Unsaturated layer dynamics during the evaporation stages in homogeneous sandy soil profiles

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1. Introduction

During the past century, drylands worldwide have been suffering from various changes arising from global warming. The increasing evaporation rates and the rare rainfall events kept many areas highly vulnerable to droughts and desertification. Finding innovative solutions for such environmental problems requires accurate evaluation of the evaporation flux, which is the dominant surface-atmosphere boundary flux in such regions.

The evaporation from bare soil profiles describes the upward movement of water from the soil pores into the atmosphere. The water transport mechanism and the unsaturated layer dynamics during evaporation depend on the boundary between the saturated and the unsaturated layer known as the drying front. Based on that, the process was divided into three stages, Stage 1: the constant rate stage, Stage 2: the falling rate stage, and Stage 3: the residual stage. During Stage 1, water moves from the receding drying front to the surface by capillary flow through liquid-filled pores. Therefore, attaining a relatively high and constant evaporation rate. At a specific drying front depth, the gravitational and viscous forces overcome the capillarity disrupting the hydraulic connectivity with the surface, which marks the onset of Stage 2 (Lehmann et al., 2008). During Stage 2, an air-dry layer is formed within the top of the soil profile underlaid by a film region, a hydraulically connected zone between the drying front and the vaporization plane. Thus, water moves from the drying front (bottom of the film region) to the vaporization plane (bottom of the air-dry layer) through water-filled pores by capillary flow and continues by vapor diffusion through the air-dry layer.

The drying front at the end of Stage 1 and the thickness of the unsaturated layer can be mathematically determined following the literature (Lehmann et al., 2008). However, the dynamics of the complex unsaturated layer formed during Stage 2 are still ambiguous. Due to the significance of Stage 2 in drylands (Hussary et al., 2021), extensive research is being done to understand its mechanisms. In this paper, new insights regarding the unsaturated layer, the drying front, and the vaporization plane are discussed for homogeneous sandy soil profiles during Stage 1 and Stage 2 of evaporation.

2. Methodology and materials

One-dimensional homogeneous drying soil column tests were conducted for initially fully saturated soil profiles. The evaporation was allowed from the soil's top, and the evaporative demand was unified using the climate control apparatus (Teng et al., 2014), as shown in Figure 1. The temperature was maintained at 27.2±1.2℃, relative humidity at 45.6±1.7%, and wind speed at 1.9±0.23 m/s. During testing, the column was set on a digital balance to continuously measure the water loss and directly calculate the actual evaporation rate (AE). The Time Domain Reflectometry probes (TDRs) were attached alongside the soil column to record the water content and delineate the water redistribution profile during drying. Testing was shut down once the AE converged to a low and constant value, announcing Stage 3.

Three different textures of silica sand, K-7, K-5, and K-4, were used for testing. Their particle size distribution curves are shown in Figure 2. The soil columns were prepared using the dry compaction method at dry density (ρ_d), corresponding to 80% relative density. A summary of the samples' physical properties is shown in Table 1.

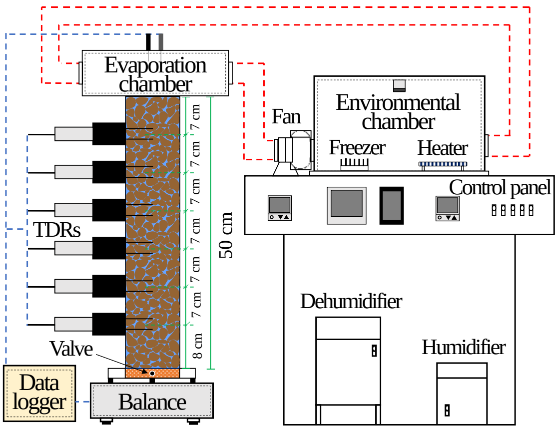

Figure 1: Experimental setup (Schematic)

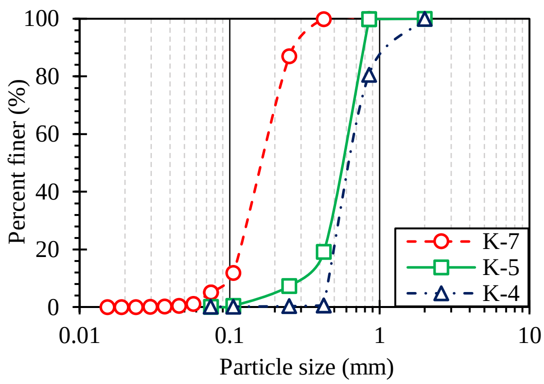

Figure 2: Particle size distribution curves

Table 1: Soil physical properties

		K-7	K-5	K-4
Specific gravity, Gs		2.65	2.65	2.65
Dry density, ρ_d	(g/cm^3)	1.48	1.50	1.51
Void ratio, e		0.789	0.763	0.754
Effective size, D_{10}	(mm)	0.10	0.31	0.47
Median diameter, D_{50}	(mm)	0.16	0.57	0.64
Uniformity coefficient, U_c		1.78	2	1.46

3. Results and discussion

Figure 3 shows the normalized AE curves of the tested profiles. The normalized AE is found by dividing the AE at any time during drying by the AE during Stage 1 (AE_i). The stages of evaporation are identified from the curves. The highest and the lowest AE indicates Stage 1 and Stage 3, respectively. Stage 2, located between them, is characterized by the sudden and continuous drop in the AE. The normalized AE reduction slope (ΔAE) during Stage 2 was found as an average slope from the onset until the end of Stage 2 as indicated on the curves in Figure 3. ΔAE varied between the soil profiles, with the K-7 profile having the gentlest slope of 2.4%/day, meaning that the change in AE was lower with time compared to K-5 (8.7%/day) and K-4 (10.3%/day). This behavior is believed to be related to the microscale development of the unsaturated layer during Stage 2.

The unsaturated layer was traced using the water redistribution profiles as delineated in Figure 4. Different times during drying, shown in the legend, were adopted considering the inflection points on the AE curve. It was confirmed that the profiles were fully saturated at the onset of Stage 1. Once the water starts evaporating, the drying front (the saturated-unsaturated boundary) is formed. The unsaturated layer thickness at the end of Stage 1 is indicated with the shadowed area in Figure 4. It was observed that at the end of Stage 2, the drying front persisted at the same depth, maintaining the same thickness of the unsaturated layer, yet a significant reduction in its

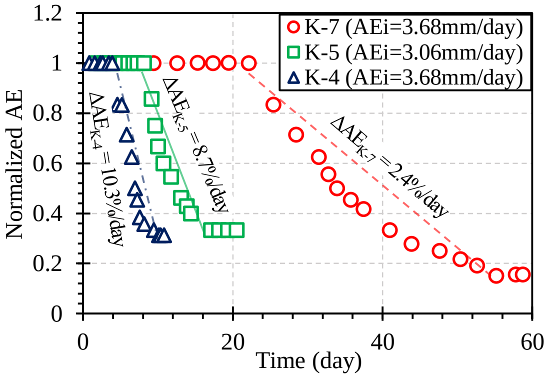

Figure 3: Normalized actual evaporation curves

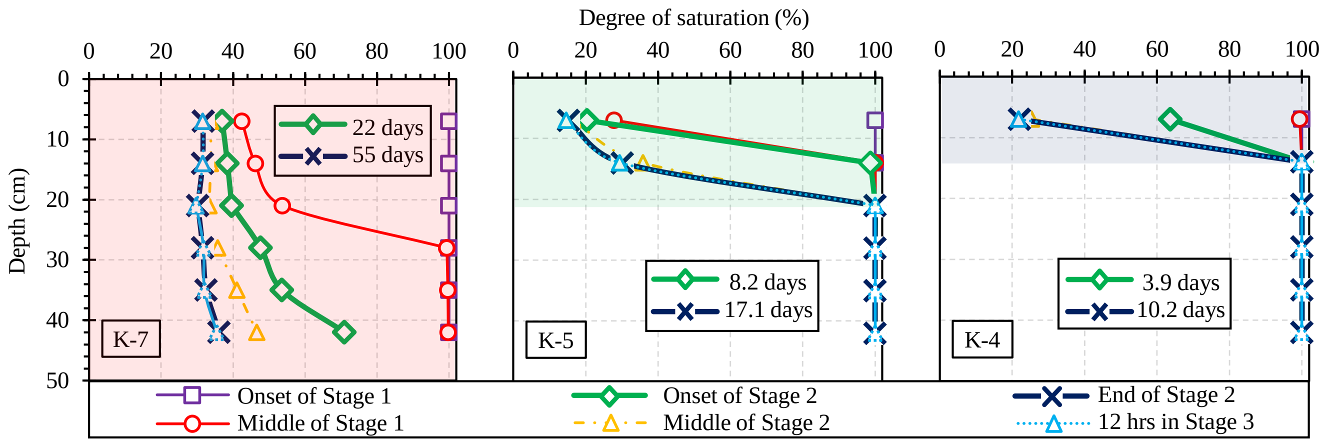

Figure 4: Water redistribution profiles

degree of saturation was noticed. Therefore, it can be concluded that during Stage 2, water gets lost from the remaining liquid-filled pores within the film region rather than the pores at the drying front.

In contrast, it was found that the air-dry layer thickness changed during Stage 2 in all the profiles. The vaporization plane (bottom of the air-dry layer) was traced at the residual degree of saturation attained at the top of the soil profiles in Figure 4. Using the onset, middle, and end of Stage 2 saturation profiles, the receding rate of the vaporization plane during Stage 2 was found to be around 0.24, 0.33, and 0.72 mm/day for the K-7, K-5, and K-4 profiles, respectively. Assuming the validity of Fick's law under steady-state conditions, the rate of change in the reciprocal of the diffusion distance, here the vaporization plane, is directly proportional to the diffusion rate change. The experimental data were plotted in Figure 5 for all the tested profiles. The results agreed well with Fick's law, where a lower receding rate of the vaporization plane (ΔL) corresponds to a lower normalized AE reduction slope (ΔAE), resulting in a gentler AE slope during Stage 2. The good correlation between the change in the AE and the vaporization plane receding rate during Stage 2 confirms that the vapor diffusion is dominant during this stage. Moreover, the result assures that the evaporation rate mainly depends on the diffusion distance in homogenous sandy soil profiles under unified atmospheric conditions.

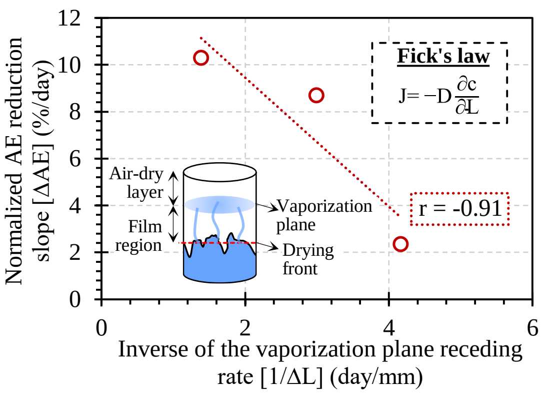

Figure 5: Relationship between the change in the normalized actual evaporation rate and the vaporization plane during Stage 2

4. Conclusion

It can be concluded that in homogenous sandy soil profiles, the drying front depth persists at the same depth during Stage 1 and Stage 2 of evaporation. However, the vaporization plane during Stage 2 recedes with time, causing an increase in the air-dry layer thickness. Additionally, it was confirmed that under unified atmospheric conditions, the vapor diffusion is the primary controlling mechanism of the evaporation rate during Stage 2, where the rate is a function of the diffusion distance, reflecting the vaporization plane depth.

References

1. Hussary, J., Alowaisy, A., Yasufuku, N., Ishikura, R. (2021). Significance of Stage 2 of evaporation in homogeneous sandy soil profiles. The 56th Annual Meeting of the Japan National Conference on Geotechnical Engineering. pp. 12-3-2-08.
2. Lehmann, P., Assouline, S., & Or, D. (2008). Characteristic lengths affecting evaporative drying of porous media. Physical Review E, 77(5), 056309.
3. Teng, J., Yasufuku, N., Liu, Q., & Liu, S. (2014). Experimental evaluation and parameterization of evaporation from soil surface. Natural hazards, 73(3), 1405-1418.