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EXPERIMENTAL AND NUMERICAL ANALYSES OF UPRISING MOISTURE IN FINE GRAINED SOILS

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ABSTRACT

Due to the microstructure of clayey platelets, fine-grained soils can retain a considerable amount of moisture. In spite of having relatively low permeability, this moisture can be transferred through the soil body even if the soil is not saturated. Due to the capillary action, deep underground water can rise upward in a soil profile consisting of clayey layers even up to several 10 meters. This phenomenon causes a thick unsaturated zone with gradually decreasing water content. Fine-grained soils are widely available around the world, not only in the natural soil strata but also in man-made earthen constructions, *e.g.,* embankment dams, waterproofing layers, or masonry walls. In this research to model a clayey profile, a block of fine-grained material was constructed using smaller clay bricks. The uprising moisture through the block and its consequent volume changes were recorded during a test. In another block, a countermeasure protection method (base ventilation method) was utilized to minimize the capillary moisture, which was exposing lower parts of the block to open air. Experimental observations proved that the applied method is able to reduce the maximum height of moisture uprise to around 50% and the consequent heave to around 30% of unprotected condition. Both unprotected and protected conditions were simulated numerically. Experimental and numerical simulations proved to be in a good match. Further geometries and protection schemes were also numerically modeled to assess the efficiency of the studied countermeasure method with various conditions.

Key words: Uprising moisture, fine grained soils, suction, SWCC, countermeasure method.

1. INTRODUCTION

Capillary uprising moisture occurs in dry and unsaturated soils under which a low suction or saturated zone is located. This phenomenon changes the suctions of the soil non-uniformly and, as proved in the literature, all hydro-mechanical properties will be affected. In unsaturated soil mechanics, soil suction is inversely related to the moisture content. This relation is depicted in a curve called Soil-Water Characteristic Curve (SWCC). The uprising rate, beside material properties and geometrical configuration, is a function of unsaturated hydraulic conductivity. The unsaturated hydraulic conductivity can be estimated based on the SWCC and the saturated hydraulic conductivity.

Typically, the hydro-mechanical properties of unsaturated soils worsen by decreasing the suction. In the foundations' subsoil, for instance, moisture can potentially soften the clay behavior. Regarding the fact that in clayey soils, change in water content is followed by volume changes, if the uprising moisture occurred disparately, differential settlement or heave in the building may happen that endangers the overall stability. Raw masonry materials are clayey soils consolidated by drying process through which water can continue rising up and deteriorate the properties (for example worsening shear strength parameters, weathering, biological molds, *etc.*). The stability of slopes having clayey layers in their profile can be threatened if the water content of the subsoil exceeds some certain values due to seasonal fluctuations of the groundwater table.

In spite of the possible problems uprising moisture can cause, among the published data in the field of unsaturated soil mechanics, the hydraulic behavior of clayey soils, especially the uprising moisture, could be more deeply investigated by researchers. It is evident that there is still room for further studies in this field. Therefore, it is worth monitoring and investigating the hydraulic distribution of uprising moisture in soils and in particular fine-grained soils.

In this research, based on what mentioned above, uprising moisture in fine-grained soils with non-uniform degrees of saturation was investigated by large-scale tests on two blocks of dried fine-grained soils; one protected and one unprotected. "Protection" or "protected condition" refers to exposing the soil to air at some particular depths and let humidity be evaporated from those surfaces in order to reduce the uprising height of moisture. And "unprotected condition" refers to the situation in that free water is in contact with the soil and there is no opening at a depth that is exposed to air. The protection method is named "Base Ventilation", one of the most frequently used countermeasures to protect earthen blocks against uprising moisture.

Both blocks were exposed to free water from their bottom surfaces. The hydraulic distributions of the absorbed moisture were mainly governed by the hydraulic properties of the material and the geometry of the models. During the tests, the water content was measured at different heights. By comparison between capillary uprise of moisture in protected and unprotected conditions, the efficiency of the implemented method (base ventilation) is assessed in terms of changes in the water content over time and volumetric behavior of the block over time.

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Both blocks were also numerically studied using results of SWCC and permeability tests. The hydraulic properties of the same soil used in the construction of the blocks were assigned to the numerical model which were derived from separate experimental element tests as explained in the following sections. After validation of the calculations with experimental results, further blocks with various geometries were modeled to assess the efficiency of the tested protection method. Therefore, the results shall be valid for the tested soil only.

The paper shows the effect of boundary conditions and environment on the rising moisture, capillary, in fine-grained soils. However, it must be highlighted that further research must be conducted to describe the effect of other material characteristics, *e.g.,* plasticity index, particle size distribution, and fines content, on the rate and level of the uprising.

2. LITERATURE REVIEW

2.1 Concepts of Suction and SWCC

According to Aitchison (1965), the thermodynamic definition of soil suction is defined as follows: total suction is the amount of useful work that must be done per unit quantity of pore water to transfer reversibly and isothermally an infinitesimal quantity of water from the soil water to a pool of pure water at the same elevation and atmospheric pressure. However, several researchers (*e.g.,* Soleimani-Fard 2014) are interested in soil suction in mechanical considerations from more practical points of view. Total suction is the sum of matric and osmotic suction, which are respectively the difference between pore air and pore water pressures, and the suction caused by various salt concentrations in the pore water.

The relationship between the amount of water (in the forms of volumetric or gravimetric water content as well as the degree of saturation) in the soil and its associated suction in the pore water is defined as the Soil-Water Characteristic Curve (SWCC). This curve describes the ability of soil to retain water in its pores at different suctions. The SWCC is the most important and affecting property in the field of unsaturated soil mechanics and related to many geotechnical and hydro-mechanical properties of soil such as hydraulic conductivity, effective stress, and volume changes (Fredlund and Rahardjo 1993). Usually, soils subjected to drainage or imbibition processes show different hydraulic behavior. Therefore, two SWCCs for drying and wetting conditions can be drawn.

Li *et al.* (2018) carried out several one-dimensional (1D) capillary uprising tests on various types of soils and used analytical methods to calculate the uprising behavior using SWCC results.

2.2 Moisture Transport in Unsaturated Soils

It is generally accepted (*e.g.,* Ng and Shi 1998; Smith 2003) that Darcy's law and its associated assumptions remain applicable to flow through unsaturated soil, except that it now takes the form:

$$v_x = -k_x(\psi)\frac{\partial h}{\partial x} \tag{1}$$

where $k_x(\psi)$, $\frac{\partial h}{\partial x}$ and v_x are the coefficient of permeability, hydraulic gradient and velocity of capillary moisture (in direction of x) as a function of suction (ψ). Freeze and Cherry (1979) developed an equation for continuity of flow for transient flow through an unsaturated soil, incorporating Darcy's law in its unsaturated form, as shown in Eq. (2) which is also called Richard's equation.

$$\frac{\partial}{\partial x}\left[k(\psi)\frac{\partial \psi}{\partial x}\right]+\frac{\partial}{\partial y}\left[k(\psi)\frac{\partial \psi}{\partial y}\right]+\frac{\partial}{\partial z}\left[k(\psi)\left(\frac{\partial \psi}{\partial z}+1\right)\right]=C\frac{\partial \psi}{\partial t} \tag{2}$$

where x, y, and z are the Cartesian coordinates and t is time. C is specific moisture capacity such that:

$$C=\frac{\partial \theta}{\partial \psi} \tag{3}$$

where θ is volumetric water content as defined Eq. (4), in that V_w and V_T are volume of water and total volume of soil body, respectively.

$$\theta=\frac{V_w}{V_T} \tag{4}$$

The equation contains two functional relationships characterizing the soil: (i) the soil-water characteristics curve (SWCC), $\psi(\theta)$, describing the relation between suction and water content and (ii) the unsaturated permeability function, $k(\psi)$, describing this parameter as a function of suction, or using $\psi(\theta)$ can be converted to function of water content. To solve Richard's equation, prior knowledge of these unsaturated hydraulic properties is required. Methods for determining the unsaturated hydraulic properties are described in following section.

In the past, geotechnical researchers had mainly interested in the saturated hydraulic conductivity of soils. With the growth of geo-environmental practices many geotechnical engineers now need to quantify flow in the unsaturated zone (*i.e.,* landfills, embankment dams, uprising capillary moisture, *etc.*). Buckingham (1907) made the first attempt on the presence of flux in an unsaturated medium. Essential elements required for analysis and calculations in each of these applications are the saturated hydraulic conductivity and the relationship between hydraulic conductivity and water content or matric suction. Fredlund *et al.* (1994) reported that for unsaturated soils there could be different permeability functions in desorption and adsorption processes.

For determining unsaturated permeability, several experimental and theoretical methods have been suggested in the literature. Experimental methods can be divided into steady and unsteady state techniques which both have been reviewed by Benson and Gribb (1997) and Masrouri *et al.* (2008). Some researches on steady-state techniques are for example Corey (1957), Olsen (1966), Klute (1972), Olsen *et al.* (1985), Klute and Dirksen (1986), Aiban and Znidarcic (1989), Znidarcic *et al.* (1991), Dirksen (1991), Bicalho *et al.* (2000), Likos *et al.* (2005), and Lu *et al.* (2006) and on unsteady state techniques such as Richards and Weeks (1953), Bruce and Klute (1956), Miller and Elrick (1958), Rijtema (1959) and Kunze and Kirkham (1962), Daniel (1983), and Chiu and Shackelford (1998).

Theoretical methods can be from either empirical or statistical methods. Richards (1931), Wind (1955), Corey (1957), Gardner (1958), Brooks and Corey (1964), Rijtema (1965), Davidson *et al.* (1969), Campbell (1973), and van Genuchten (1980) have suggested some empirical equations, and Burdine (1953) and Mualem (1976) have suggested statistical methods. Agus *et al.* (2003) compared some of the statistical models for various soils. In Section 5, the empirical equation used in this study will be explained.

2.3 Uprising Moisture

Capillary rise in porous media has been studied for many years, since the pioneering work of Washburn (1921). The Washburn equation was derived originally for a liquid rising in a cylindrical capillary tube by the effects of capillary forces. Washburn's equation for calculation of uprising water table is as follows:

$$t = \frac{\theta_s (h_e + z_R)}{K_s} \ln\left(\frac{h_e + z_R}{h_e + z_R - z_f} \right) - \frac{\theta_s z_f}{K_s} \tag{5}$$

where, as shown also in Fig. 1, z_f is the height of the wetting front, z_R is the positive pressure head imposed at $z = 0$ (it could be zero), θ_s is the saturated water content (often taken as equivalent to the effective porosity), K_s is the saturated hydraulic conductivity, and t is time. h_e in this equation is the equilibrium height for a capillary tube but is a fitting parameter for complex porous media. Other required parameters are determined experimentally.

Some limitations of the Washburn equation have been discussed in the literature (Dullien 1992; Lago and Araujo 2001; Lockington and Parlange 2004). Alsamia *et al.* (2020) evaluated and compared 3 different widely used methods, including Washburn, using experimental results and highlighted some deficiencies for its predictions.

Hall (1977) proposed a method for steady-state flow in construction materials between two parts of a building which are assumed to have constant water content (*e.g.,* completely dry and saturated). This flow can be either horizontal or vertical. With some simplifications on the separation of θ and *t* in equations, he also introduced a method to solve the time dependency of the flow.

Yuan and Lu (2005) derived some analytical solutions for vertical flow in unsaturated soils using Richard's equation to describe the distribution of pressure head, water content, and fluid flow for rooted and homogeneous soils with varying surface fluxes. The solutions assume that (i) the constitutive relations for the hydraulic conductivity and water content as a function of the pressure head are exponential, (ii) the initial water content distribution is a steady-state distribution, and (iii) the root water uptake is a function of depth. Three simple forms of root water uptake are considered, that is, uniform, stepwise, and exponential functional forms. Lu and Likos (2004) and Fries and Dreyer (2008) proposed an analytical time-dependent method for the prediction of uprising moisture.

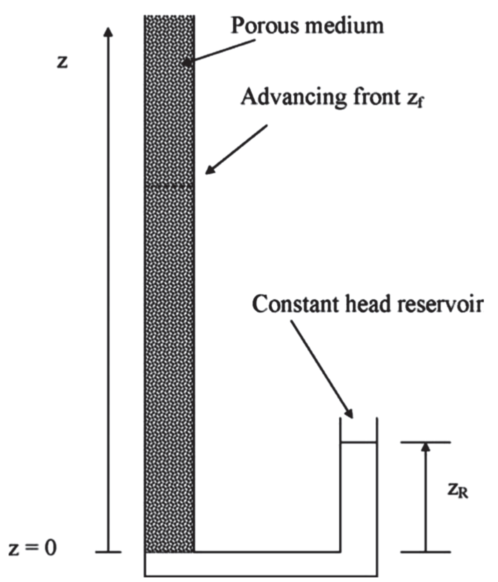


Fig. 1 Capillary rise experiment (modified after Lockington and Parlange 2004)

Siddique *et al.* (2009) and Naseem *et al.* (2017) performed experimental and numerical studies on the 1D capillary rise into the sponge as a deformable porous material. Many parameters (*e.g.,* solid to liquid density ratio, capillary pressure, gravity, *etc.*) were taken into account in their research.

Xing *et al.* (2019) experimentally studied the influence of salt content in the water using different kinds of salts and concentrations on the capillary uprise.

Similar to this study Hird and Bolton (2017) used Time Domain Reflectometer (TDR) to measure the capillary risen humidity in sand columns with different conditions, *e.g.,* with and without evaporation possibilities.

Researchers of other fields also investigated the capillary uprising water through soils or other geo-materials. Gombi *et al.* (2008) carried out experimental studies on uprising capillary moisture in blocks of stones for cultural heritage preservation interests. They evaluated the time dependency of the capillary rise. Nugraha *et al.* (2017) and Amer (2019) experimentally studied the uprising moisture in the soil from the groundwater table for agricultural purposes. Chandler *et al.* (2017) and Tran *et al.* (2018) developed experimental programs to assess the capillary rise in the soil to evaluate the efficiency of soil stabilizer additives. In Chandler's research, two 1-year capillary tests were conducted. Li *et al.* (2018) assessed the uprising moisture to back-calculate the unsaturated hydraulic conductivity.

2.4 Proposed Countermeasure Methods

Mainly for man-made earthen constructions, protective countermeasures will help prevent further damp problems and may reduce the severity of an existing problem to an extent that major works are not necessary. Young (1997) and Torres and Freitas (2007) have reviewed the countermeasure methods implemented against uprising moisture. Some of the more frequently used methods are listed as reducing the absorbent section, placing watertight barriers, injecting chemical barriers, creating a potential against the capillary potential, changing the facades and inter daces, concealing anomalies, and base ventilation. The last method whose efficiency has been evaluated experimentally and numerically in this study is described below. In this method, the concerned body of fine-grained soil body (mostly man-made, *e.g.,* hand fill grounds, embankment dams, or masonry heavy walls) shall be exposed to open air, at least partially, to let the absorbed water evaporate and be not raised further upward. This practice is extended in the technique known as air drains, a method for controlling damp by encouraging evaporation to occur at the lowest possible level. Creating ventilated channels increases the evaporation of absorbed water. This evaporation can take place below the ground level. Installing a hygro-regulated mechanical ventilation device can increase this system's efficiency (see Fig. 2).

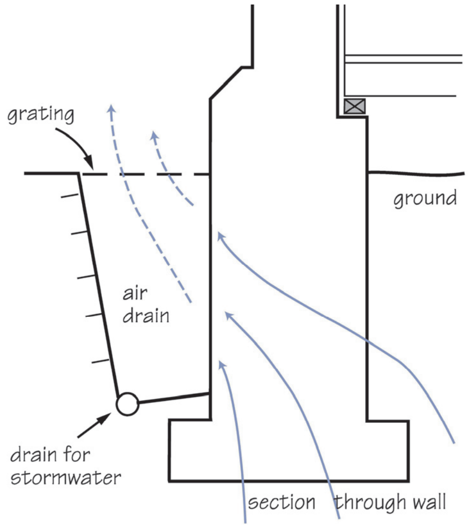


Fig. 2 Base ventilation method for reducing the uprising moisture (Young 1997)

3. MATERIALS

The physical characteristics of the adopted mixture were determined in accordance with DIN standard (the German national standard, DIN 18122-1:1997-07). The adopted soil has a liquid limit of 20.5%, plasticity limit of 12.5%, plasticity index of 9%, specific gravity of 2.67 g/cm^3. In the unified soil classification system, this soil is classified as CL. Figure 3 shows the grain size distribution of the used material and Atterberg limits on the Casagrande plasticity chart.

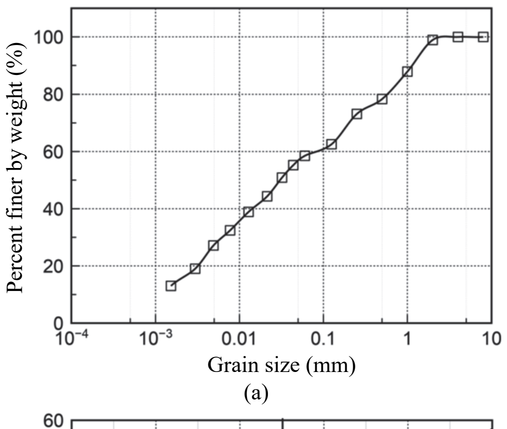


Fig. 3 (a) Grain size distribution curve of the adopted soil; (b) Atterberg limits on Casagrande plasticity chart

In this study, in order to measure the permeability of the soil, the constant head hydraulic conductivity test was carried out. The samples were compacted in a cylindrical mold with 120 mm height and 100 mm diameter. For this purpose, water was added to the soil gradually to reach a 5% gravimetric water content. In order to have the same compaction at different levels, water must be distributed evenly through the mixture. In the compaction process, the void ratio of soil had to reach the void ratio of the blocks after completion of drying and shrinkage. In this study, the desired void ratio for measuring permeability was 0.39. After samples were made and saturated under isotropic water pressure, a back pressure of 350 kPa was kept constant during the test. Hydraulic conductivity of soil is measured to be 4×10^{-8} cm/s, which is equivalent to the permeability of 3.7×10^{-17} m^2:

$$k_s = K_s \frac{\mu}{\rho_w g} \tag{6}$$

where k_s, K_s, μ, ρ_w, and g are saturated intrinsic permeability (m^2), saturated hydraulic conductivity (m/s), viscosity of water (9×10^{-4} Pa.s for the lab condition), density of water (1,000 kg/m^3) and gravitational acceleration (9.81 m/s^2), respectively.

Soleimani-Fard (2014) performed a series of experiments to determine SWCC of the studied soil that is used in this paper for estimation of unsaturated hydraulic conductivity and numerical calculations. More details about the SWCC tests are provided in Section 4.2.

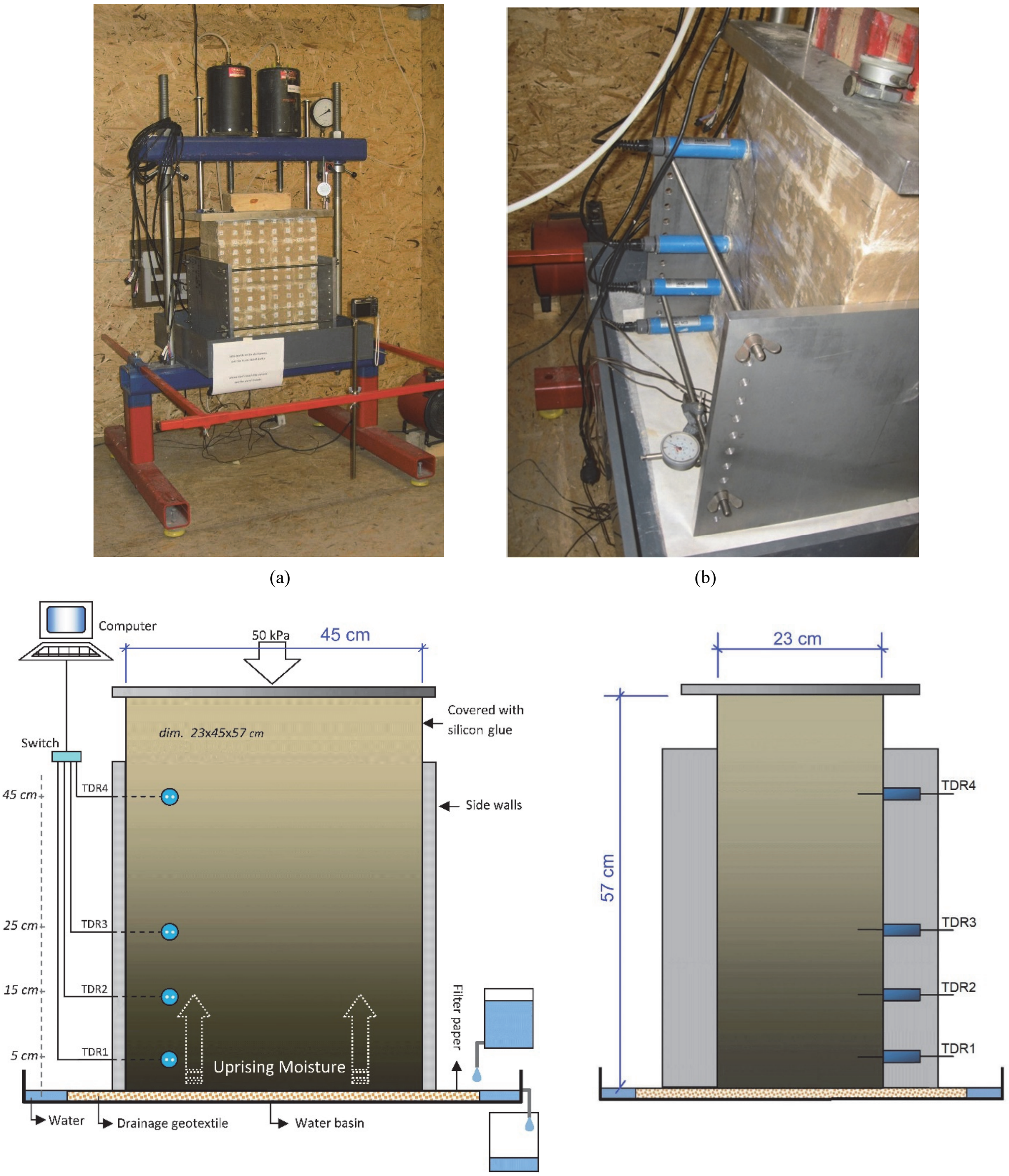
4. EXPERIMENTAL PROCEDURE

The laboratory program of this study consisted of two large scale block tests (for observing the uprising moisture and the consequent volume changes) and a permeability test for measuring the saturated coefficient of permeability of the studied fine-grained soil mentioned above. Soleimani-Fard (2014) performed a series of experiments to determine the SWCC of the studied soil which is used in this paper for estimation of unsaturated hydraulic conductivity and numerical calculations.

4.1 Large Scale Block Tests

In order to realize the uprising moisture phenomenon and its effects two large scale tests were performed. In these experiments, fine-grained blocks with different conditions were subjected to the uprising moisture from the bottom. Depth of source of water (*e.g.,* groundwater table) in many cases is in the range of 2 to 4 m. A vertical load of 50 kPa was applied on the top of the block to represent the weight of overlying soil layers or a construction. This load represented a thickness of 2.6 m of the tested soil (with a density of 19.2 kN/m^3 as derived by Soleimani-Fard (2014). Adding the height of the block to this thickness, the total simulated depth will be around 3.20 m.

As can be seen in Figs. 4(c) and 4(d) the blocks were built over a geotextile and filter paper. This geotextile worked as a draining surface in order to transport water to the entire bottom surface of the block. Using continuous drops from a water source that was located at a higher elevation, the geotextile was always kept saturated.



(c) (d)

Fig. 4 **(a) A photograph for the test, (b) installation of TDRs at the back side of the block, (c) schematic sketch of the front view, and (d) the side view (unprotected condition)**

Volumetric water contents were measured using four Time Domain Reflectometers (TDRs) during the experiments. Figures 4(a) and 4(b) show the positions of TDRs in the first test. Later using mass-volume equations the volumetric, as presented in Eq. (4) and below (Eqs. (7) to (9)), water content can be converted to degree of saturation or gravimetric water content. Before performing the tests, the TDRs were calibrated with the same material and condition of the tests, although they had been calibrated by the producer and the calibration data were recorded in the sensors and their software.

$$w = \frac{m_w}{m_s} \tag{7}$$

$$\theta = w \times \frac{G_s}{1+e} \tag{8}$$

$$S_r\, e = G_s\, w \tag{9}$$

where θ and w are volumetric and gravimetric water content, S_r is degree of saturation, and m_w, m_s, and e are mass of water, mass of soil and void ratio.

Preparation of the Blocks

In this study, the blocks of fine-grained soil were prepared using district clayey pieces (similar to earthen bricks). The soil mixture was first mixed and blended thoroughly with water content 25% more than its liquid limit (1.25 × LL) to reach a soft and uniform slurry mud. To have a good distribution of water in all parts of the sample, the mud was left for 2 days in a closed container. Afterward to make the earth bricks, the fine-grained slurry was poured in molds to get the required form while drying. The mold had a dimension of 100 × 120 × 240 mm (height × width × length), however, due to shrinkage, and the bricks were rather smaller than the mold, around 95 × 113 × 230 mm on average. They were left in the lab atmosphere and weighed from time to time to reach a constant weight with a tolerance of < 10 grams. At this condition, the blocks of fine grained soil were built with 6 rows of 4 bricks. However, it was tried to make the whole block as homogeneous as possible, by placing fresh slurry (with the same mixture as used in the construction of bricks) between the rows of bricks. Figure 4 presents pictures and the schematic arrangements of the test.

Unprotected Block

In the first test as Fig. 4(a) shows, a block with a dimension of 230 × 450 × 570 mm was built from the earthen bricks as explained above. The setup and position of TDRs are shown in Figs. 4(c) and 4(d) (at heights of 5, 15, 25, and 45 cm). In the applications mentioned in Section 1, the clayey soil layer shall be continued horizontally. To simulate this condition, the boundaries of the block shall be hydraulically closed. Therefore, in the experimental model, all vertical sides of the block were covered with silicon glue and nylon foils to prevent the evaporation of moisture from these surfaces. The bottom and top surfaces were not covered.

During the test when the water content of the lower parts of the block reached to or exceeded the plastic limit of the soil, the volume changes were observed, which were due to (i) expansion of the clay and/or (ii) vertical settlement against the applied load. Although the mechanical behavior of the block (including these deformations) was not in the scope of this research, the volume changes were measured during the test to calculate the degree of saturation and void ratio more accurately at different heights of the block. To be able to read the volumes more precisely, the block was confined between two parallel metal plates as shown in Fig. 4, and the deformations were measured horizontally and vertically by analyzing photos taken by a camera installed in front of the block.

Protected Block with Base Ventilation Method

In the second test, one of the widely used countermeasure methods against uprising moisture, base ventilation, was adopted and evaluated. This method is explained in Section 2.4 and can be applied from either one side or both sides of the block. In this experiment same as the first test (unprotected block), the block was covered by silicon glue and nylon foil. But, in the front and back sides, 100 mm from the bottom was left open and exposed to air from which moisture was allowed to evaporate. In this situation, a slower rate and a lower height of uprising moisture were expected. Therefore, TDRs were installed at lower heights of 5, 10, 20, and 30 cm. Unlike the first test in which impermeable covering resulted in unique water content in any horizontal plane, in this test water content did not have the same value in all points of a horizontal section, but its maximum value occurred at the centerline of the horizontal plane, and near front and back facades lower values were expected. Thus, TDRs were placed on the side of the centerline. Figure 5 shows two photographs of this test.

4.2 SWCC Tests (ATT and VET)

As mentioned above, SWCC was one of the requirements of the numerical calculations in this study. The SWCC tests on the concerned fine-grained soil have been studied by Soleimani-Fard (2014), and the test procedures and theoretical details were elaborated there and briefly summarized here.

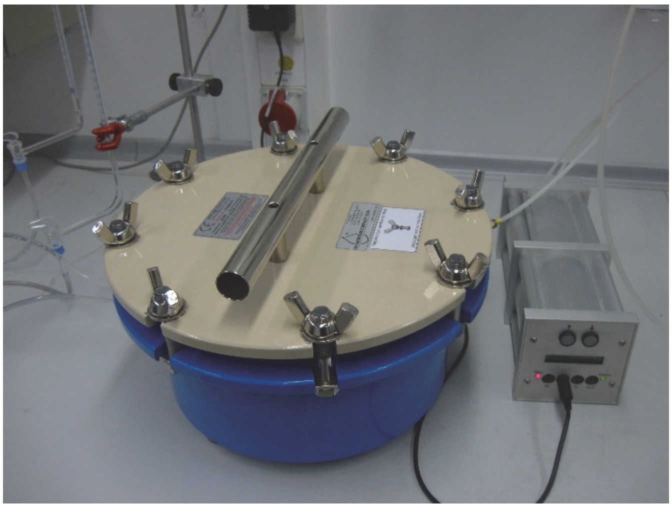
(a)

(b)

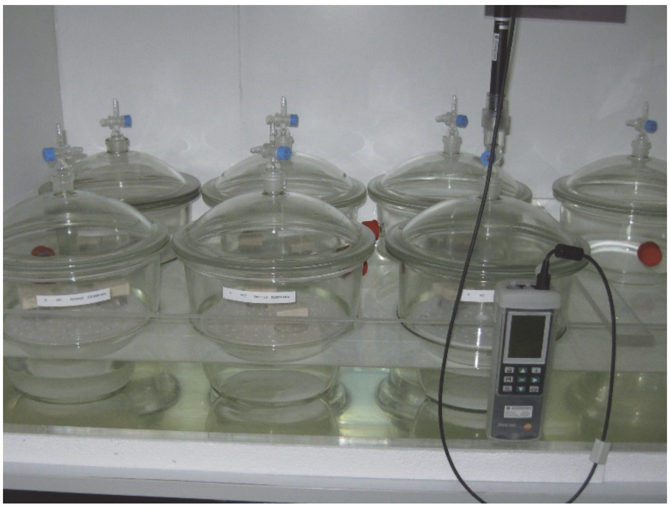
Fig. 5 Protected block: (a) TDRs installed at the center line of the left side of the block before placing the confining metal plates, and (b) TDRs passed through the metal plates

Two series of tests were performed by Soleimani-Fard (2014) in order to draw full SWCC of the soil; namely, Axis Translation Technique (ATT) and Vapor Equilibrium Technique (VET) for lower and higher ranges of suctions, respectively. In ATT, matric suction is associated with the soil matrix and is defined as the difference between pore-air and pore-water pressure of the soil ($u_a - u_w$) (Hilf 1965). Both pore air and pore-water pressures can be controlled in the Pressure Plate Apparatus in the laboratory. The device used is shown in Fig. 6(a).

Salt solutions with different types of salt and concentrations produce various relative humidity in the atmosphere above the solution in a close container. According to the thermodynamic rules, each relative humidity provides its corresponding suction. Figure 6(b) shows the desiccators containing salt solutions for applying suction via VET. For the drying path fully, saturated samples were subjected under suctions starting from 10 kPa to more than 200 MPa, and vice versa for the wetting path. Full SWCC of the studied fine-grained soil is presented in Fig. 7.



(a)



(b)

Fig. 6 Devices used in SWCC tests after Soleimani-Fard (2014); (a) pressure plate apparatus and (b) desiccators

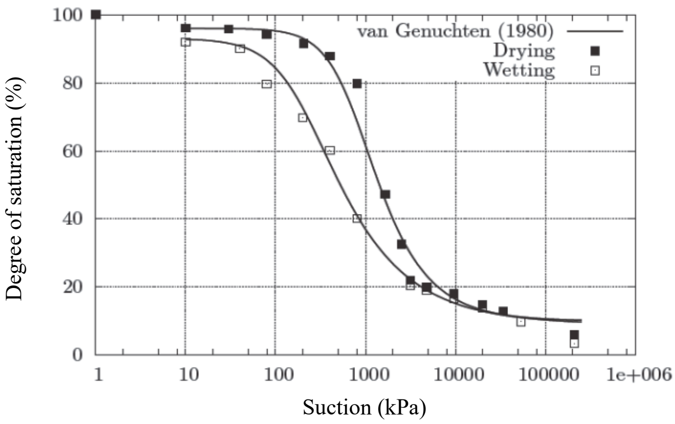


Fig. 7 SWCC in form of degree of saturation *vs.* suction in drying and wetting paths, experimental results (Soleimani-Fard 2014) and predicted with van Genuchten's equation

5. NUMERICAL SIMULATION

Capillarity in porous media has been studied in numerous research, particularly in recent years. Several studies modeled water transport in unsaturated soils (*i.e.,* Polmann 1990; Pel 1995; Mortensen 2001; Smith 2003), and some studies analyzed and modeled uprising moisture and capillary action (*i.e.,* Washburn 1921; Pachepsky and Scherbakov 1984; Lago and Araujo 2001; Lockington and Parlange 2004; Yuan and Lu 2005; Torres and Freitas 2007; Mullins and Braddock 2012). The current study analyzed the hydraulic distribution of uprising moisture in the fine-grained blocks as explained above using software Code-Bright 2.3. The main equations and assumptions used in this simulation are as follows.

Incorporating Darcy's law, Eq. (1), in its unsaturated conditions, Freeze and Cherry (1979) developed an equation for continuity of transient flow through an unsaturated soil as shown in Eq. (10). This equation is a simplified and 1D version of Richard's equation.

$$\frac{\partial}{\partial z}\left[k(\psi)\left(\frac{\partial \psi}{\partial z}+1\right)\right]=\frac{\partial \psi}{\partial t} \tag{10}$$

One of the most fundamental properties in uprising moisture is unsaturated hydraulic conductivity, $k(\psi)$. Several empirical and statistical methods have been introduced to calculate $k(\psi)$ as a function of some basic properties and variables such as degree of saturation, water content, suction, saturated hydraulic conductivity, and SWCC. Van Genuchten's models for predicting SWCC and unsaturated permeability were used in the simulations of this study, presented respectively in Eqs. (11) and (12).

$$S_e=\left(\frac{1}{1+\alpha\,\psi^{1/(1-m)}}\right)^{-m} \tag{11}$$

where S_e is effective degree of saturation and a and m are fitting parameters.

$$k_r(\psi)=S_e^{\frac{1}{2}}\left[1-\left(1-S_e^{\frac{1}{m}}\right)^{m}\right]^2 \tag{12}$$

where $k_r(\psi)$ is ratio of unsaturated to saturated coefficient of permeability.

$$S_e = \frac{S_r - S_{r,res}}{S_{r,sat} - S_{r,res}} \quad (13)$$

where $S_{r,sat}$ and $S_{r,res}$ are, respectively, saturated and residual degrees of saturation.

Regarding the hydraulic loading path of the material during process of uprising water, the adapted model for wetting curve of SWCC was used in this study. The parameter m is assumed to be equal to the fitting parameter of van Genuchten's SWCC model. Parameters of these simulations are given in Table 1. The SWCC of the used material is determined is determined by Soleimani-Fard (2014) and shown in Fig. 7.

The blocks were simulated numerically in 2D rectangular models. Constant water pressure of zero was assigned to the bottom surface of the blocks that modeled the presence of free water at this face. The assigned water pressure for upper face and ventilation openings in the protected condition (exposed to the atmosphere) was −20 MPa, which was the initial suction of soil as found in the SWCC tests by comparing the water content of samples dried in the lab atmosphere with the samples placed in the desiccators with certain water pressure (or suctions) as discussed by Soleimani-Fard (2014). No predefined constant water pressure was given to the sides, which indicated that they were covered, and their suction (and correspondingly their water content) were not determined by boundary condition but by the progress of the test.

Table 1 Parameters used in simulation of the fine-grained soil used in this study

Description	Parameter	Value
SWCC (van Genuchten)	a	0.35 MPa
	m	0.5
	$S_{r,res}$	0.13
	$S_{r,sat}$	0.93
Permeability	k_s	3.7×10^{-17} m^2
Void ratio	e	0.39

6. EXPERIMENTAL AND NUMERICAL RESULTS AND DISCUSSIONS

6.1 Unprotected Block

Figure 8 presents experimental and numerical results. The solid and dotted lines present the experimental and numerical water contents, respectively, at 4 different levels of the block at which the TDRs were installed. In the numerical simulations, maximum or saturated degree of saturation, $S_{r,sat}$, was determined from the wetting path of SWCC (see Fig. 7). The numerically calculated water content reached the equilibrium at a value slightly higher than 0.14; however, experimental results for heights of 5 and 25 cm were 0.155 and 0.13, respectively. This difference was due to the swelling of the bricks. Since the bottom surface of the block is exposed to free water and the swelled soil is a few centimeters above that, the degree of saturation of this part is always at or slightly below 1. Therefore, swelling led to higher gravimetric water content. In the simulations, the void ratio was assumed to be a constant value (0.39). In reality, however, the void ratio at the end of the tests was in the range of 0.39 to 0.45 depending on the time and height. This phenomenon can be seen also in Fig. 8. The water content measured by the first sensor (installed at 5 cm) showed higher values compared to numerical water content at the same height. For other levels, on the other hand, experimental and numerical water contents were reasonably close.

Figure 9 presents the experimental and numerical water contents at the end of the test (after 1,350 hours). The experimental results were measured from samples collected from 18 different levels of the block. For each level, three samples were taken, and results were averaged. This figure confirms a relatively good match between numerical and experimental results. As it can be seen here at very low heights, numerical simulation underestimated the results. In contrast, for the higher heights (where uprising moisture has not reached and the initial water content should be measured), the numerical results are overestimating the experimental results. These mismatches are due to idealizations of the numerical simulations. The reason is the same as explained above: swelling of lower parts was not considered in the numerical simulation. For the higher parts of the block which received relatively less moisture content until the end of the test, the numerical simulation overestimated the actual water content. It can be due to the dissimilarity of laboratory conditions in which the SWCC and the large-scale tests had been performed. Residual water content in the numerical modeling was defined from the SWCC results. In the SWCC analysis of Soleimani-Fard (2014), the water content at the suction of 20 MPa was slightly more than 0.02, while the measured water content of the blocks at the initial stage was less than this value.

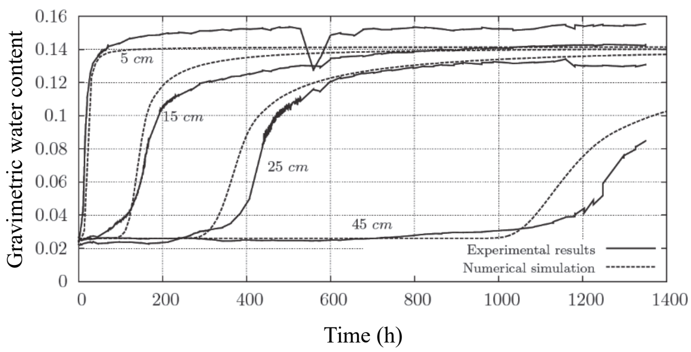


Fig. 8 Experimental and numerical results for 4 positions at which TDRs were located in the unprotected block

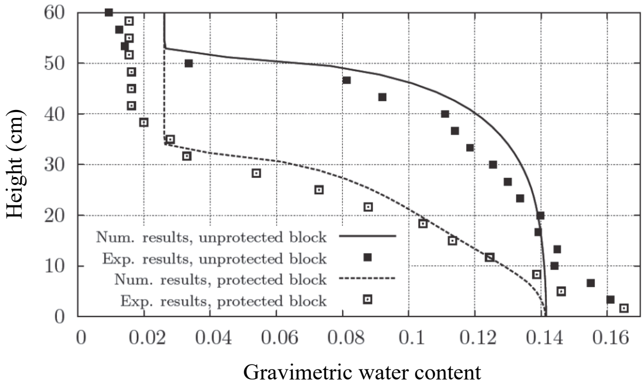


Fig. 9 Experimental and numerical results at the end of the test in unprotected and protected blocks

The rate of the uprising was an inverse function of time. At the beginning of the test, the moisture rose faster compared to the later stages and reached its equilibrium at a height of 5 cm in around 50 hours, whereas for the height of 15 cm, it took around 800 hours to reach the equilibrium. In both experimental and numerical models, as time passed the uprising rates decreased.

Vertical deformation (dilation) of the soil in the unprotected condition is depicted in Fig. 10 versus time for every 4 cm of block's height (as specified in the legend). The maximum heave at the end of the test was 2.9 mm. As it can be seen, in the first 200 hours of the test, vertical deformation was only monitored in the bottom 15 cm of the block, while by the passage of time and rise of the water through the block, the volumetric change was also observed in the higher positions and reached to around 47 cm at the end of the test. The gravimetric water content in which the soil starts to dilate was around 0.08, which is the AEV (air entry value) of the wetting path of SWCC.

Figure 11 shows the numerically calculated gravimetric water content using the simulation mentioned above (color contour). The uprising front calculated as per Washburn's equation is shown by the white solid curve.

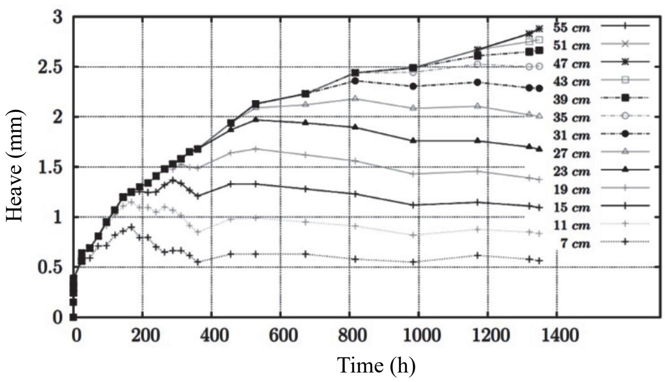


Fig. 10 Vertical displacement of different points of the unprotected block

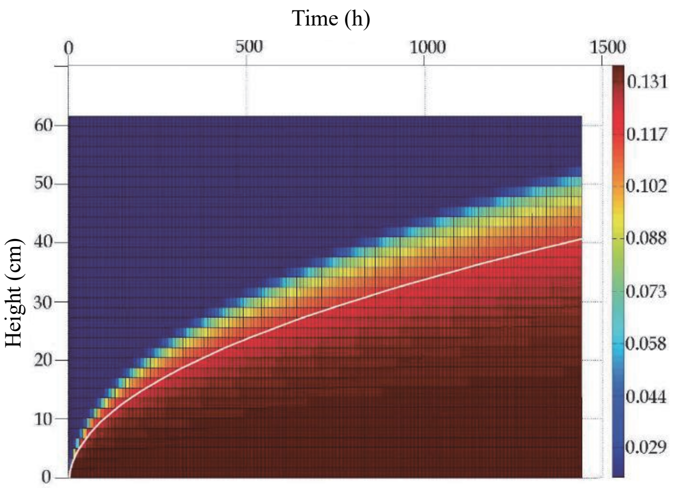


Fig. 11 Predictions of uprising moisture in unprotected block; color contour: numerically calculated gravimetric water content; solid white curve: predicted from Washburn's equation

In this study, Washburn's fitting parameter was selected based on the best fit of the prediction results with the experimental results of four TDRs which measured the water content. Washburn assumed that the uprising capillary moisture has an advancing front below which the material is saturated; however, a more realistic assumption could be a gradually distributed humidity over the height. In order to adapt Washburn's method to this study, the advancing front of the uprising moisture was assumed to be at the level where the water content was equal to the water content at the AEV in the wetting path of SWCC. The best fit was occurred at $h_e = 23$ m. Comparing the Washburn's results with numerical simulations of this study (Fig. 11) proved that in spite of the simplicity and the old age, owing to its fitting parameter, this method is able to predict the uprising moisture not so far from reality.

6.2 Protected Block with Base Ventilation Method

Figure 12 shows the numerical and experimental water contents at 4 different levels of the block at which the TDRs were installed on the centerline, and Fig. 9 shows numerical and experimental water contents at the end of the test on the centerline. The efficiency of the implemented countermeasure method can be evaluated from a comparison between the results of protected and unprotected blocks in this figure. Similar to the unprotected model, for lower heights of the block, the numerical simulation underestimated the water content values, and for the higher heights vice versa. As mentioned before, the reason for the underestimation in lower parts was the swelling of material which was ignored in the calculations, and the difference in higher parts was probably due to deficiency of the model in dry conditions. Most likely in high ranges of suction, van Genuchten model for unsaturated hydraulic conductivity, Eq. (12), predicts higher values for $k(\psi)$ than its real values.

Figure 13 presents the vertical deformation of the soil in the protected condition over time measured at the same heights as Fig. 10 for the protected test. In this test, no deformation was monitored for heights above 20 cm. The maximum vertical deformation was around 0.95 mm, which is almost 30% of that in the unprotected condition.

Figure 14 shows the numerically calculated hydraulic distribution (2D) of moisture after various periods of time in form of gravimetric water content. Figure 14(h) is the result at the end of the test (after 69 days), which its counterpart experimental result is given in Fig. 16. As it can be seen here in the numerical simulations, the assigned constant suction to the first 10 cm of the sides

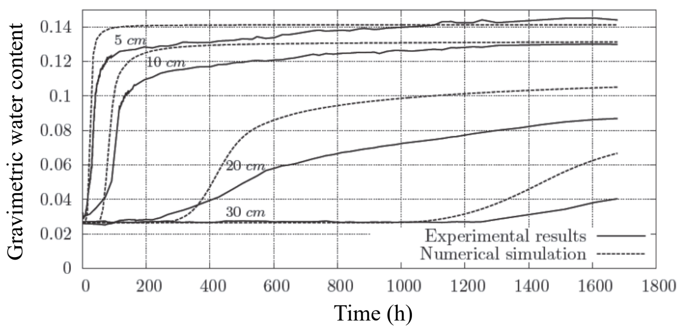


Fig. 12 Experimental and numerical results for 4 positions at which TDRs were located on the protected block

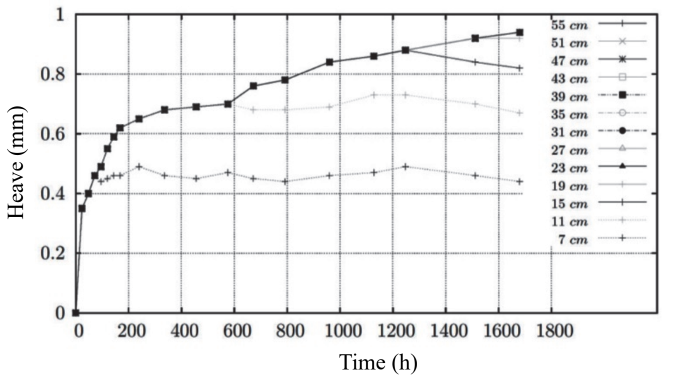


Fig. 13 Vertical displacement of different points of the protected block

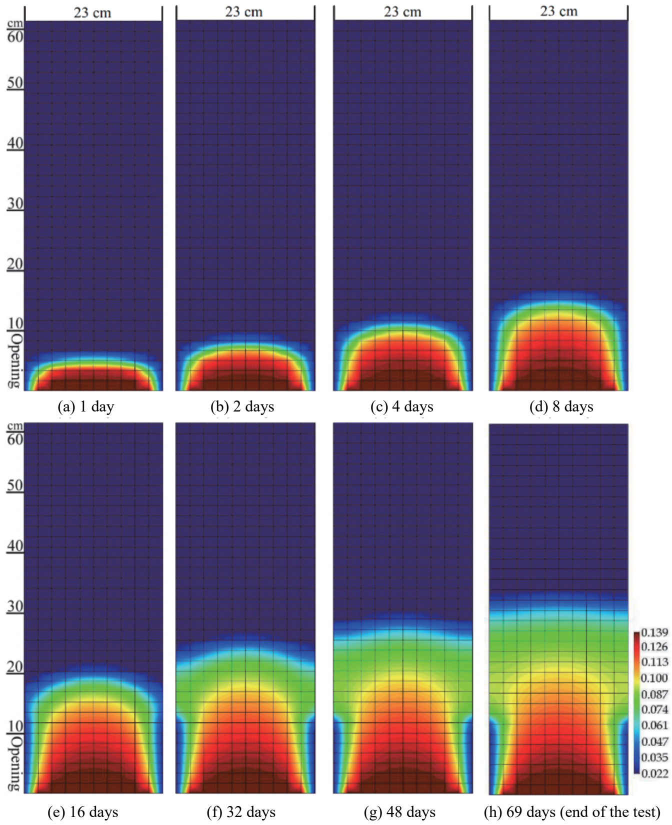


Fig. 14 Numerically calculated degree of saturation distributed through the block after various periods, in protected condition

was the initial suction of the material; however, in the experiment, the water content of openings also increased (see Fig. 16). Another shortcoming of this test was the measurement of water content during the test with four TDRs, which could not cover the whole vertical cross-section of the block, but only read the water content at the four given points on the centerline (see Fig. 5).

As shown in Fig. 9, after more than two months, the moisture content in the unprotected block was increased much more than in the protected block. For instance, at a height of around 40 cm, where no increase in the water content of the protected block compared to the initial condition was observed, the unprotected block showed a water content of approximately 0.11. As the simulation of protected block resulted (Fig. 14), during the period of 2 months, the degree of saturation of the facades never exceeded 0.022, while in the same period the lower 40 cm of the unprotected block had a degree of saturation of more around 0.12 to 0.14 (Fig. 15).

6.3 Efficiency of Implemented Countermeasure Method (Base Ventilation)

Not always the base ventilation method can solve the problem of uprising moisture for various applications with different geometries, boundary conditions, soil types, fluctuations of underground water, *etc.* Before recommending this (or another) method, its efficiency and capability must be analyzed experimentally or numerically. In order to evaluate the base ventilation method, 20 blocks with the same material as tested here but with different thicknesses and openings in Fig. 17(b) and Fig. 17(c) were numerically simulated and evaluated. Boundary condition, duration of the test, and type of material were the same in all models.

In Fig. 17, the black lines represent the covered areas and the blue line shows the presence of water. Modeling assumptions and parameters were similar to what described in Section 5 and Table 1 about the modeling of the unprotected blocks. The rise of the capillary water over a given period of time was calculated by changing b and c (height of opening and thickness of the block as shown in Fig. 17).

Twenty models (M0 to M19) with wide ranges of block thicknesses and opening sizes, as listed in Table 2, were simulated. In this table, the models are categorized based on the thickness of the blocks. M0 is the unprotected block without any ventilation (see

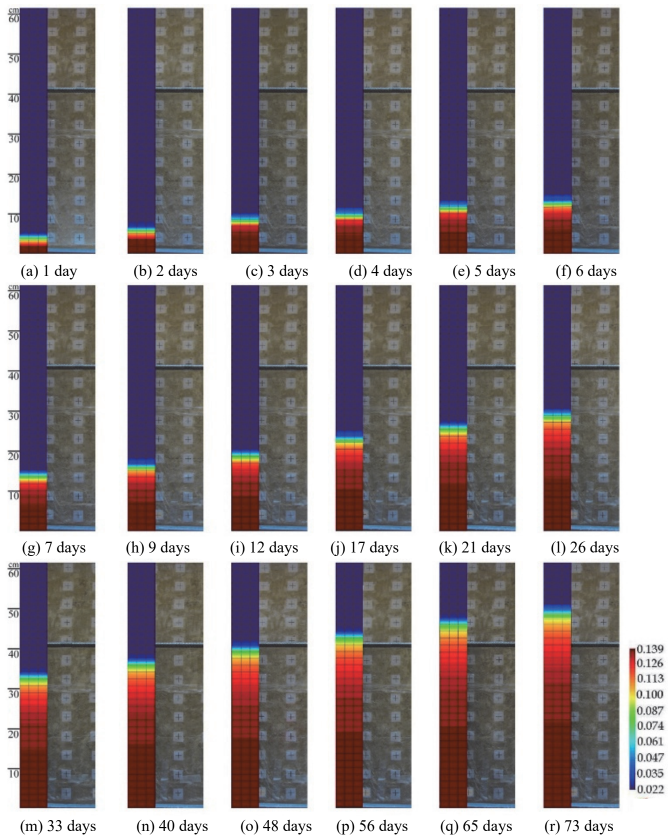


Fig. 15 Numerically calculated degree of saturation for unprotected block (color contours), and pictures of the block at the mentioned stages

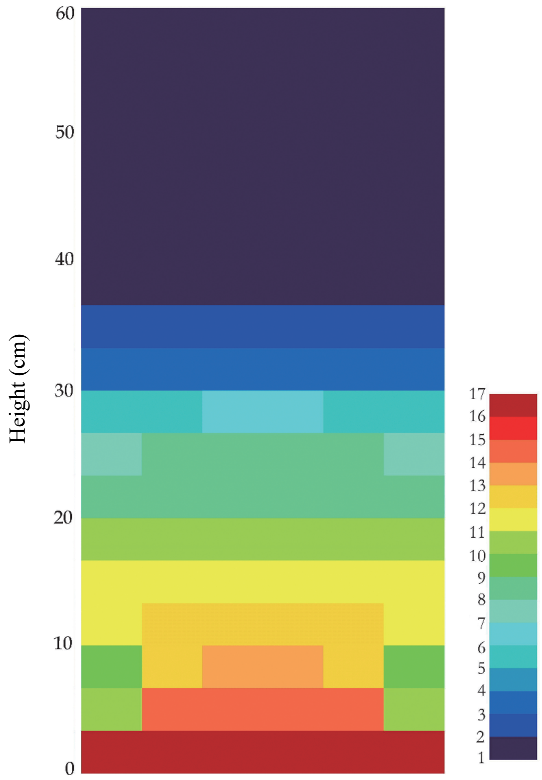


Fig. 16 Experimentally measured gravimetric water content (%) at end of test, for protected condition

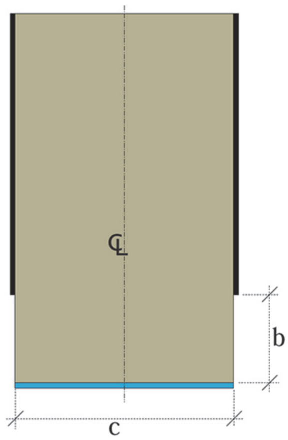


Fig. 17 Cross sectional view of base ventilation method used in numerical studies

Section 6.1) and M7 was the protected block tested experimentally in this research (see Section 6.2). The centerline is shown with a dotted line in Fig. 17.

Figures 18 to 21 present the calculated water contents on the centerline of the blocks with different thicknesses and openings (mentioned in Table 2) subjected to uprising moisture for 2 months. In all these graphs, M0 is 23-cm thick unprotected block (no ventilation openings). Since capillary uprise in the unprotected condition is a 1D phenomenon (see Fig. 15), the height and shape of M0 curves are independent of the block thickness, and M0 graphs can be compared with the protected blocks with any thickness.

From these figures, efficiency of countermeasure can be assessed. It can be clearly concluded from Fig. 18 that for thin blocks,

Table 2 Configurations of simulated countermeasure methods

Model name	*c* (cm)	*b* (cm)	*b/c*
M1	11.5	3.3	0.287
M2	11.5	5	0.435
M3	11.5	7.5	0.652
M4	11.5	10	0.870
M5	11.5	11.5	1.000
M6	23	6.6	0.287
M7	**23**	**10**	**0.435**
M8	23	13.2	0.574
M9	23	15	0.652
M10	23	20	0.870
M11	23	30	1.304
M12	46	13.2	0.287
M13	46	20	0.435
M14	46	30	0.652
M15	46	52.8	1.148
M16	46	80	1.739
M17	92	26.4	0.287
M18	92	40	0.435
M19	92	60	0.652
M0	23	0	0

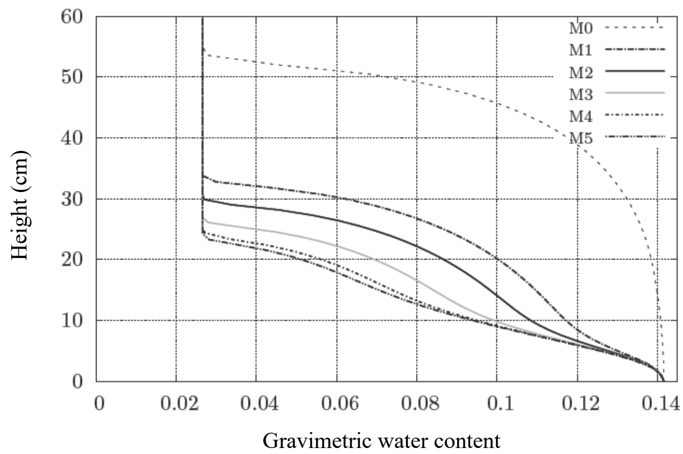


Fig. 18 Calculated gravimetric water content on the center lines, configurations M1 to M5 (*c*: 11.5 cm)

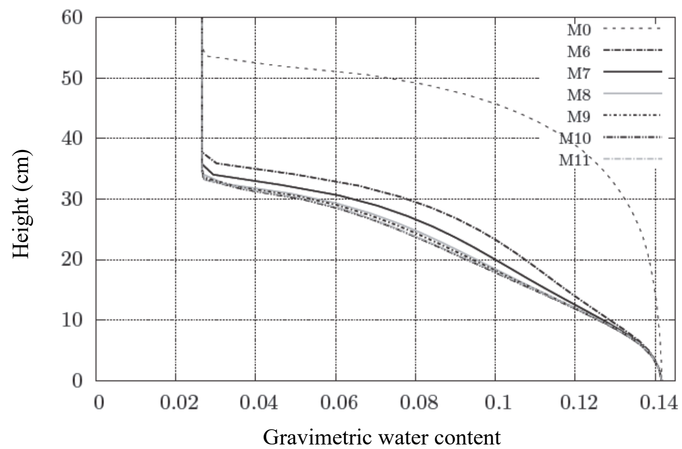


Fig. 19 Calculated gravimetric water content on the center lines, configurations M6 to M11 (*c:* 23 cm)

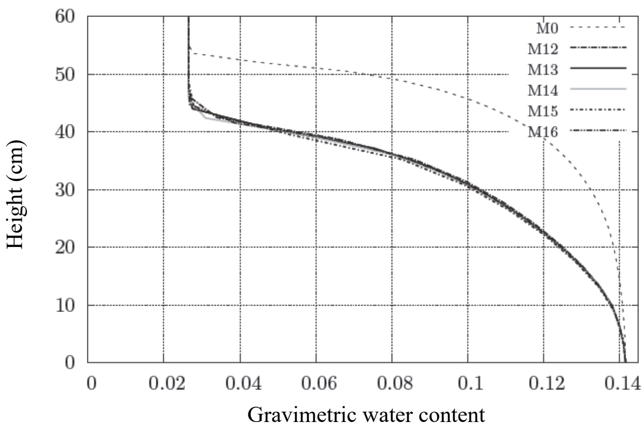


Fig. 20 Calculated gravimetric water content on the center lines, configurations M12 to M16 (*c:* 46 cm)

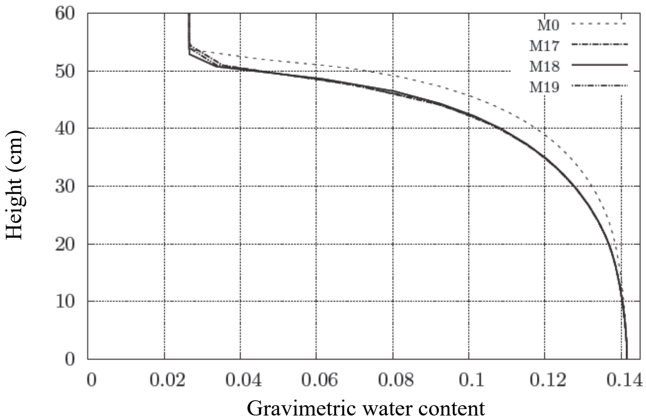


Fig. 21 Calculated gravimetric water content on the center lines, configurations M17 to M19 (*c:* 92 cm)

this method could significantly reduce the water content in the centerline which had the maximum humidity compared to the other parts. But, as the thickness increased, the inner parts of the block receded from the openings, hence the base ventilation method lost its efficiency for wider blocks. If the thickness exceeded a certain value, the size of the opening had almost no effect on the height of uprising water on the centerline. For blocks thicker than 20 cm, widening the openings more than 10 cm was not beneficial, and for thicknesses greater than 40 cm, the base ventilation method for protecting the blocks against uprising moisture probably was not a suitable countermeasure method.

7. CONCLUSIONS

In this paper, uprising moisture phenomenon in blocks of fine-grained soil was analyzed. The used material was a mixture of sand, silt, and clay, classified as CL in the unified soil classification system. The efficiency of the base ventilation method, one of the suggested countermeasure methods, has been experimentally and numerically evaluated. After the implementation of this method, the height of uprising was almost half, and the maximum heave was one-third of that in the similar but unprotected condition. In general, for practical purposes, the base ventilation is an efficient measure to control the moisture uprise from underground water tables, leakages from pipelines, or any other source of humidity in the soil. This moisture can potentially affect the shear strength parameters as well as short-term and long-term volumetric behaviors.

Numerical simulations of physically modeled conditions were in acceptable matches, which further validates numerical analyses. After performing basic laboratory tests on the soil (*e.g.,* physical properties, permeability, SWCC), distribution and movement of moisture through the ground can be trustworthily analyzed. In order to check the ability of the base ventilation method in reducing the uprising moisture in other geometries, several blocks protected with this method but with different geometries were simulated and assessed. Similar to experimental models, numerical results also showed that the base ventilation method can potentially reduce the uprising height as a function of geometry and protection design. However, the outcomes declared that in soil blocks thicker than a certain value, this method does not effectively work.

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DATA AVAILABILITY

This study does not generate new data and/or new computer codes.

CONFLICT OF INTEREST STATEMENT

The authors certify that there is no conflict of interest.

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