Webology (ISSN: 1735-188X)
Volume 19, Number 4, 2022

Capillary Ascension In Fine-Grained Soil Using A Reduced Model

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ABSTRACT

The main objective of this article is to analyze the capillary rise of a fine soil of sedimentary origin in a scale model in the laboratory. The results showed that water's velocity rising through the capillaries of soil increased when the soil was compacted with higher dry unit weight. The soil expansion started to manifest after the capillary water reached an average of 1/3 of the total height. Over time, the permeability coefficient decreased in all cases from 0.0005 cm/s to 0.0003 cm/s. It was found that the air intake was located at 25 cm in height and that the matric suction in the soil registered values of 600-800 kPa for saturation degrees between 90%-100%. It was verified that the rise height vs. time curve is mainly influenced by the molding porosity, saturated state permeability coefficient, and air entry height.

Keywords: Rising Damp, Matrix Suction, Fine Soils, Reduced Model, Filter Paper.

1. INTRODUCTION

The capillarity of water in soil due to surface tension is a common phenomenon in nature. This phenomenon refers to water at an elevation above the groundwater level or the water table. The phenomenon of capillary rise is associated with the matrix suction, a component of the total suction, and is different for several wetting and drying processes as a function of variations in capillary pore size. Mathematical models have been developed to estimate the rise height and rise time, mainly in coarse-grained soils. Thus, experimental studies in fine-grained soils are necessary to understand the phenomenon better.

Several capillary rise studies have been performed using open tubes. Baldovino et al. (2017) studied the capillary rise of uniform sand. The authors identified that the sand presents two zones after completing the test: saturated zone and unsaturated zone. In addition, the air entry point was found at 1/3 of the maximum height for the sand studied. Baldovino et al. (2018a, 2018b) molded fine sand at different porosities to study the capillary behavior and thus estimate the maximum rise height using mathematical models. The authors found that analytical solutions of capillary rise can be employed in sands and their use in geotechnical engineering and soils for agriculture. Izzo et al. (2018) used analytical models to estimate the capillary rise curve of compacted sedimentary silt in a 2m column. The authors concluded that by comparing the analytical solutions with the results obtained in the laboratory, it can be said that the solution proposed by Terzaghi (1943) has a better fit, with porosity and saturated permeability coefficient being the main control parameters of the capillary rise curve. Although there are studies in open pipes, there are no studies in reduced models with large soil volumes. Therefore, this paper discusses the capillary behavior of fine soil when compacted in three different porosities.

2. EXPERIMENTAL PROGRAM

The characterization of the soil and the procedures for the rising damp tests are detailed below.

2.1 Ground

The capillary rise tests used a silty soil from the Guabirotuba Formation (Curitiba/Brazil). The soil was previously characterized in the studies by Baldovino et al. (2020a, 2020b, 2020c). The physical properties of the soil are presented in Table 1. X-ray fluorescence (XRF) was used to determine the chemical composition of the soil. The soil consists mainly of silica (48.78%) and alumina (44.51% by weight). The soil is classified as high plasticity silt (MH) and has 5% clay, 60% silt, and 35% sand.

2.2 Rising Damp Tests

Soil originating from the Guabirotuba Formation of Curitiba/BR was compacted in a transparent acrylic box with dimensions 30×30 and 40cm high. Layers were compacted every 5 cm of silty soil over a thin layer of medium sand to allow water to enter the system. 2 water inlets were installed in the box at the bottom and 2 Wathmann filter papers were placed every 4 cm in height to measure the matrix suction (ASTM D5298-16) after the completion of capillary rise. The water inlet system was connected to an external system that kept the water level constant with a reservoir graduated in liters. Dial gauges were installed on top of the soil in the box to record the expansion due to water entering the system. During the test, rising damp height was recorded by time on all four sides of the acrylic box.

A total of 3 tests were performed: Box A, B, and C. In each test, the soil was compacted with a different dry density (ρd) of molding to study the effects on capillary behavior. Box A was compacted with ρd = 1.057 g/cm3, Box B with a dry density of 1.138 g/cm3, and Box C with 1.040 g/cm3. Box A and B were compacted at 0% moisture content, while Box C was compacted at 5% moisture content.

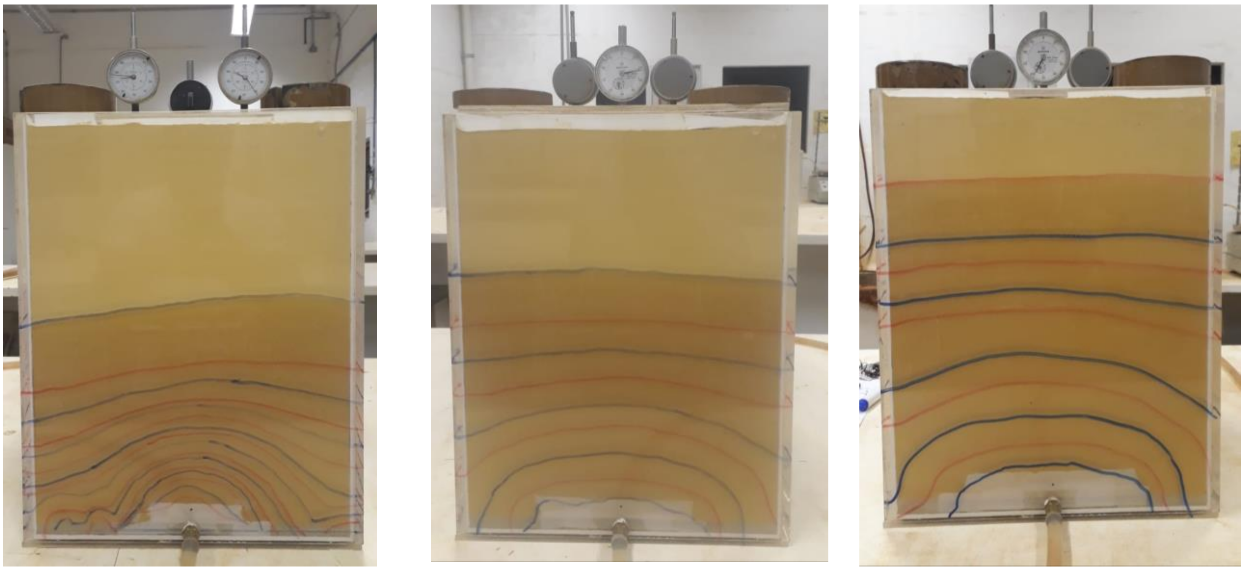
Table 1. Physical properties of soils

Properties	Value	Standard followed
Liquids Limit, %.	50.82	NBR 6459
Plasticity Limit, %.	35.96	NBR 7180
Plasticity index, %	14.86	
Actual grain density	2.62	ASTM 854-14
Coarse sand (0.6 mm< diameter<2 mm), %.	5	NBR 6502
Medium sand (0.2 mm< diameter <0.6 mm), %.	12	NBR 6502
Fine sand (0.06 mm< diameter <0.2 mm), %.	18	NBR 6502
Silt (0.002 mm < diameter <0.06 mm), %.	60	NBR 6502
Clay (diameter < 0.002 mm), %.	5	NBR 6502
Effective diameter (D_{10}), mm	0.003	
Average diameter (D_{50}), mm	0.038	
Coefficient of uniformity (C_u)	12.67	

Coefficient of curvature (C_c)	0.88	
Classification (SUCS)	MH	ASTM 2487-11
Color	Yellow	
Pre-consolidation Stress, kPa	300	ASTM D2435
Coefficient of consolidation, cm^2/s	0.02	ASTM D2435
Friction angle, degrees	26	ASTM D3080
Cohesion, kPa	23	ASTM D3080

3. RESULTS AND DISCUSSIONS

Figure 1 shows images of boxes A-C during the rising damp test. The rise height on each of the four faces of the boxes was marked along with the time. At the beginning of each test, the water started to rise radially, and then the behavior was utterly vertical due to the sand at the bottom of the box helping to normalize the rise. This can be seen clearly in Figures 2, 3, and 4. In the two cases where the soil was compacted with no moisture content, the radial rise ceased to manifest itself after the 25 cm height, while in Box C, compacted with 5% moisture content, the radial behavior disappeared after 15 cm. In this small height and time interval, the change in water content in the wetting zone is assumed to be very small compared to the change in water content due to the advancement of the wetting zone, as seen by Li et al. (2009). Moreover, the boundary conditions in front of the wetting zone can be assumed to be unchanged for short time intervals.



(a) (b) (c)

Figure 1. Capillary behavior of soil through time. (a) Box A (b) Box B (c) Box C

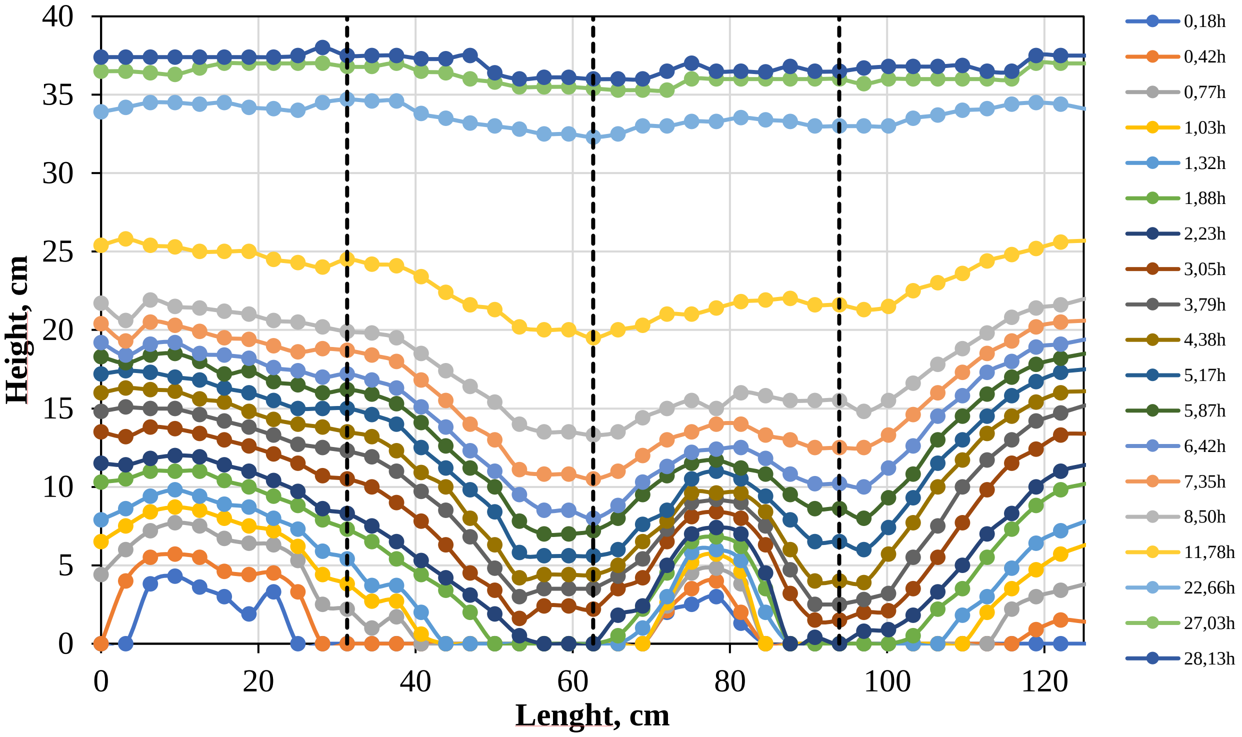


Figure 2. Capillary rise lines of water over time for box A and faces 1-4

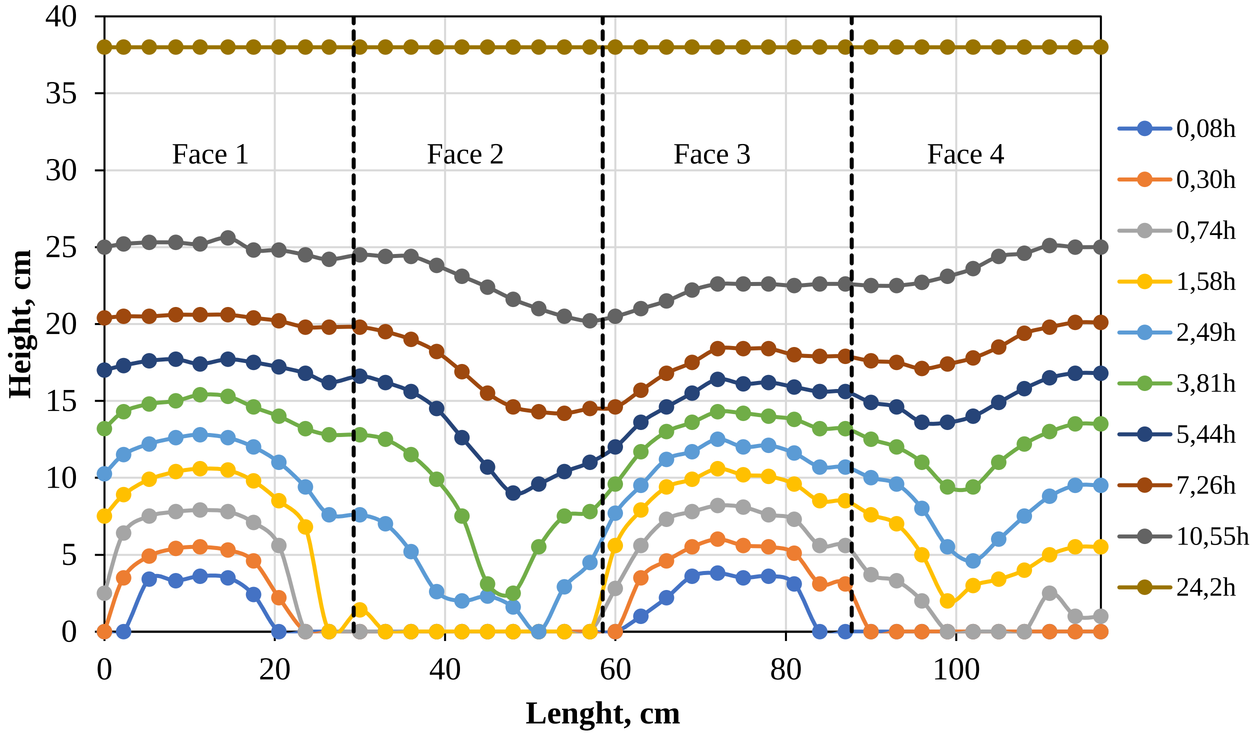


Figure 3. Rising water lines over time for box B and faces 1-4

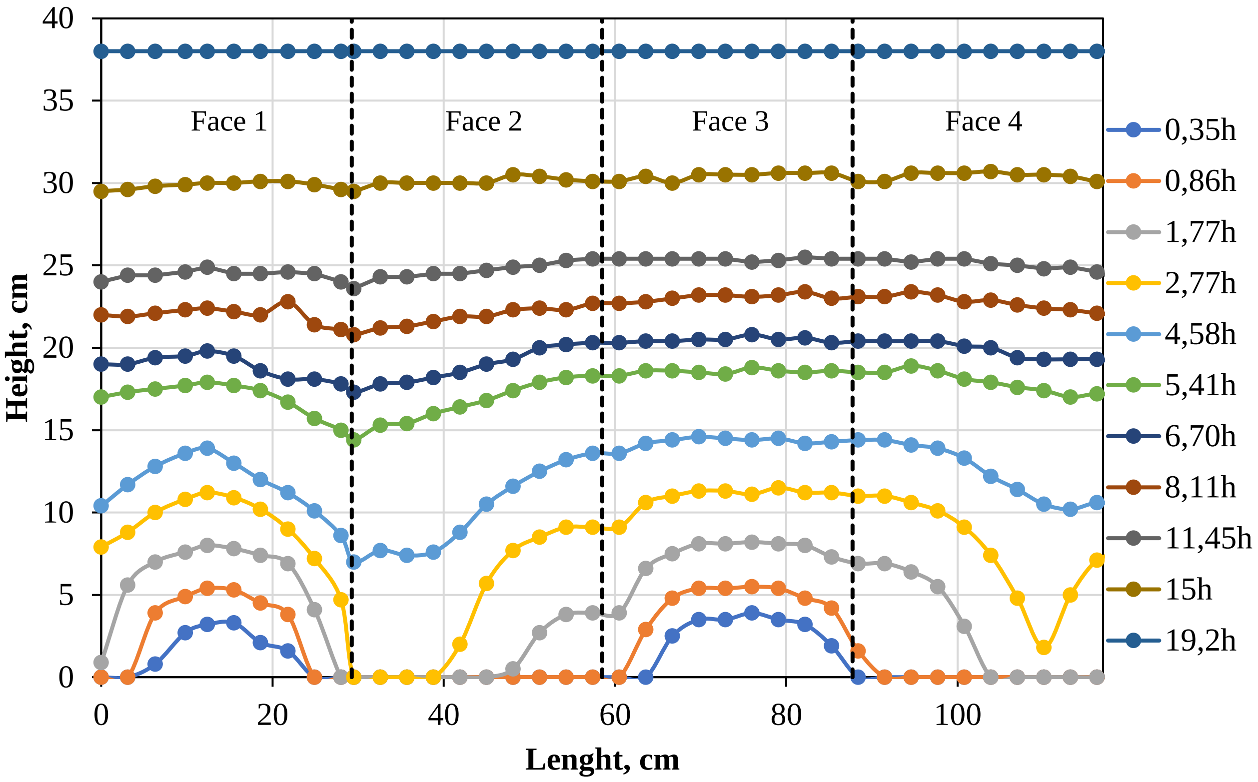
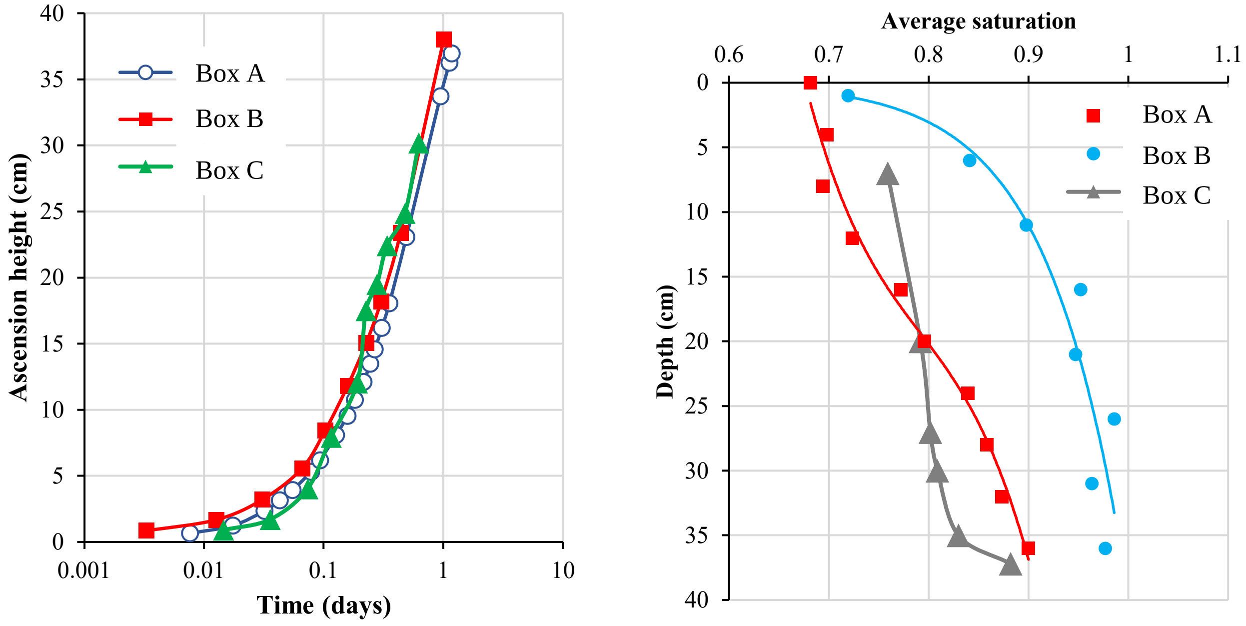


Figure 4. Rising water lines over time for box C and faces 1-4

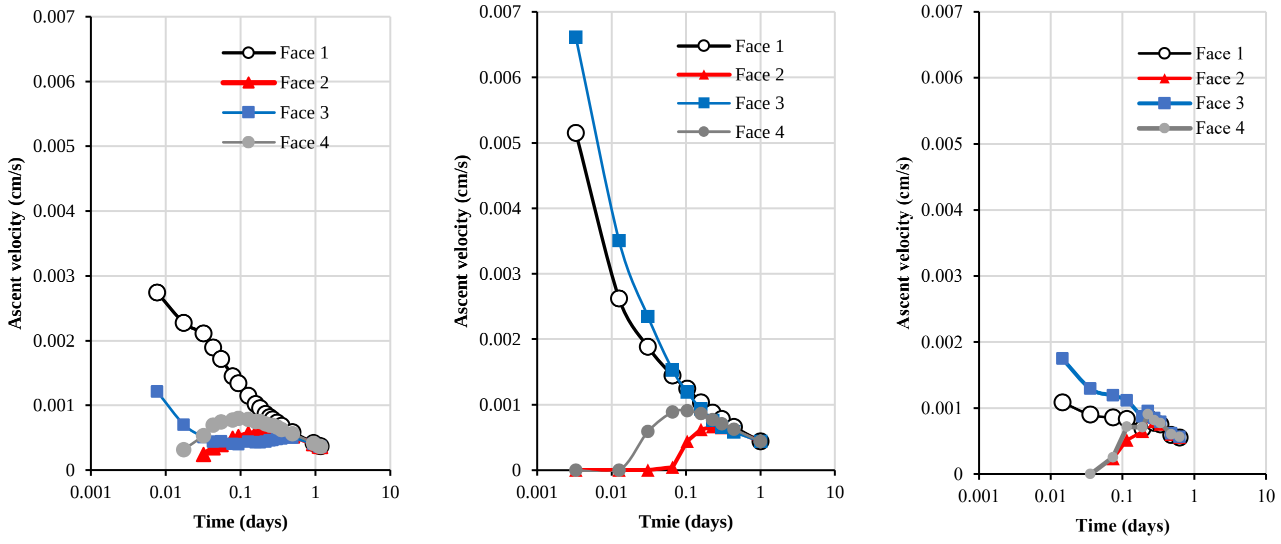
Figure 5 shows the profiles of the three boxes, showing the rise height by time and average saturation by box depth. There was an increase in rising time when the soil was compacted to a higher dry density. This is due to the low permeability of the soil, which increases the suction and retention of water in the voids, as shown in Figure 5b, where it is notorious that the compacted soil in Box B was able to retain more water. In the case of soil saturation, it is observed in Figure 5b that there is a zone with higher saturation after 25 cm height. This zone is approximately 1/3 of the total height as found in sandy soils studied by Baldovino et al. (2017, 2018a, 2018b) and silty soils studied by Izzo et al. (2018).



(a) (b)

Figure 5. (a) Influence of time on rising damp height in boxes A-B-C. (b) Saturation vs. rising damp height in boxes A-B-C

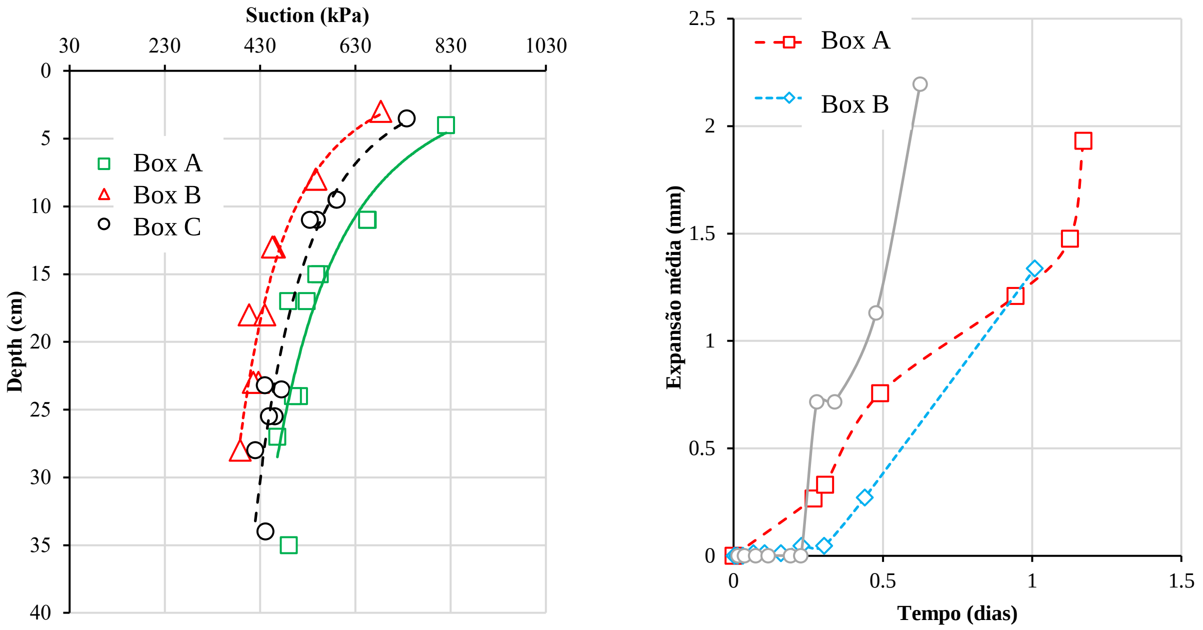
Figure 6 shows the results of the water rising velocity by time in days. On the faces where the air inlet is located (1 and 3), and the wetting front was radial, the velocity started higher relative to the faces where there was no water inlet (2 and 4). The velocity at the inlets and faces 1 and 3 started to decrease until it normalized with faces 2 and 4, as can also be seen in Figures 2-4. At the end of each test on the boxes, the velocity normalized to 0.0003 cm/s, 0.0004 cm/s, and 0.0005 cm/s for boxes A, B, and C.



(a) (b) (c)

Figure 6. Rising damp velocity by time (a) Box A (b) Box B (c) Box C

After completing each test in each box, the previously installed filter papers were removed to measure the matrix suction. Thus, Figure 7a shows the suction values that reached each soil column. The highest suction values were recorded after the 15 cm height. As shown in Figure 5a, Box A, compacted with lower dry density, obtained lower degrees of saturation, while Box C was compacted with a similar density but with 5% water content in the voids, which allowed for higher saturation after 15 cm depth. With this, it was demonstrated that the final suction obtained was correlated with the values of degree of saturation and compaction as reported by Li et al. (2009) and Baldovino et al. (2019b). The highest recorded suctions were from 680 kPa in Box B to 820 kPa in Box A. Figure 7b presents the record of the soil expansion due to water entering the system. After 6 hours of testing, the expansion began to manifest itself in less than 1 mm in all the boxes. Box C showed the most remarkable expansion (2.20 mm) in a short time of 0.6 days when the capillary rise was stopped. On the other hand, Box A and B showed an average expansion of 1.9 mm and 1.3 mm, respectively.



(a) (b)

Figure 7. (a) Matrix suction by depth measured in boxes A-B-C. (b) Average expansion measured due to water ingress in boxes A-B-C

4. CONCLUSION

The proposed reduced model was effective in recording the influence of capillary rise height on soil matric suction values and recording the capillary rise time for any established degree of compaction. The forward advancing wetting method is economical and efficient in measuring the unsaturated hydraulic conductivity for fine-grained soils. Thus, the soil can record high and low hydraulic conductivity and matrix suction values depending on the initial porosity.

A nearly saturated zone was found in the soil profile. Approximately 1/3 of the total height is saturated as reported in previous studies. Material suction recorded higher values when the soil was compacted to a higher dry density. The values varied depending on depth, reaching 600-800 kPa for saturation grades of 90-100%.

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