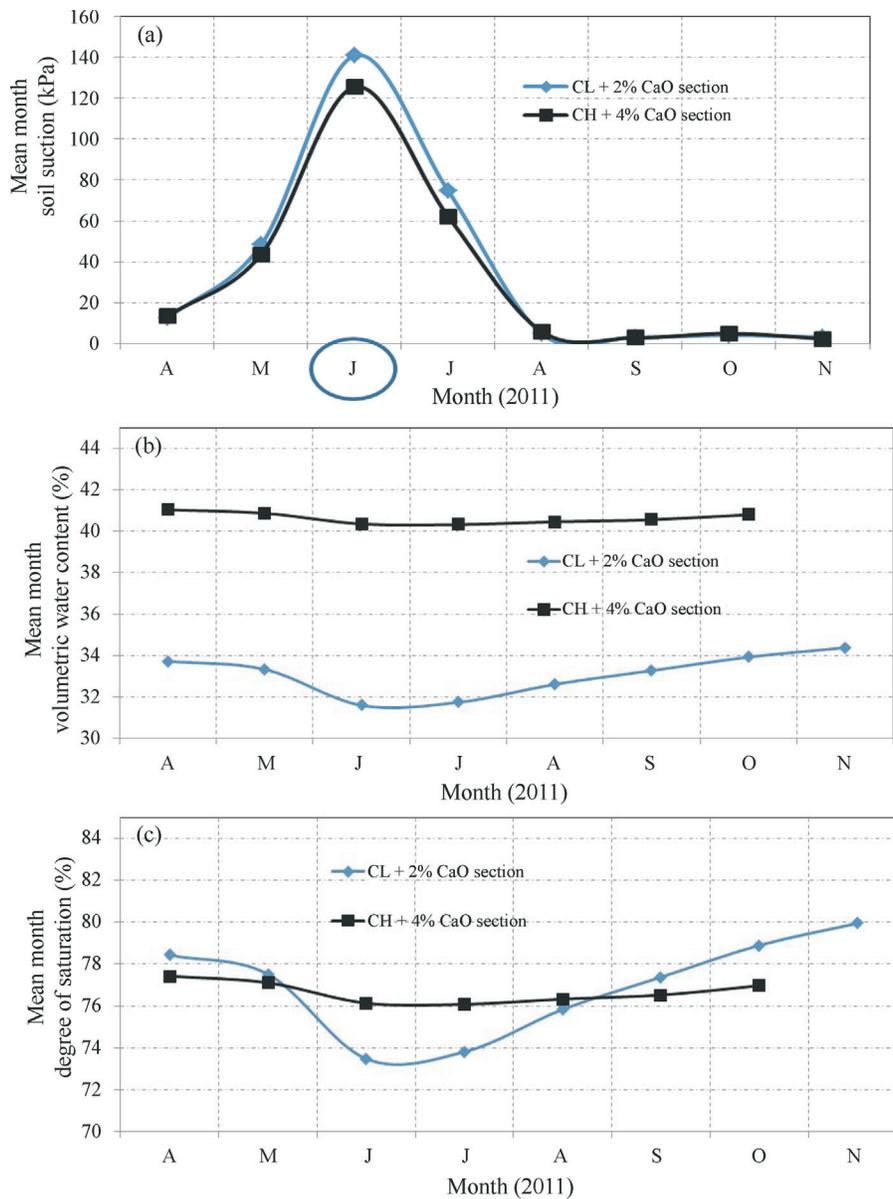


Figure 7 - Comparison among mean monthly measured (a) soil suctions, (b) volumetric water contents, and (c) degrees of saturation at mid-slope in the two treated soil sections from April to November 2011.

standard meteorological observations in the region, presented in Fig. 3, describes well the period of water deficit observed in the responses of the mean monthly suction and moisture measurements (see Fig. 7). There is an qualitative agreement between the period of water deficit observed in the responses of the mean monthly suction and moisture measurements in the treated soils and the atmospheric water balance (B values) based on mean monthly potential evaporation calculated using standard meteorological observations (*i.e.* Thornthwaite, 1948; Romanenko, 1961) in the region. The mean values data (observational and estimated by Romanenko (1961) using the air relative humidity recorded at 1.5 m, RH2, above the ground surface) show a

similar defined shift from dry to wet climate (in terms of soil suction) in June (J) 2011.

Figure 8a shows the mean daily air temperatures recorded at soil surface, 0.5 m and 1.5 m above the soil surface and there are no substantial differences between the two observed results (T). From the results presented in Fig. 8a, it can be seen that the mean daily temperatures recorded at soil surface (T_s) are higher than the temperatures recorded at 0.5 m and 1.5 m above the soil surface (T). June (month 06) and August (month 08) were the hottest months in 2011 and November (month 11) was the coldest. The temperature fluctuations at the ground surface are diminishing as the depth of the ground increases in the two treated soils. Deeper soils experience less extreme seasonal

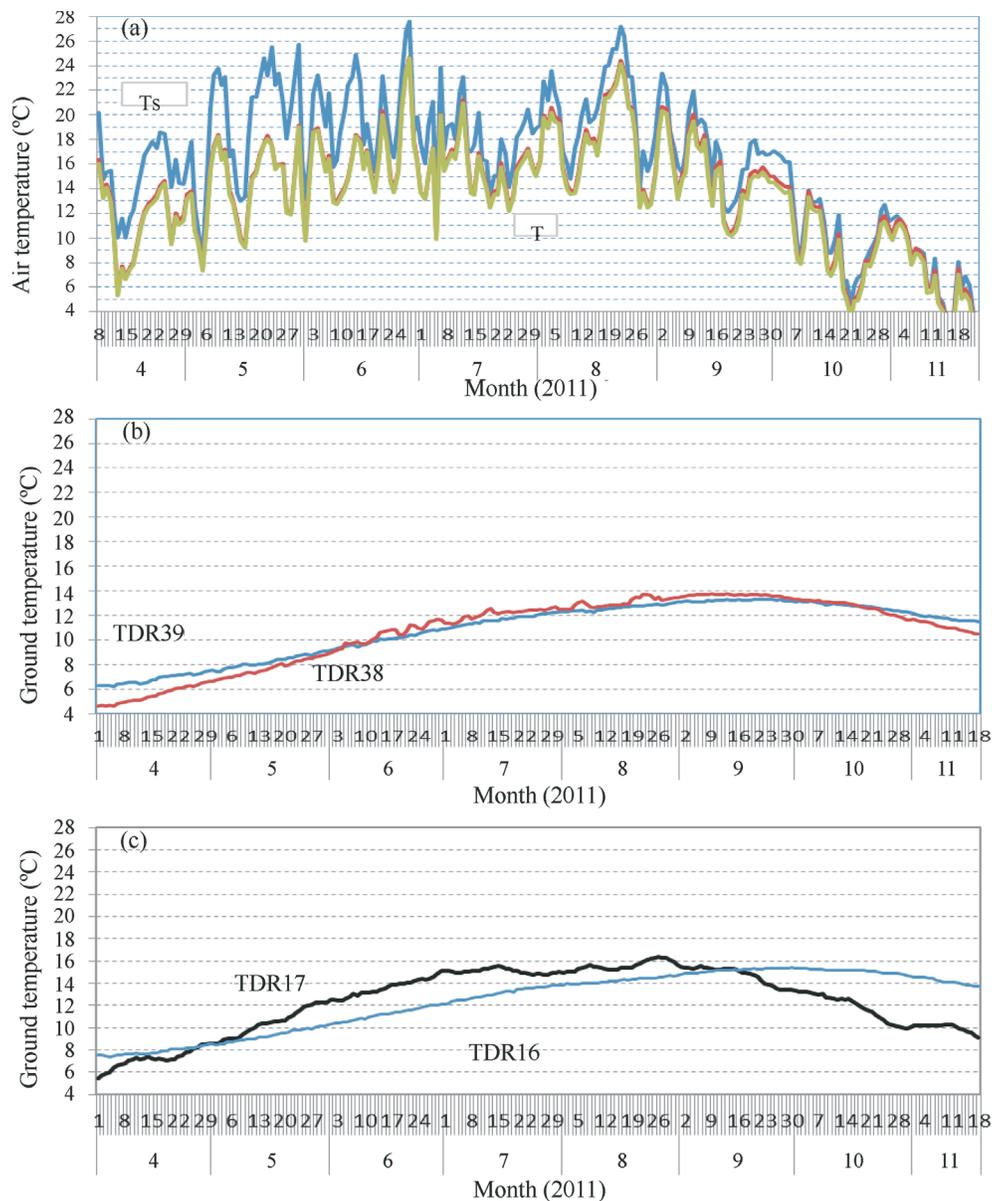


Figure 8 - Mean daily measured (a) air temperatures, and ground temperatures in the (b) CL+ 2% CaO (c) CH+ 4% CaO at mid-slope at different locations from April to November, 2011.

variations in the ground temperatures than shallower soils and the amplitude of seasonal soil temperature changes with the depth from soil surface. Liu *et al.* (2005) stated that the period of soil temperature variation increases and the amplitude of temperature fluctuation drops remarkably with the increase in depth.

Alike the observed soil moisture responses (Fig. 5b), the soil temperatures observed in the sensors TDR 38 and TDR39 are almost the same in the lime treated CL soil (Fig. 8b). The sensor TDR 38 is located at a greater depth, about -0.875 m from TDR39 and -1.5 m from the ground surface or the mid-slope face (see Fig. 1). It can be seen that a similar trend is observed in the treated CH soil (Fig. 8c). Therefore the zone in which the interchange of water between the atmosphere and the soil occurs is different from the one in which the interchange of heat between the atmosphere and the soil takes place. Heat transfer capability tends to increase as soil texture decrease and the degree of saturation increase (Van Rooyen & Winterkorn, 1957; Mitchell, 1991; Leong *et al.*, 1998).

One should be aware that the soil moisture sensors can behave differently with soil types, different soil depths and different parts of the embankment. Weather and soil physical conditions may be additional factors which directly or indirectly influence the sensitivity of the sensors. In this paper, the locations of the instrumentation for both treated fine-grained soils are similar. For the particular site of Hericourt, France, the data show similarities in the daily variations trend of suctions in the two treated soils.

The used soil moisture and soil suction sensors worked well on monitoring the soil suction and moisture responses to the meteorological changes in the two fine-grained soils. The data have also shown a consistent correlation between the increase in the soil suction and the relative decrease in the soil moisture. Even though a small variation was observed in the volumetric water content and corresponding soil suctions in the two treated soils (*i.e.*, a very small piece of the in situ soil water retention curves) over a period of eight months.

4. Conclusions

Some of on-going field monitoring of an experimental embankment constructed with two different clays, a silty clay and an expansive clay, treated with lime and/or cement in northeast of France, have been presented and evaluated herein. Field monitoring showed that weather effects are limited to a shallow depth. The results suggest similarities in the suction daily variations in the two treated fine-grained soils, and that the daily suctions are recovered gradually in response to soil evaporation during the period of water deficit. Even at the location of -0.75 m from the slope face the effect of evaporation was observed in the daily suction measurements.

No significant hydrologic response of the soils to rainfall was observed during the period of water deficit.

The rainfall events showed a significant effect on the soil suction changes (dramatic drop) at the initial period of rainy season (July 2011) after long and warm dry period (or higher soil suction values).

The used sensors Watermark soil suction and Quasi-TDR based TRIME PICO 64 worked well on monitoring the soil suction and moisture responses to the meteorological changes in the two fine-grained soils in the instrumented embankment. The soil moisture responses observed in the TDR measurements are consistent with the soil suction measurements: the volumetric water content gradually decreased as the water moved down into the soil or evaporated from April to June 2011 for the investigated site in France.

Generally, the atmospheric water balance (B values) based on mean monthly potential evaporation calculated using standard meteorological observations (*i.e.* Thornthwaite, 1948; Romanenko, 1961) in the region describes well the period of water deficit observed in the responses of the mean monthly suction and moisture measurements in the treated soils. The uncertainties regard to the potential evaporation value, which depends on the model structure and input data, resulted in different values of B. The difference (5-10%) observed in the air relative humidity recorded at 0.5 m (RH1) and 1.5 m (RH2) above the ground surface resulted in variation of about 25% (over 20 mm in June 2011) in the potential evapotranspiration values ET_{R1} and ET_{R2} estimated by Romanenko (1961). The mean values data observational (*i.e.*, soil suction and moisture measurements) and predicted by Romanenko (1961) (using the air relative humidity recorded at 1.5 m, RH2, above the ground surface) show a similar defined shift from dry to wet climate (in terms of soil suction and moisture).

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References

- Bell, F. G. (1996). Lime stabilization of clay minerals and soils. *Engineering Geology*, 42:4, p. 223-237.
- Blight, G. E. (1997). Interactions between the atmosphere and the earth. *Géotechnique*, 47: 4, p. 715-767.
- Blight, G. E. (2013). *Unsaturated Soil Mechanics in Geotechnical Practice*. CRC Press, Taylor & Francis Group, London, 597 p.
- Bicalho, K. V. (1999). *Modeling Water Flow in an Unsaturated Compacted Soil*. PhD. Thesis, Department of Civil Engineering, University of Colorado, Boulder, 235 p.

- Bicalho, K. V.; Znidarcic, D. & Ko, H. Y. (2000). Air Entrapment Effects on Hydraulic Properties. *Geotechnical Special Publication*, 99:1, p. 517-528.
- Brand, E.W. (1981). Some Thoughts on Rain-induced Slope Failures. *Proceedings of the International Conference on Soil Mechanics and Foundation Engineering*, Stockholm, Swed., v. 3, pp. 373-376.
- Chen D.; Gao, G.; Xu, C-Y; Guo, J. & Ren, G. (2005). Comparison of the Thornthwaite method and pan data with the standard Penman-Monteith estimates of reference evapotranspiration in China. *Climate Research*, 28:1, p. 123-132.
- Croft J. B. (1967). The influence of soil mineralogical composition on cement stabilization. *Géotechnique*, 17:2, p. 119-135.
- Cui, Y.J.; Lu, Y.F.; Delage, P. & Riffard, M. (2005). Field simulation of in-situ water content and temperature changes due to ground-atmospheric conditions. *Géotechnique*, 55:7, p. 557-567.
- Cui, Y.J.; Gao, Y. B. & Ferber, V. (2010). Simulating the water content and temperature changes in an experimental embankment using meteorological data. *Engineering Geology*, 141:3, p. 456-471.
- Fetter, C.W. (1994). *Applied Hydrogeology*, 3rd ed. Macmillan College Publishing, Inc., New York, 616 p.
- Froumentin, M. (2012). TerDOUEST, Projet ANR-07-PCGU-006-10, Rapport de construction de l'ouvrage expérimental RD438 Héricourt (70), Ministère de l'Ecologie, du Développement durable, des Transports et du Logement.
- Gens, A. (2010). Soil-environment interactions in geotechnical engineering. *Géotechnique*, 60:1, p. 3-74.
- Hemmati, S.; Gatmiri, B.; Cui, Y.J. & Vincent, M. (2012). Thermo-hydro-mechanical modelling of soil settlements induced by soil-vegetation-atmosphere interactions. *Engineering Geology*, 161:6, p. 139-140.
- Huang, C.C.; Ju, Y.J.; Hwu, L.K. & Lee, J.L. (2009). Internal soil moisture and piezometric responses to rainfall-induced shallow slope failures. *Journal of Hydrology*, 370:1, p. 39-51.
- Irrrometer. (2005). *Watermark Soil Moisture Measurement: Installation and Operation Manual*.
- Leong, W. H.; Tarnawskib, V. R. & Aittoma, A. (1998). Effect of soil type and moisture content on ground heat pump performance. *Int J. Refrig.*, 21:8, p. 595-606.
- Le Runigo, B. (2008). *Durabilité d'un Limon Traité à la Chaux et Soumis à Différentes Sollicitations Hydrauliques: étude des Comportements Physico-chimique, Hydraulique, Microstructural et Mécanique*. PhD. Thesis, Department of Civil Engineering, Ecole Centrale de Nantes, Nantes, 276 p.
- Lim, T.T.; Rahardjo, H.; Chang, M.F. & Fredlund, D.G. (1996). Effect of rainfall on matric suctions in a residual soil slope. *Canadian Geotechnical Journal*, 33:4, p. 618-628.
- Liu B.C.; Liu W. & Peng, S. W. (2005). Study of heat and moisture transfer in soil with a dry surface layer. *International Journal of Heat and Mass Transfer*, 48:2, p. 4579-4589.
- Lund, O.L. & Ramsey, W.J. (1959). Experimental lime-stabilisation in Nebraska. *Highway Res. Board Bull.*, 231:1, p. 24-59.
- Mitchell, J.K. (1991). Conduction phenomena: From theory to geotechnical practice. *Géotechnique*, 41:3, p. 299-340.
- Okyay, U.S. & Dias, D. (2010). Use of lime and cement treated soils as pile supported load transfer platform. *Engineering Geology*, 114:4, p. 34-44
- Rahardjo, H.; Li, X.W.; Toll, D.G. & Leong, E.C., (2001). The effect of antecedent rainfall on slope stability. *Journal of Geotechnical and Geological Engineering*, 19:3, p. 371-399.
- Rahardjo, H.; Lee, T.T.; Leong, E.C. & Rezaur, R.B. (2005). Response of a residual soil slope to rainfall. *Canadian Geotechnical Journal*, 42:5, p. 340-351.
- Romanenko, V.A. (1961). Computation of the Autumn Soil Moisture using a Universal Relationship for a Large Area. *Proceedings Ukrainian Hydrometeorological Research Institute, Kiev*, v. 1, pp. 1-3.
- Shock, C. C.; Barnum, J.M. & Seddigh, M. (1998). Calibration of Watermark Soil Moisture Sensors for Irrigation Management. *Proc. of the International Irrigation Show, San Diego*, v.1, pp. 139-146.
- Spaans, E.J.A. & Baker, J.M. (1992). Calibration of Watermark soil moisture sensors for soil matric potential and temperature. *Plant and Soil*, 143:2, p. 213-217.
- Springman, S.M.; Jommi, C. & Teysserie, P. (2003). Instabilities on moraine slopes induced by loss of suction: a case history. *Géotechnique*, 53:1, p. 3-10.
- Strunk, R. L. (2009). *An Evaluation of the Performance of prototype instrumented soil covers at the Regina Municipal Landfill*. M.Sc. Dissertation, Department of Civil Engineering, University of Saskatchewan, Canada. 240 p.
- Taibi, S. (1994). *Comportement mécanique et hydraulique des sols soumis à une pression interstitielle négative – Etude expérimentale et modélisation*. PhD. Thesis, Department of Civil Engineering, Ecole centrale de Paris, 374 p.
- Taibi, S.; Bicalho, K. V.; Sayad-Gaidi, C. & Fleureau, J-M. (2009). Measurements of unsaturated hydraulic conductivity functions of two fine-grained materials. *Soils and Foundations*, 49:2, p. 176-181.
- Thornthwaite, C.W. (1948). An approach toward a rational classification of climate. *Geographical Review*, 38:1, p. 55-94.
- Topp, G.C.; Davis, J.L. & Annan, A.P. (1980). Electromagnetic determination of soil water content: Measurement in coaxial transmission lines. *Water Resources Res.*, 16:2, p. 574-582.

- Toll, D. G. ; Lourenço, S.D.N. ; Mendes, J. ; Gallipoli, D. ; Evans, F.D. ; Augarde, C.E. ; Cui, Y.J. ; Tang, A.M. ; Rojas, J.C. ; Pagano, L. ; Mancuso, C.; Zingariello, C. & Tarantino, A. (2011). Soil suction monitoring for landslides and slopes, *Quarterly Journal of Engineering Geology & Hydrogeology*, 44:2, p. 23-33.
- Van Rooyen, M. & Winterkorn, H.F. (1957). Structural and Textural Influences on Thermal Conductivity of Soils. *Highway Research Board Proceedings*. v.39, pp.576-621.
- Wilson, G.W.; Fredlund, D.G. & Barbour, S.L. (1997). The effect of soil suction on evaporative fluxes from soil surfaces. *Canadian Geotechnical Journal*, 34:1, p. 145–155.
- Wolle, C.M. & Hachich, W. (1989). Rain-induced Landslides in South-eastern Brazil. In: *Proceedings of 12th international conference soil mechanics and foundation engineering*, v. 3, pp.1639–1644.
- Xu, C.-Y. & Singh, V. P. (2001). Evaluation and generalization of temperature-based methods for calculating evaporation. *Hydrol. Process.*, 15:2, p. 305–319.