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Unsaturated soil variables response within the vadose zone at the UNIWA field station

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ABSTRACT: The unsaturated soil variables response, saturation degree, water content and suction, in Mediterranean to continental climates within the vadose zone vary between the extremes of excessive evaporation–dry season and flooding–wet season, in which soil suction takes the lowest value, zero, at the near surface soil. The University of West Attica field station at the backyard of Soil Mechanics Laboratory consists of two monitoring pits. Pit 1 constructed in July 2023 includes three porous block sensors and tensiometers for soil suction measurement at 0.45m, 0.75m, and 1.40m depths and one volumetric water content sensor at 0.45m. Pit 2 constructed in April 2025 is 3 m away from pit 1 and includes two porous block sensors at 0.45m and 0.80m and one volumetric water content sensor at 0.80m. The sensors have responded in various rainfall events from extreme rainfall to dry. The patterns show that at cumulative rainfall of 100mm/day suction dropped to zero at 0.45 and 0.75m depths, at 50mm/day suction dropped to zero at 0.45m, while for lower rainfall intensities soil suction is either unaffected or only slightly affected. The paper presents collected data and the experimentally determined physical properties and the WRC, providing a coherent thermohydromechanical (THM) field response information for creating behavioural models and performing THM analysis of real response in all possible weather conditions and to include trees canopy and distance from station effect.

Keywords: unsaturated soil variables; vadose zone; suction; volumetric water; field monitoring

1 INTRODUCTION

The dynamics of unsaturated soil variables is critical for various fields, including geotechnical engineering, hydrology, agriculture, and environmental engineering. Suction and water content variables response and variation with depth and time is a key in water infiltration, plant growth, and the mechanical response of soil. Their field monitoring is a challenging task due to complex interactions of soil texture, moisture, and atmospheric conditions, but still not widespread and systematic enough both in research and engineering practice.

This article presents the continuously evolving unsaturated soil field station by the SOMELAB (Soil Mechanics Laboratory) team at University of West Attica (UNIWA) in cooperation with EDAFOS Engineering Consultants S.A. as industrial partner, first presented by Belokas et al (2025). The station, located at the backyard of SOMELAB, operates seamlessly from July 2023 (Phase 1 – Pit 1), while it has been upgraded in April 2025 and September 2025 (Phase 2 – Pits 1 and 2). The article also presents typical responses during these last two years for different rainfall characteristics, including Medicane Daniel (Belokas et al, 2025) of September 2023. Moreover, it examines how the data align with initial expectations and outlines next steps in refining the monitoring system to better understand the unsaturated soil variables and their variation over time. The aim through this research is to enhance the understanding of the spatial and temporal variability of unsaturated soil conditions, ultimately contributing to more accurate models for hydrological studies and the mechanical behaviour of unsaturated soil. This article includes responses from Phase 1.

2 SOIL PROFILE

Soil sampling was performed down to 1.40m. Phase 1 sampling in July 2023 did not allow for intact sampling due to extremely low water content. Phase 2 in April 2025 allowed better quality sampling.

2.1 Soil Classification

The soil profile is presented in Figure 1, which includes three distinct layers, thicknesses may vary locally. Phase 1 results formed a range of classification tests that are presented in Table 1, while the detailed grain size distribution is found in Belokas et al (2025).

Key observations include (see also Table 1):

- Depth 0.00-0.10m: SM (Silty Sand), with low clay content (5.5%) and high silt content (40.1%). It is topsoil with lots of dried roots and vegetation remnants. Liquid limit (w_L) is relatively high at 42.7%, indicating that the soil could behave more like clay.

- Depth 0.40-0.50m: Classified as ML-CL (Silty Clay), with high silt and clay content (69.8%). No other specific tests were conducted for this depth.
- Depth 0.50-0.75m: Classified as CL (Clay) with 16.0% clay and 69.5% silt. Plasticity index (I_P) is 16.7%, and liquid limit (w_L) is 37.4%, indicating moderately plastic behaviour.

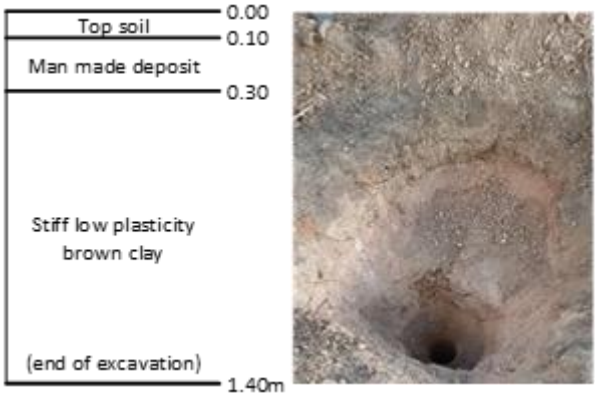


Figure 1. Soil profile of the station (Belokas et al, 2025)

Table 1. Index properties of the soil profile from Phase 1 (Belokas et al, 2025)

Soil Depth (m)	Clay Fraction (%)	Fines (%)	w_L (%)	I_P (%)	G_s	USCS
0.00-0.10	5.5	45.7	42.7	13.1	2.52	SM
0.10-0.25	-	14.5	N.P.	N.P.	-	SM
0.40-0.50	-	69.8	-	-	-	ML-CL
0.50-0.75	16.0	85.5	37.4	16.7	2.70	CL

2.2 WRC - Water Retention Curve

WRC was determined by the axis translation technique in a Soilmoisture Equipment Corp. pressure extractor with 1500 kPa air-entry value porous ceramic disks for matric suction control. Tests were performed on the undisturbed samples taken from:

a) Manmade deposit (0.10 to 0.20m depth, Phase 1, Figure 2a), which was prepared in the form of slurry because the specimen crumbled at the moment it was removed from the corer (an initial water content of 15% using deaired, deionised water).

b) UNIWA Clay (0.45 to 0.80m depth, Phase 2, Figure 2b), which was prepared in the form of a slurry with initial water content of 1.25×w_L, then consolidated one-dimensionally to 125 kPa of vertical stress, unloaded and subjected to drying in the pore pressure extractor.

Additionally to the axis translation method, the salt solutions total suction control method was used to cover a greater range of suction values.

The Van Genuchten (1980) empirical equation was used to fit the experimental data and simulate the soil water retention curve of the manmade deposit (Eq. 1 with normalised water content w/w_o used instead of degree of saturation S_r) and the UNIWA clay (in the original form of the equation, Eq. 2). This fitting includes three parameters. Parameter *a* relates to the value of the air entry pressure, i.e., the basic or initial pressure required for air to appear in the material. Parameter *n* relates to the slope of the simulation curve between the air entry pressure and the residual moisture content. In other words, the value of *n* affects the linearity of the curve that links pore pressure and moisture or degree of saturation. If the value of *n* is high, the curve will have a steeper slope, while if it is low, the curve will be more gradual. Parameter *m* relates to the shape of the simulation curve near the suction value, where the material approaches residual moisture content/degree of saturation. The value of m influences the system's behaviour at this stage, determining how sharp or smooth the curve is in this region. The parameters and the estimated air entry pressure are presented in Table 2 and the simulated WRC in Figure 2.

$$\frac{w}{w_o} = \frac{1}{[1+(as)^n]^m} \quad (1)$$

$$S_r = \frac{1}{[1+(as)^n]^m} \quad (2)$$

Table 2. WRC Equation 1 fitted constants and estimated air entry pressure

Soil Depth (m)	WRC Equation 1 constants			air entry pressure
	a	*n*	*m*	(kPa)
0.10-0.25	3	0.08	0.15	12.5
0.50-0.75	0.0011	3.1	0.09	300-400

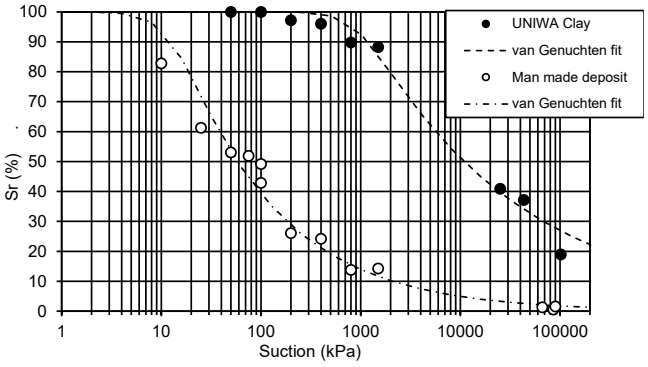


Figure 2. WRC graph data in terms of degree of saturation versus suction and simulated curve: a) for the manmade deposit (Belokas et al, 2025) and b) for the UNIWA Clay

3 THE SOMELAB – UNIWA STATION

The unsaturated soil variables field station at UNIWA is in the backyard of SOMELAB, ensuring easy access for continuous data recording and instrumentation maintenance. It serves both research purposes and the opportunity to introduce students to the principles of un-

saturated soil mechanics (Belokas et al, 2025). Equipment was installed in two phases at excavated pits and inside intact soil down to 1.40 m, i.e. within the shallow vadose zone (rhizosphere). All pits were backfilled with the same material. The location, under the trees canopy, was selected to ensure low interference with trees' roots, which would further complicate excavation and sensors' installation and response. Its current setup (Phase 2 from April 2025) is shown in Figure 3.

The equipment specifications are:

1. **Suction Ceramic Stone Sensors** (TEROS 21, PS1,2,3 in Phase 1, PS4,5 in Phase 2) (porous block sensors, Phase 1): They measure soil suction (range 0 to 100 MPa, res. 0.1 kPa, accur. ±10% of reading + 2 kPa from 9 to 100 kPa) and temperature (range: -40.00 to 60.00 °C, res. 0.10 °C, accur. ±1.00 °C). For installation see Belokas et al (2025). They are suitable for suctions encountered in Greece and have been used in other stations in Greece and Cyprus (Bardanis, 2015; Bardanis & Loukidis; 2020 Lazarou et al, 2019; Bardanis, 2016; Bardanis & Kokoviadis, 2023).

2. **Tensiometers** (TM1,2,3, Phase 1): They measure suction (range from 0 to -90 kPa) and are installed with their ceramic tips at the depths of PS1,2,3 sensors. Due to their narrow range, which makes them not operative for most of the days on a yearly basis, it is intended to use them in future wetting field tests. Additionally, the tensiometers will serve as a calibration tool for the TEROS 21 sensors over the range of low suction values.

3. **Volumetric Water Content and Temperature Sensor** (TEROS 11, MT1 Phase 1 and TEROS 10, MT2 Phase 2): TEROS 11 measures three key soil variables: Volumetric Water Content (range 0 to 100%, res. 0.1% and accur. ±3%), Temperature (range -40 to +50°C, res. 0.1°C and accur. ±0.5°C), Electrical Conductivity (range 0 to 20 dS/m, res. 0.001 dS/m and accur. ±5 to 10 dS/m). TEROS 10 measures only Volumetric Water Content.

All sensors, except tensiometers, are connected to two Zentra ZL6 Data Loggers that record every 15 minutes. Recordings every 5 minutes will be utilized for greater accuracy during future wetting tests. This system enables continuous monitoring and data collection, providing valuable insights into the soil's response to varying environmental conditions over time. The redundant sensor channels in the loggers will be used for additional future sensors to extend station capabilities or as back-up for malfunctioning channel circuitry.

4 RESPONSE OF UNIWA STATION

During a period of 2 years, the station faced the Medicane Daniel (see Belokas et al 2025) and other less intense rainfall incidents (Figure 4). Interestingly, the following three qualitative responses have been identified, depending on the rainfall intensity – distribution – frequency characteristics:

- 6/9/23 – 109 mm single rainfall, preceded by 28 mm in 3 months: suction dropped from 1200 kPa to zero at 0.45m, within 30 min. At 0.75m it zeroed at 6 hours delay.
- 26/2/24 – 40 mm & 1/3/24 – 20.2mm (two events), preceded by 96.4 mm in 3 months: suction dropped from 485 kPa to 465 kPa (within 3 days, after 1st event) and then to 24 kPa (within 2 days, after 2nd event) at 0.45m. Insignificant response at 0.75m.

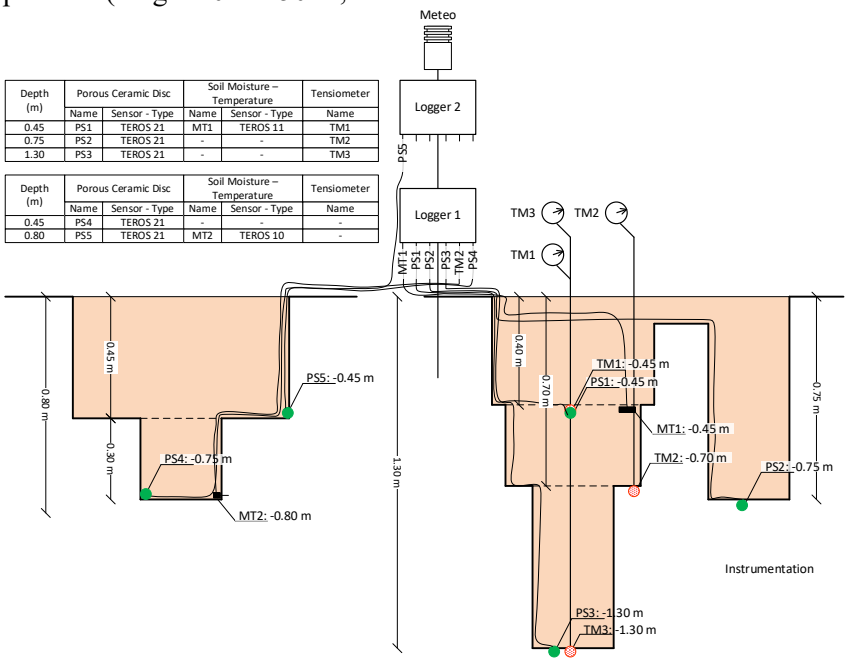


Figure 3. The current SOMELAB – UNIWA field station setup (Phase 2 from April 2025, results presented are from Phase 1)

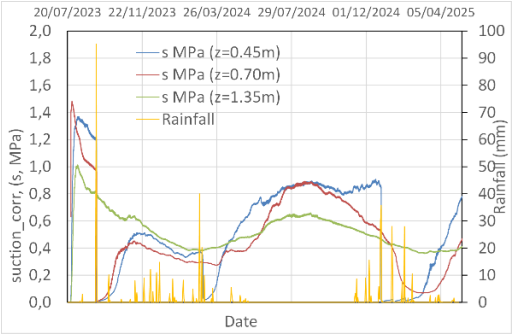


Figure 4. Suction response at the three depths (Phase 1)

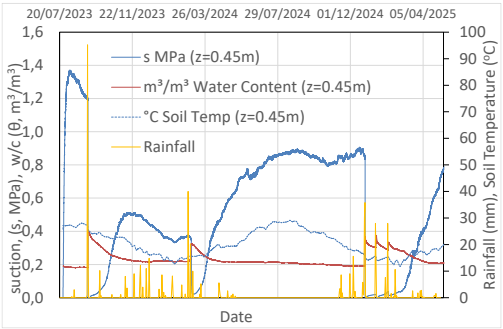


Figure 5. Sensors' response at 0.45 m depth (Phase 1)

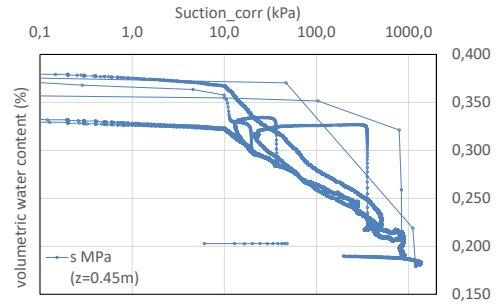


Figure 6. Volumetric Water Content vs suction response at 0.45 m depth (Phase 1)

• 22/12/24 to 27/12/24 – 74.2 mm (cumulative), preceded by 47.0 mm in 3 months: suction drop from 835 kPa to zero at 0.45m, within 30 min. Suction then increased to about 20 kPa. A subsequent event from 13 to 14/1/25 – 42.2 mm dropped suction to zero again. In both cases suction remained zero for about 3 days. A less intense event on 3/2/25 – 35.6 mm dropped suction to -13.5 (within 2 days). Next, suction didn't rise above 40 kPa by 26/2/25 and above 100kPa by 7/3/25. At 0.75 m depth there was a delayed response without oscillations affected by the cumulative rainfall, as suction dropped to about 52 kPa in 13/4/25, which implies downwards infiltration for 2 months after the last major event.

The volumetric water content sensor responded faster than suction sensor (Figure 5), which results in a non-typical response under wetting (Figure 6), erroneous in terms of a field soil-water retention curve. The comparison of laboratory WRCs with field response is not straightforward, as they correspond to different materials. Pit 2 field sensors will provide a direct comparison.

5 CONCLUSIONS

The response of the unsaturated soil variables at the SOMELAB – UNIWA field station highlights the complex infiltration processes that develop in – situ. Down to about 0.45 m they are closely tied with the combined rainfall IDF characteristics, of both short (a few days) and intermediate term (a few months before the rainfall incident). Down to about 0.70 m there was a delayed response, from 6 hours for the high intensity event to 2 months of more evenly distributed lower intensity events. At about 1.35 m no oscillations occurred, apart from typical seasonal fluctuation. These observations do not consider the evapotranspiration as part of the complete thermohydromechanical response.

Next research steps include continuous monitoring of pits 1 and 2 complete characterization of UNIWA Clay including unsaturated soils constitutive properties, systematic description of field response through mathematical models, and the numerical modelling, along with a fully controlled wetting test. In addition, the local effect of the trees canopy as well as the influence of the trees distance from the station will be examined.

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