# The importance of desiccation cracks in water migration inside expansive ground

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**Abstract.** Highly plastic clays are generally regarded as very impermeable materials. However, it is well known that desiccation cracks, as well as inherent fissuring, increase the in-situ apparent permeability inside the active zone. The paper presents long-term measurements of matric suction and moisture sensors installed under a mat foundation, on the shaft of bored piles, and at the free field in expansive marls in area of Nicosia, Cyprus. The data reveal the ease with which rainwater percolates in the ground due to the presence of shrinkage cracks, especially adjacent to foundation elements. Several episodes of full saturation conditions are recorded under the mat close to its perimeter during the course of a hydrological year after significant rainfall events, even during the dry season. Moreover, rapid migration of rainwater along the gap forming between the soil and pile shaft during the dry season can lead to brief full saturation incidents down to at least 1.5m depth. Back-analysis of field wetting experiments using the finite element method indicates that the equivalent in-situ saturated hydraulic conductivity of highly expansive marl near the ground surface is 3 to 4 orders of magnitude larger than the one measured on intact marl samples in the laboratory.

## 1 Introduction

Clays are characterized by very small hydraulic conductivity when unfissured, with $k$ values often less than $10^{-9}$ m/s, depending on the plasticity and void ratio [1]. As such, compacted clays are used in many engineering applications in which water-tightness is a requirement, such as earth dams or landfills. However, clays in natural ground may contain structural discontinuities and fissures, especially if they are aged and overconsolidated. Notable cases of highly fissured clays can be found around the world, e.g. Canada, China, Italy, UK, USA [2-5]. Moreover, high plasticity clays develop a network of desiccation cracks due to soil shrinkage caused by moisture loss during the dry season (Fig. 1). Inherent structural discontinuities and desiccations cracks constitute preferential paths for moisture migration, resulting in an increase in permeability in the field than can be of several orders of magnitude [1,6].

This paper aims to highlight the importance of desiccation cracks in the phenomenon of water migration inside the unsaturated zone of Pliocene marls found in Nicosia, Cyprus. In this context, the paper presents the results of field wetting experiments as well as long-term measurements of ground moisture and matric suction made at two sites where high plasticity Nicosia marl outcrops. Ground sensors are placed both in the free field and in contact with model foundations, namely a square mat foundation and two bored piles.

**Fig. 1.** Visible desiccation cracking at outcrop of very highly expansive Nicosia marl.

## 2 Experimental sites

Nicosia marl was deposited during the Pliocene in a shallow marine environment. It has a moderate calcite content that most often is smaller than 50% [7]. Its clay content is about 35% on average, with large part of it comprising smectites. Due to these characteristics and its relatively young age, Nicosia marl is a weak geomaterial, with unconfined compressive strength (UCS) less than 1MPa. As such, Nicosia marl can be considered as a calcareous overconsolidated clay. Its plasticity varies strongly depending on the clay content,

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with plasticity index values (PI) from as low as 17 to as high as 86 [7].

The two instrumented sites (named Site 1 and Site 3) are in the eastern part of the city of Nicosia, at locations where marl of high plasticity is outcropping. In both cases, the ground surface is excavated to create a level ground and remove any surficial topsoil. The soil profile down to 2m depth below finished grade at Site 1 consists of a 1m thick layer in which the marl has PI equal to 38 and clay content 43%, followed by a horizon in which the marl becomes more sandy and the PI drops to 25-32 and the clay content to 34%. The Nicosia marl at Site 3 is more clayey and less calcareous, with the clay content in the upper 2m of the soil profile being in the 45%-55% range and the PI in the 40-50 range. With these physical properties values, the marls at Site 3 as well as in the upper 1m of the ground profile at Site 1 are classified as very highly expansive according to the van der Merwe chart [8]. Fig. 1 shows the desiccation cracking on the free surface at Site 3 on September 2019.

## 3 Instrumentation

### 3.1 Free-field monitoring stations

A "free-field" ground monitoring station (Fig. 2) was established in each of the two sites, following the lines of previous instrumentation in Nicosia marl [9,10]. This was done by excavating a narrow pit and installing pairs of matric suction and volumetric water content sensors (TEROS 21 and TEROS 12, respectively, by METER Group, Inc.) on one of the side walls. In each pit, three pairs of sensors (A, B, C) were installed (Fig. 2b), two at a small depth (0.5m to 0.78m) and one at larger depth (1.5-1.56m). The pits were backfilled with compacted native soil. At Site 1, the sensors were installed in shallow notches dug on the pit sidewall that were subsequently covered with plastic film. A different configuration was used in the case of Site 3 in order to minimize backfill interference with the sensor measurements. The sensors at Site 3 were placed inside horizontal holes 0.4m long (Fig. 2a). After sensor placement, the remaining space was filled by pressing native soil in the form of a putty. The openings of the holes were sealed with non-shrinking cement mortar. The sensor cables were connected to Zentra dataloggers (METER Group, Inc.) for frequent recording of the measurements at regular intervals.

### 3.2 Instrumentation of foundations

A square mat foundation 5m wide and 0.4m thick was constructed at Site 1 at the end of July 2019. The concrete was poured in direct contact with the marl all-around (i.e. "neat" excavation). The top surface of the mat is 5cm below the finished ground surface. Before reinforcement and concrete placement, pairs of matric suction and volumetric water content sensors (TEROS 21 and TEROS 12) were installed at the bottom of the excavation at three locations (Fig. 3): mat corner (A), middle of mat edge (B) and near the mat center (C). The sensors are roughly at the same depth (0.5m) as the upper sensors in the free-field station. The mat is loaded by dead weights equivalent to a 1-storey building.

Two bored piles (P1 and P2) having 0.8m diameter and 15m length were constructed at Site 3 in December 2019. Before reinforcement and concrete placement, pairs of TEROS 12 and TEROS 21 sensors were installed on the wall of the drilled holes at two different depths (Fig. 4). Given that the piles were constructed during the wet season, it is expected that the upper portion of pile shaft will lose contact with the ground due to shrinkage of the marl during most of the year.

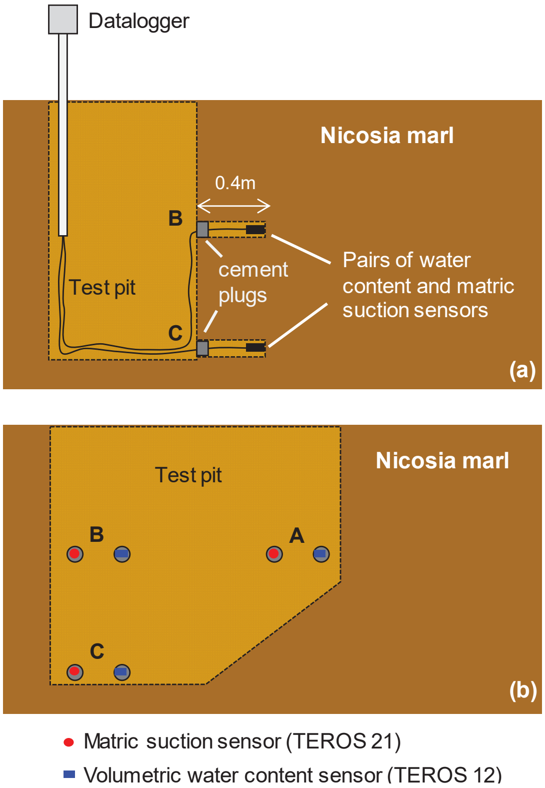

**Fig. 2.** Schematic of free-field monitoring station at Site 3: a) cross-section, b) view of pit wall where sensors are installed.

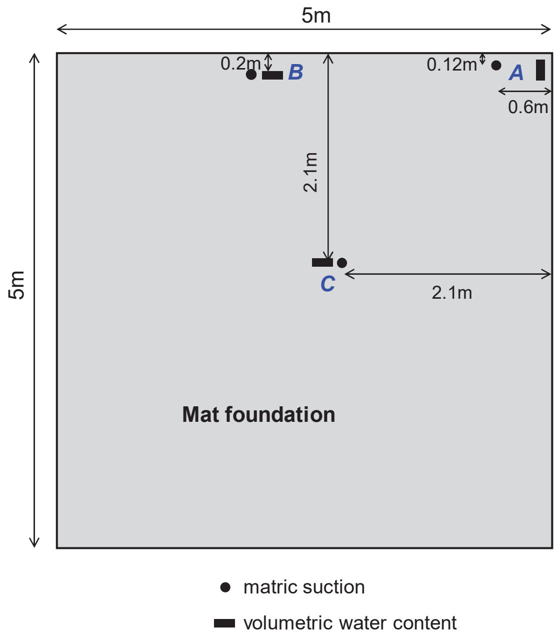

**Fig. 3.** Instrumentation of model mat at Site 1 (plan view).

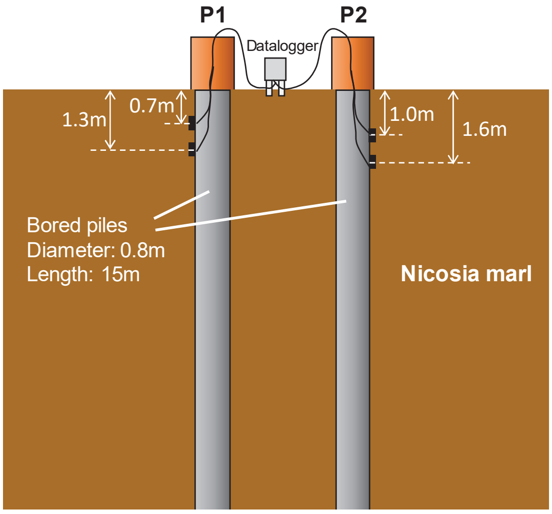

**Fig. 4.** Instrumentation of bored piles at Site 3.

## 4 Sensor measurements

The monitoring period includes roughly three hydrological years, namely 2019/20, 2020/21 and 2021/22. The annual precipitation recorded by a nearby weather station (0.9km from Site 1 and 2.6km from Site 3) of the Cyprus Meteorological Department was respectively 384mm, 232mm and 333mm. This period includes two very rainy months, December 2019 and December 2021, in which the monthly precipitation exceeded 100mm (Fig. 5). The climate of the Nicosia region is hot semi-arid (according to Köppen classification) with average annual precipitation 340mm. Figs. 6-9 present the sensor recordings from the time of their installation until June 2022. The shaded regions mark the time periods during which the field wetting experiments were conducted. The matric suction measurements have been corrected for temperature effects according to the correction proposed by Walthert & Schleppi [11] for similar sensors (MPS-6) of the same manufacturer. The volumetric water content ($\theta$) values are those obtained directly from the dataloggers using factory sensor calibration and no temperature correction has been applied to them.

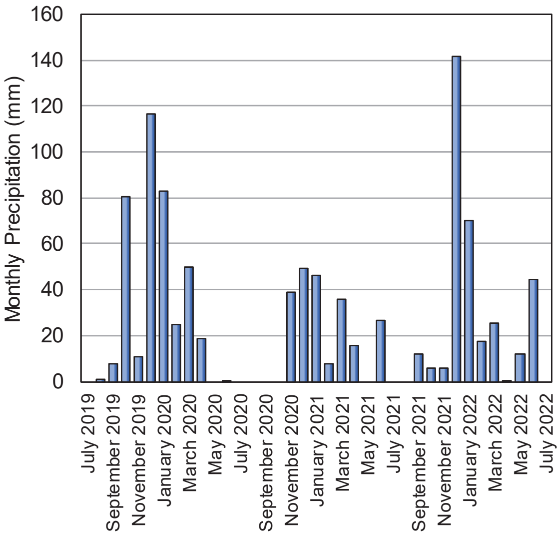

**Fig. 5.** Monthly precipitation in the period 7/2019-7/2022.

### 4.1 Site 1

After sensor installation (July 2019), there is a short adjustment period during which the sensors come into equilibrium with the surrounding natural soil. In the free field, the ground desaturates progressively during the summer and autumn months of 2019 (Fig. 6), with the matric suction $s$ at 0.5m depth reaching values in excess of 1.5MPa. Due to the intense rainfalls of December 2019, the upper pairs of sensors (0.5m depth) develop full saturation conditions abruptly, with $s$ practically equal to zero (Fig. 6a). On the contrary, the marl at 1.5m depth seems to be largely unaffected by rainwater percolation. The same pattern is observed during the winter 2021/22. Full saturation at 0.5m depth happens also in mid-June of 2022 immediately after an episode of daily precipitation of 43mm. All matric suction sensors appear to reach full saturation state during the relatively dry winter of 2020/21 (Fig. 6a), but this is probably due to the fact that the ground had not yet recovered its usual state after the wetting experiment.

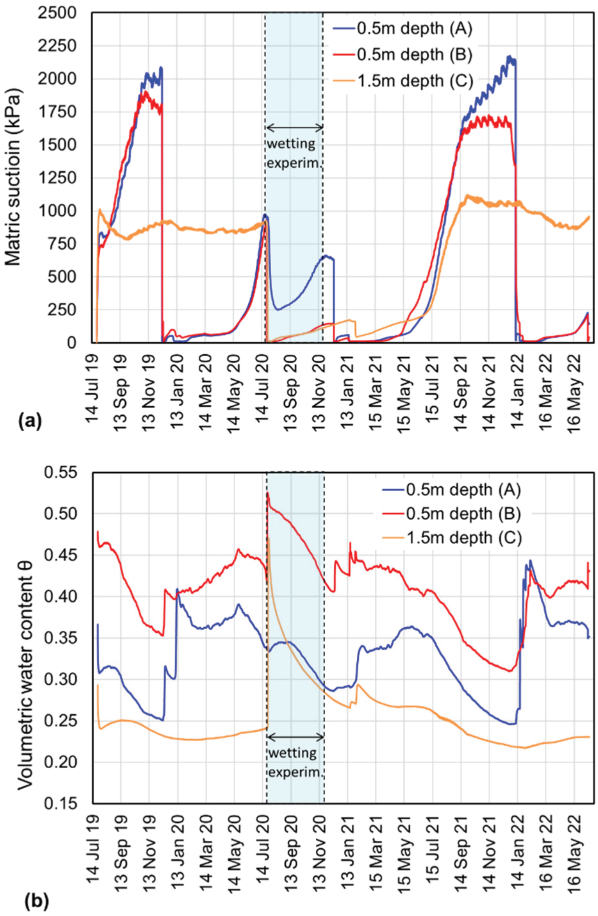

**Fig. 6.** Free-field sensor measurements at Site 1: a) matric suction, b) volumetric water content.

Fig. 7 presents the measurements of the sensors installed under the mat foundation. As expected, the sensors C near the center of the mat (at distance 2.1m from the mat edges) never reach a state of full saturation. Nevertheless, the seasonal fluctuation of matric suction is still significant, with the amplitude being of the order of 1.0-1.5MPa. Regarding the sensor pairs at the corner and at the side of the mat (A and B), there are several episodes of near full saturation, more than those observed in the free field, happening shortly after episodes of daily rainfall larger than 16mm. This can be attributed mainly to the gap forming between the sides of the mat and the ground during the dry months.

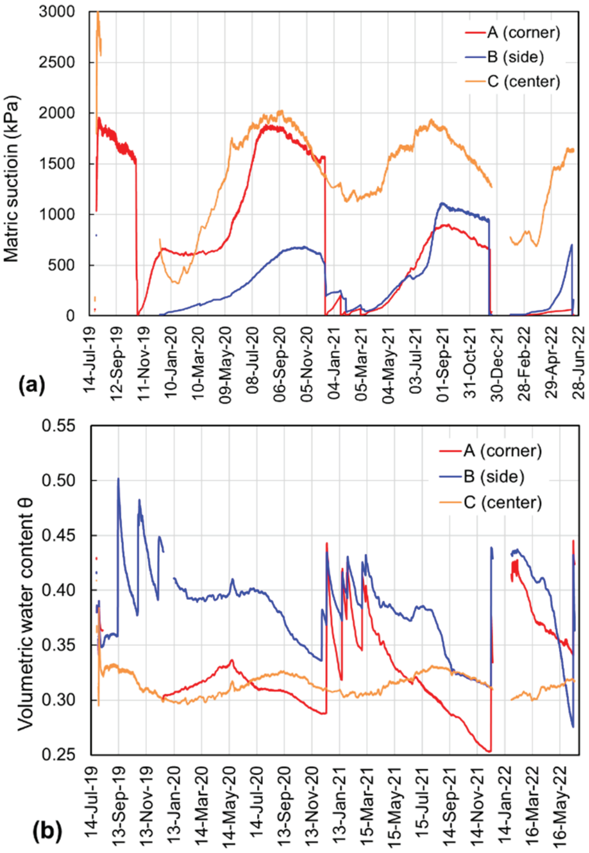

**Fig. 7.** Mat sensor measurements: a) matric suction, b) volumetric water content.

## 4.2 Site 3

The free-field measurements at Site 3 are heavily influenced by the two wetting experiments that span most of the monitoring period. Unlike Site 1, full saturation incidents are not evident during the winter of 2019/20 (Fig. 8). Large and abrupt change in $s$ and $\theta$ are observed in the time histories in the winter 2021/22, However, they are not consistent with each other. For example, full saturation is detected by the matric suction sensor at 0.6m depth at the end of December but not by the corresponding water content sensor. Moreover, $\theta$ at 1.56m depth exhibits a sharp peak while $s$ drops only slightly. This is probably due to rainwater percolation through cracks that formed irregularly during the desaturation and recovery of swelling that followed the wetting experiments.

Abrupt reduction in $s$ accompanied with spikes in $\theta$ in the time histories from the sensors installed at pile shafts are observed mainly in December 2020 and December 2021, signifying water percolation though the gap that forms during the dry months (Fig. 9). Nevertheless, both $s$ and $\theta$ quickly recover their smoother seasonal trends, indicating that these incidents of percolation though the pile-soil gap have little effect

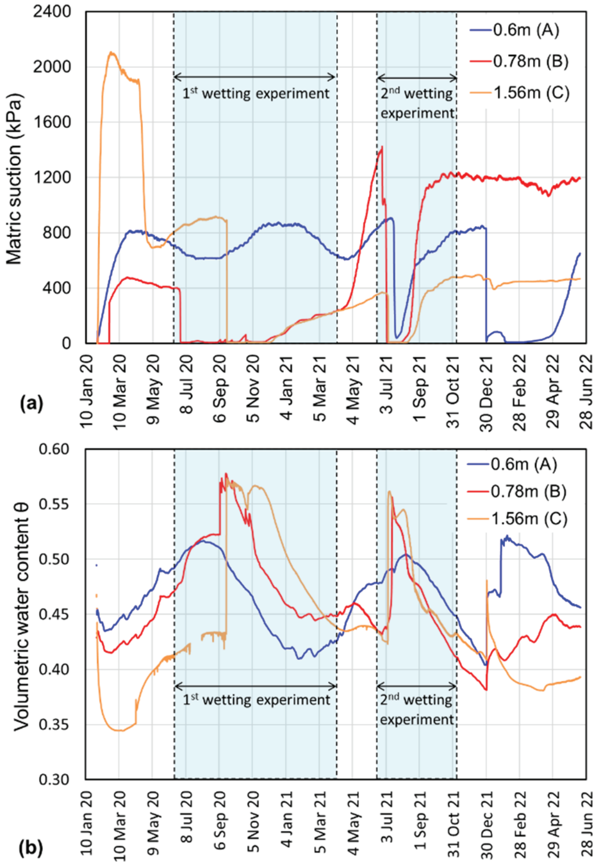

**Fig. 8.** Free-field sensor measurements at Site 3: a) matric suction, b) volumetric water content.

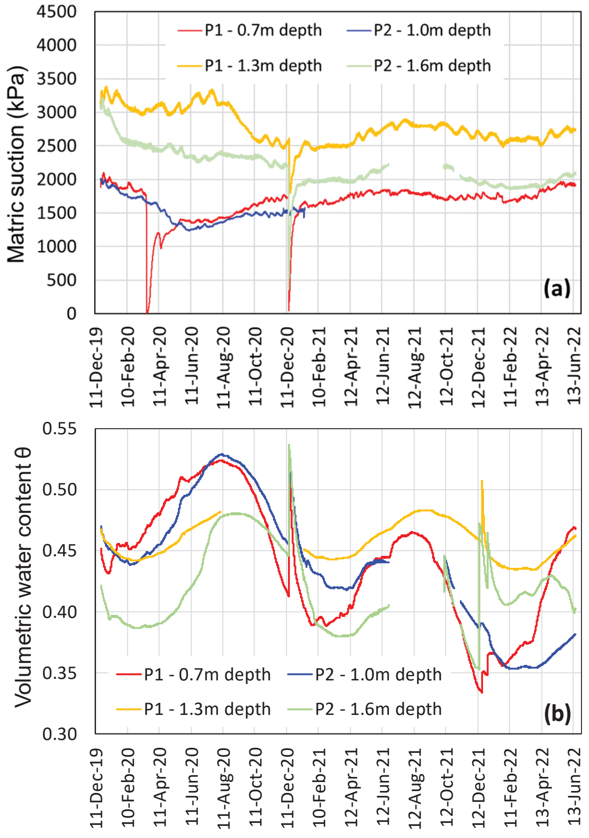

**Fig. 9.** Pile sensor measurements: a) matric suction, b) volumetric water content.

on the regime in the matrix of the soil. Finally, the data also demonstrate that the matric suction values in this very highly plastic marl (PI=40-50) can be in excess of 2MPa even at 1.3-1.6m depth (Figs. 8,9).

## 5 Wetting experiments

### 5.1 Experimental procedure

In order to establish the in-situ equivalent permeability of the marl, field wetting experiments were conducted at the two experimental sites. Ground wetting was done though a cylindrical drum that was placed directly above the location of the sensor pairs B and C (Fig. 2), i.e. the pairs that lie on the same vertical axis at two different depths. The drum was supplied with water from a large tank and the water level inside the drum was kept at a constant level with the help of an overflow outlet (Fig. 10). To prevent leakage at the contact between the drum and the soil, the drum was placed at a depth of a few centimeters from the ground surface in a notch filled with marl putty and additional soil was subsequently placed around the drum walls. An area 2m × 2m around the drum was covered with plastic sheets in order to minimize evaporation of water from the ground to the atmosphere or infiltration of rainwater.

**Fig. 10.** Field wetting experiment setup at Site 3.

The wetting experiments consisted of a wetting phase, which lasted until full saturation conditions were observed in both B and C pairs of sensors, followed by a desaturation phase. During the desaturation phase, the drum was removed and the test area was fully covered with plastic sheets.

The wetting experiment at Site 1 started on 20/7/2020 and its wetting phase lasted until 27/7/2020. Subsequently, the plastic sheet covers were left in place for four months (desaturation phase). At Site 3, the wetting experiment was performed twice, in the summer of 2020 and in the summer of 2021. The first experiment started on 19/6/2020 and its wetting lasted until September of the same year due to interruptions in the supply of the drum with water. Hence, it was decided to repeat the experiment the following year. The 2nd experiment lasted from 24/6/2021 until 6/11/2021, with the duration of the wetting phase being 25 days.

### 5.2 Back-calculation of in-situ permeability

The back-calculation of the in-situ hydraulic characteristics of the marl was done following the methodology of Lazarou et al. [9]. The field wetting experiments were simulated in the commercial finite element software Plaxis 2D. The back-calculation procedure consisted of varying the hydraulic properties of the ground that are considered unknowns in a large number of trial-and-error analyses. The unknown properties are the in-situ values of the vertical and horizontal hydraulic conductivity coefficients under full saturation conditions, $k_{y,sat}$ and $k_{x,sat}$, as well as the parameter $g_l$ [12] that controls the dependence of the hydraulic conductivity on the suction. These variables were also considered to vary with depth at increments of 0.5m. The soil water characteristic curves (SWCC) inputted in the program were assumed to be the same as those established in the laboratory in terms of total suction using a WP4C chilled mirror hygrometer. Moreover, the $k_{y,sat}$ and $k_{x,sat}$ at depth greater than 3.5m were set equal to the hydraulic conductivity coefficient values measured in flexible wall permeameter tests in the laboratory on “intact” marl specimens ($1.4\times10^{-9}$ m/s and $6.4\times10^{-11}$ m/s for Sites 1 and 3, respectively), effectively assuming that desiccation cracking is negligible below that depth.

Fig. 11 shows contours of the degree of saturation ($S_r$) at the end of the wetting phase from a simulation of the wetting experiment at Site 3 that best fits the sensor recordings. It can be seen that the saturation bulb is quite narrow. Fig. 12 plots the profile of back-calculated values of equivalent $k_{y,sat}$. The $k_{y,sat}$ near the ground surface turns out to be 4000 (Site 1) and 6000 times (Site 3) larger than that measured in the laboratory on intact samples, a finding that can be attributed to the dense network of wide desiccation cracks observed near the ground surface for these very highly expansive marls.

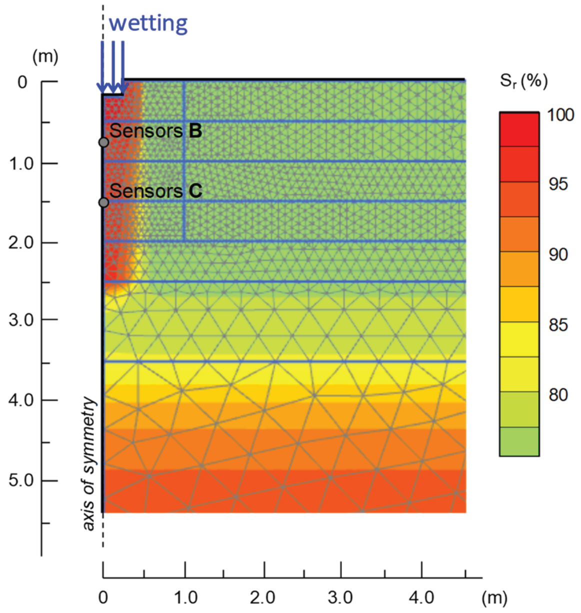

**Fig. 11.** Contours of degree of saturation at the end of the wetting phase from simulation of the experiment at Site 3.

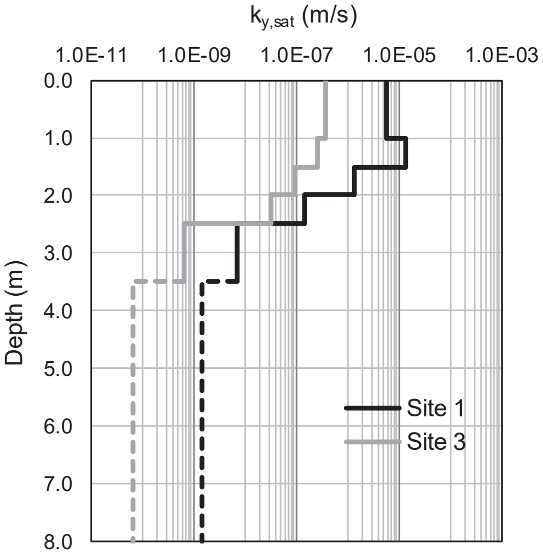

**Fig. 12.** Back-calculated profiles of equivalent vertical hydraulic conductivity coefficient under saturated conditions.

It is interesting to note that this amplification of permeability in-situ is much larger than the value of 400 observed for medium expansive Nicosia marl with PI=23 and clay content 20% on average [9]. Measurements by Ankeny et al. [13] show that the in-situ permeability of silty clay loam (topsoil) can be up to 30 times larger than the one measured in the laboratory, and 3 times on average. Tsaparas & Toll [14] found that the saturated hydraulic conductivity of the surficial (0.25m thick) desiccated crust of silty clay of moderate plasticity (PI=19) needs to be in numerical simulations two orders of magnitude larger than that measured at 0.4m depth.

## 6 Conclusions

Matric suction and volumetric water content sensors were installed in highly expansive Nicosia marl in the free field and in contact with foundation elements in order to study the seasonal migration of water inside the marl and perform experiments for establishing the equivalent permeability of the ground inside the active zone. Based on the sensor measurements and testing results, the following conclusions can be drawn:

1) Matric suction values in excess of 2MPa develop in high plasticity Nicosia marl. Moreover, the seasonal amplitude of matric suction fluctuation at shallow depth can be of the order of megapascals. This is true even at a distance more than 2m from the edges of a mat foundation.
2) Incidents of full saturation of the ground down to at least 0.5m depth are observed during periods of heavy rainfall due to the presence of desiccation cracks. Moreover, the gap forming between expansive ground and foundations during dry periods facilitates even further the infiltration of rainwater in the following winter months.
3) The in-situ equivalent vertical saturated hydraulic conductivity in the desiccated crust of high plasticity Nicosia marl can be 3 to 4 orders of magnitude larger than the one measured in the laboratory.

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