A new simple image analysis-based technique for tracing the unsaturated soil layer during evaporation

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1. Introduction

Global warming has led many lands to degrade and lose their soil's productive capacity. Optimizing innovative solutions to prevent such environmental disasters requires a thorough understanding and accurate prediction of the water fluxes, especially evaporation that dominates in drylands. However, this has been a great challenge due to the process's complexity. The evaporation process defines the water movement and loss into the atmosphere. It is divided into three stages based on the actual evaporation rate. It was confirmed in the literature that the evaporation rate is influenced by the dominant water transport mechanism within the soil profile, which in turn depends on the unsaturated layer formation and dynamics during drying. In Stage 1, the evaporation is sustained by capillary flow from the drying front to the surface, where the drying front is the region between the saturated and unsaturated zones. At a specific drying front depth, the hydraulic connection with the surface is disrupted, announcing Stage 2 (Lehmann et al., 2008). Consequently, a new vaporization plane is formed below the soil surface, and the evaporation continues by vapor diffusion through the air-dry layer. In contrast, the vaporization plane remains hydraulically connected with the drying front below via capillary-induced liquid flow through the so-called film region (Shokri et al., 2009). With time, the diffusion pathways from the receding vaporization plane become deeper, leading to an insufficient water supply, announcing Stage 3.

Considering the essential role of the unsaturated layer dynamics in the evaporation process, studying its formation and tracing its development is crucial for accurately predicting evaporation rates and water loss. Therefore, a simple yet effective technique involving experimental investigation and image analysis is developed and proposed in the present study. The accuracy and reliability of the newly developed technique in tracing the unsaturated layer during drying are discussed.

2. Materials and drying column testing

A 1-D homogeneous drying soil column test was conducted using K-6 silica sand. The profile's properties are shown in Table 1. The profile was initially fully saturated and compacted, as in Hussary et al. (2022). The experimental setup is shown in Figure 1 (front view). The evaporation was allowed from the top under constant atmospheric conditions, where the temperature was maintained at 27.6±0.5℃, relative humidity at 44.7±0.6%, and wind speed at 2.3±0.2m/s. The column was instrumented with Time Domain Reflectometry (TDRs) installed alongside the column's depth and connected to a data logger to continuously record the column's saturation. All data was recorded at 120-second intervals during testing.

3. Image acquisition and analysis

Table 1: Soil profiles' properties

		K-6
Specific gravity	G_s	2.636
Dry density	ρ_d (g/cm^3)	1.502
Void ratio	e	0.75
Effective particle size	D_{10} (mm)	0.20
Median particle size	D_{50} (mm)	0.33
Uniformity coefficient	C_u	1.74

Several methods were reported in the literature to trace the unsaturated layer during drying. However, they were associated with many limitations, such as difficulty taking high-quality images or using costly tools and other sophisticated techniques. Therefore, a new technique was developed to capture high-quality images during testing, while a series of image analysis operations were used to investigate the unsaturated layer.

The image acquisition setup is shown in Figure 1 (Side view). The testing column side surface was confirmed to be flat, transparent, and well-polished, with minimal scratches to capture the soil exclusively. The profile was saturated using a blue dye (brilliant blue, 0.2 g/L) to enhance the visual contrast between the saturated, unsaturated, and dry layers based on the color intensity. Fully saturated profiles have dark blue color; however, the color starts fading when water evaporates, and dry soil returns to its original color with hints of blue dots. Two reference soil columns, a fully saturated and dry column, were placed next to the primary one (Figure 1 (front view) and Figure 2a). The reference columns were used to calibrate the blue color intensity for fully saturated and dry soil profiles, allowing the detection of these zones in the primary column. The saturated column was compacted and saturated as the primary one, while the dry column was compacted with a dry soil sample previously saturated with blue water. The reference columns were well sealed from all sides during testing to

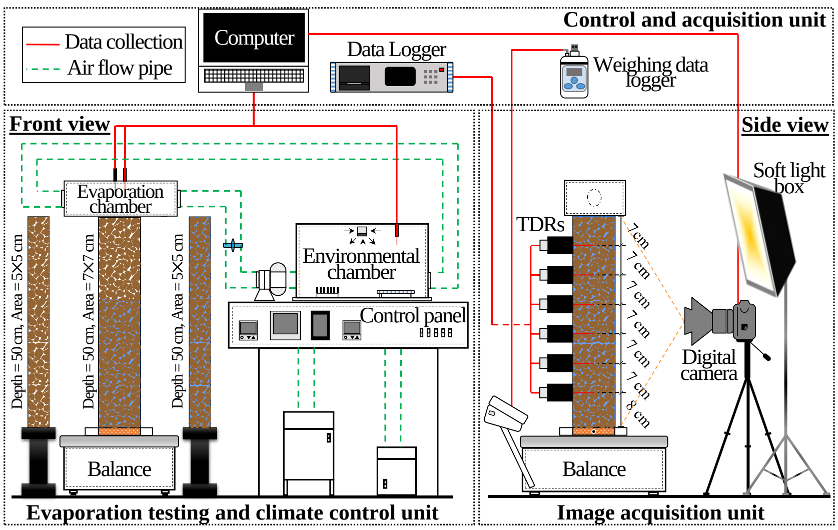

Figure 1: Experimental and image acquisition setup

maintain their saturation and their colors' intensity. A high-resolution digital camera (7952×5304 pixels) connected to a PC was mounted and fixed on a tripod in front of the three columns to allow remote image acquisition. Finally, two soft light boxes were added to the sides to unify the light intensity.

A series of image analysis operations were conducted to detect the drying front and vaporization plane during drying. The RGB (Red, Green, Blue) acquisition images were first converted to HSV (Hue, Saturation, Value) color space. The saturation image, which includes the intensity values from 0 to 1, was extracted. The average intensities of the saturated and dry soil were determined from the reference columns and were then assigned as threshold values corresponding to the saturated and dry zones in the primary column. For the K-6 profile, all values > 0.7 were considered saturated soil and designated white, while the values < 0.1 were considered dry and designated black. Consequently, the grey color, values between 0.7 and 0.1, were considered unsaturated. Based on that, two different intensity images were generated, all black and all white. The images were carefully improved using morphological opening, an image filtering operation based on the neighboring pixels' intensities. The resulting images were layered over the original image to make the zones more visible. Finally, a minimum opening operation was conducted on the final image to avoid any essential data loss while refining the boundaries between the zones (Figure 2b).

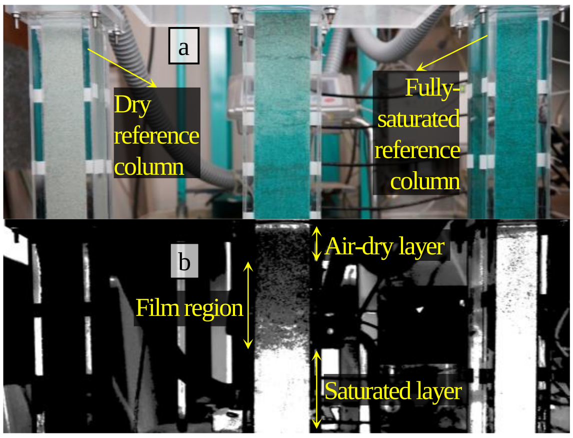

Figure 2: (a) RGB acquisition image
(b) Processed image used for analysis

4. Results and discussion

Figure 3a shows the analyzed images, while Figure 3b delineates the water redistribution profiles determined using the TDRs' readings, while each line indicates the profile's saturation corresponding to each captured image. The information was extracted from the images and confirmed from the saturation profiles. The white connected zone extending from the profile's bottom was considered the saturated layer, corresponding to 100% saturation. The connected black zone extending from the surface was considered the air-dry layer, corresponding to almost residual saturation. The connected grey zone was considered the film region, corresponding to saturation between 100% and residual. Consequently, the drying front was indicated between the white and grey zones, delineated with the red line considering all white patches connected to the saturated zone. The white patches within the grey zone are considered wet isolated clusters and not part of the front. Likewise, the black patches are considered drying clusters, gradually forming drying zones. Finally, the vaporization plane was indicated between the grey and black zones, and it is delineated with the yellow dotted line where the disconnected grey patches are not considered part of it. By definition, the formation of the vaporization plane highlights the onset of Stage 2, which was around Day 6.4 for the K-6 profile. As a result, this high agreement between the images and saturation profiles validates the accuracy and reliability of the proposed technique in tracing the unsaturated soil layer.

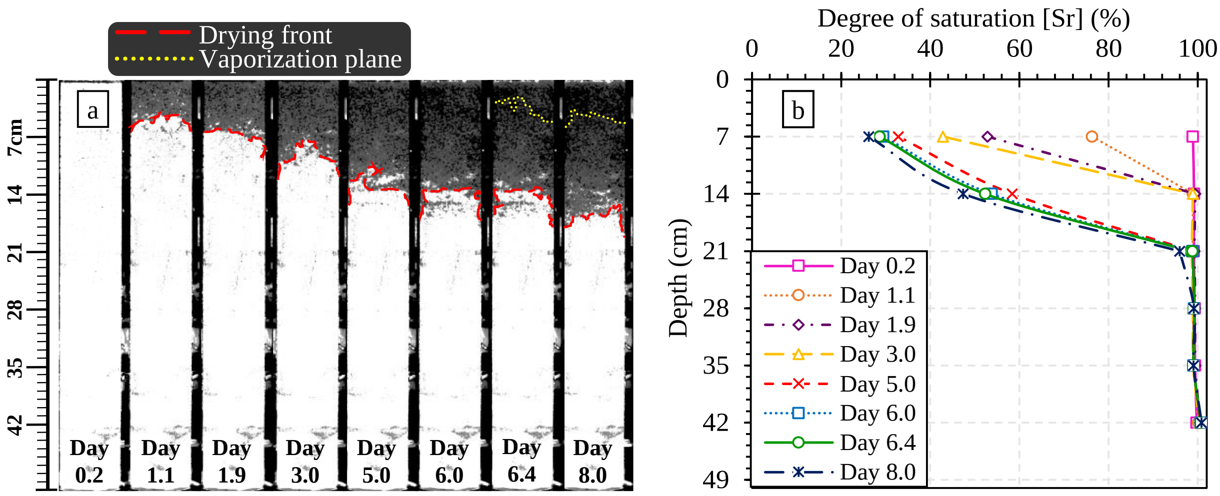

Figure 3: K-6 soil profile (a) Processed images (b) Corresponding water redistribution profiles

5. Conclusion

A new technique based on image analysis was proposed to trace the unsaturated layer during drying. The study's results confirm the accuracy and reliability of the technique, which is currently deployed to detect the unsaturated layer dynamics along with the drying front and the vaporization plane for different soil profiles varying in their pore structure.

References

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