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Some examples and lessons from long-term field measurements of suction in Greece

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Abstract. The occurrence of unsaturated soils in the field has been well documented worldwide by measurements of the degree of saturation on samples taken during geotechnical investigations. On the other hand, the suction of unsaturated soils in the field, especially as part of long-term measurements, is documented very rarely and references on the subject are very few and for very few places around the world. The scarceness of this kind of measurements denies researchers perception of the anticipated suction and its possible loss, or retention, as a result of climatic conditions, especially in countries with warm temperate climate. Suction measurements from temporary and permanent stations in Greece and Cyprus have been presented in the past showing that considerably high values of suction can develop and be maintained even during wet periods. This paper focuses on examples and lesson learned from stations in Greece, especially magnitude and change of suction with time, as well as longevity of stations and associated problems.

1 Introduction

Common engineering experience in Greece with soils especially during summer is that they are dry, leading to an overall better engineering performance, be that slope stability and strength in general or lower deformation under loading. The climate of Greece is Mediterranean in the islands and close to the seashore, transitional between continental and Mediterranean in the northern parts of the country, Alpine Mediterranean in the large mountain ranges like Pindus and Rhodope and Mediterranean with some aspects of maritime climate along the western seaside areas of the country. A stricter classification, for instance according to the Köppen–Geiger climate classification system [1] is Csa: hot- dry-summer Mediterranean Climate [2]. The effect of these climatic conditions is that ground formations near the surface are often very dry with the expected consequences on their behaviour, consistent with common engineering experience: strength increases, compressibility decreases, micro-permeability decreases, fissures and cracks appear in fine-grained soils causing macro-permeability to increase close to the surface, and all these are heavily affected if abundance of water appears for any reason. Common engineering experience related to this behaviour relates mostly to the increase of strength as open cuts will stand for a long time without collapsing, piles of materials will stand at angles much higher than the angle of repose, large loads will be transferred to the ground without failures, swelling will take place, in areas where expansive soil formations outcrop. This observed behaviour is perceived by the engineering community as a 'dry' state in many parts of Greece that can enhance engineering behaviour of soils. The question however remains: "how dry is dry?" Despite many measurements of water content, this property alone does not suffice to describe effectively how dry the soil really is and how its engineering behaviour will be affected. Seasonal changes of water content also fail to indicate whether the soil became fully saturated or not. A better understanding is obtained if suction is monitored. These measurements however are very few and for very few places around the world. Data from a small number of stations both in Greece and in Cyprus have already been published [3, 4, 5, 6, 7] exhibiting that suction values can be very high, can be maintained even during wet seasons and that sensors used must be able to maintain high values of suction for a very long time.

This paper presents some more long-term measurements from older and new stations installed. The measurements come from various locations in Greece and include measurements of both soil suction and volumetric water content allowing a better understanding of both "how dry is dry" or perhaps not, and perhaps an even more important question for the transition of unsaturated soil mechanics to unsaturated soils engineering: "how long will it remain dry". Emphasis is given on measurements extending both in dry and wet seasons (as they indicate that soil suction is not easily lost during rainy seasons), temperature corrections for the sensors used to measure suction [4, 7, 8] and problems associated with longevity of stations and other conditions that may appear. The results presented in the paper are by no means typical or representative of hydraulic conditions in the vadose zone throughout Greece. Still they constitute evidence of the range of soil suction that should be expected, the

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possibility of soil suction being lost or not during winter and the risks involved if it is indeed lost, given the measured values of soil suction. The suction values measured also indicate the kind of sensors that should be used in regions with similar climatic conditions and the range of suction that should be targeted by research into the development of sensors. Increasing overall awareness for the need for long-term suction measurements in the field is also always a primary scope in order to facilitate transition of “unsaturated soil mechanics” to “unsaturated soils engineering”.

2 Sensors used, available stations and an attempt for their classification

Early work in 2013 focused on the use of various types of sensors installed at shallow depth in order to compare values of suction and volumetric water content that develop during summer in Greece [3]. Since then, stations have been installed in Nicosia, Cyprus, in order to monitor suction and volumetric water content in the expansive Nicosia Marl [4, 5, 6, 7, 9] and in various locations in Greece in an attempt to create a network of unsaturated soils’ monitoring stations in the country. A collective presentation of measurements at these stations has been presented at a special purpose event in Greece [4] and again at previous conferences [5, 6] and an invited lecture [7]. This paper presents an update of some of these measurements and focuses on new lessons learnt since last report on the network in Greece. The properties of soil at the installation depths at the stations are presented in Table 1 and the sensors installed with their depths in Table 2.

As the range of stations increases, a need for their classification for unsaturated soils engineering purposes emerges. At this stage and with the experience gathered so far, a classification may be proposed as follows:

- Shallow depth stations: Stations with sensors at depths affected by precipitation at the surface within a matter of minutes to hours. Experience so far indicates that max depth for this category is in the order of 0.50m.
- Medium depth stations: Stations with sensors at depths not affected readily by precipitation at the surface. Experience so far indicates that the time lag may range from several days to months and the associated depth is larger than 0.50m down to 3-4m.
- Large depth stations: Stations with sensors installed at depths where no time lag with climatic conditions at the ground surface is readily identified. Depths of sensors at these stations in excess of 4m.

The depths mentioned in this classification are by no means strict and will probably be updated as more stations become available. What should be the guide is the magnitude of the time lag between climatic conditions at the ground surface: minutes to hours, days to months, not readily identifiable time lag. This means that depth classifying stations is a function soil type. Currently four large depth stations have been installed in Greece but not with sufficient amount of data to allow presentation yet. Data from selected stations are presented in this paper; namely Acropolis, Bassales and Polyrracho. It is noted, that at this point of the research, established methods of suction sensor readings corrections have been introduced to cope with problems associated with temperature changes [8]. Temperature effects are a problem observed frequently [4, 7, 8]. Increasing temperature causes recorded suction values by porous block sensors to decrease from those at a

Table 1. Properties of soils at suction monitoring stations.

Station	w_L (%)	I_p (%)	% Passing No 200	USCS
Artemis, Attica (NIS)	NP		32-33	SM
Maritsa, Rhodes island, SE Aegean (TEM)	33-35	9-11	32-35	SM
Bassales, Skiros island, N Aegean (IS)	41-50	21-24	53-78	ML-CL
Polyrracho, Kozani, Western Macedonia (IS)	50-120	30-80	95-100	CH / OH
Acropolis, Athens (IS)	20-22	5-6	19-21	GM
Corinth Canal, Corinth (IS)	A total of 4 stations (3 IS, 1 NIS), with soil being low plasticity silts and silty sands			

* NIS: not in service at time of publication, TEM: a temporary station, IS: in service at time of publication.

Table 2. Sensors and installation depths at suction monitoring stations (all sensors are frequency domain reflectometry type).

Station	Suction sensors	Vol. water content sensors	Depth
Artemis, Attica (NIS)	Meter TEROS21	Meter TEROS10 & Decagon GS3	0.15 & 0.30m
Maritsa, Rhodes island, SE Aegean (TEM)	Decagon MPS2	Decagon GS3	0.30m
Bassales, Skiros island, N Aegean (IS)	Decagon MPS2	Meter TEROS10 & Decagon GS3	0.60, 1.10 & 1.70m
Polyrracho, Kozani, Western Macedonia (IS)	Meter TEROS21	Meter TEROS10	0.55, 1.20 & 2.20m
Acropolis, Athens (IS)	Decagon MPS6	Decagon GS3	0.80 & 2.00m
Corinth Canal, Corinth (IS)	A total of 4 stations (3 IS, 1 NIS), with Meter TEROS21 & TEROS12, at depths between 0.5 and 7.0m (depths > 4m in boreholes)		

reference temperature of 22 °C and decreasing temperature causes them to increase. Good thermal insulation ensures better results but unfortunately does not alleviate the problem fully, making the use of corrections proposed in the literature [8] necessary in order to obtain a clear picture of changes taking place.

3 Selected stations

3.1 Acropolis station, Athens

The Acropolis of Athens constitutes one of the most emblematic monuments of Ancient Greece. The hill is surrounded by ancient circuit walls retaining backfill of considerable height (locally up to 15m). The backfill is a silty sandy gravel with traces of clay exhibiting very small plasticity (w_L=20-22%, I_p=5-6%) medium dense to very dense (e=0.45-0.50). An extensive geotechnical investigation was performed in 2015 consisting of excavation pits (being a combination of archaeological and geotechnical investigation) that allowed retrieval of samples and lightweight dynamic cone penetration tests. In one of the excavated pits, two couples of suction and volumetric water content sensors were installed at 0.80 and 2.00m depth (Table 2) and connected to an automatic logger for continuous measurements recording. Automatic logging started in February 2016 and continuous to this day on the suction sensors. It is the longest-running suction measurement station for geotechnical engineering purposes in Greece and has measurements over more than 7 years despite gaps

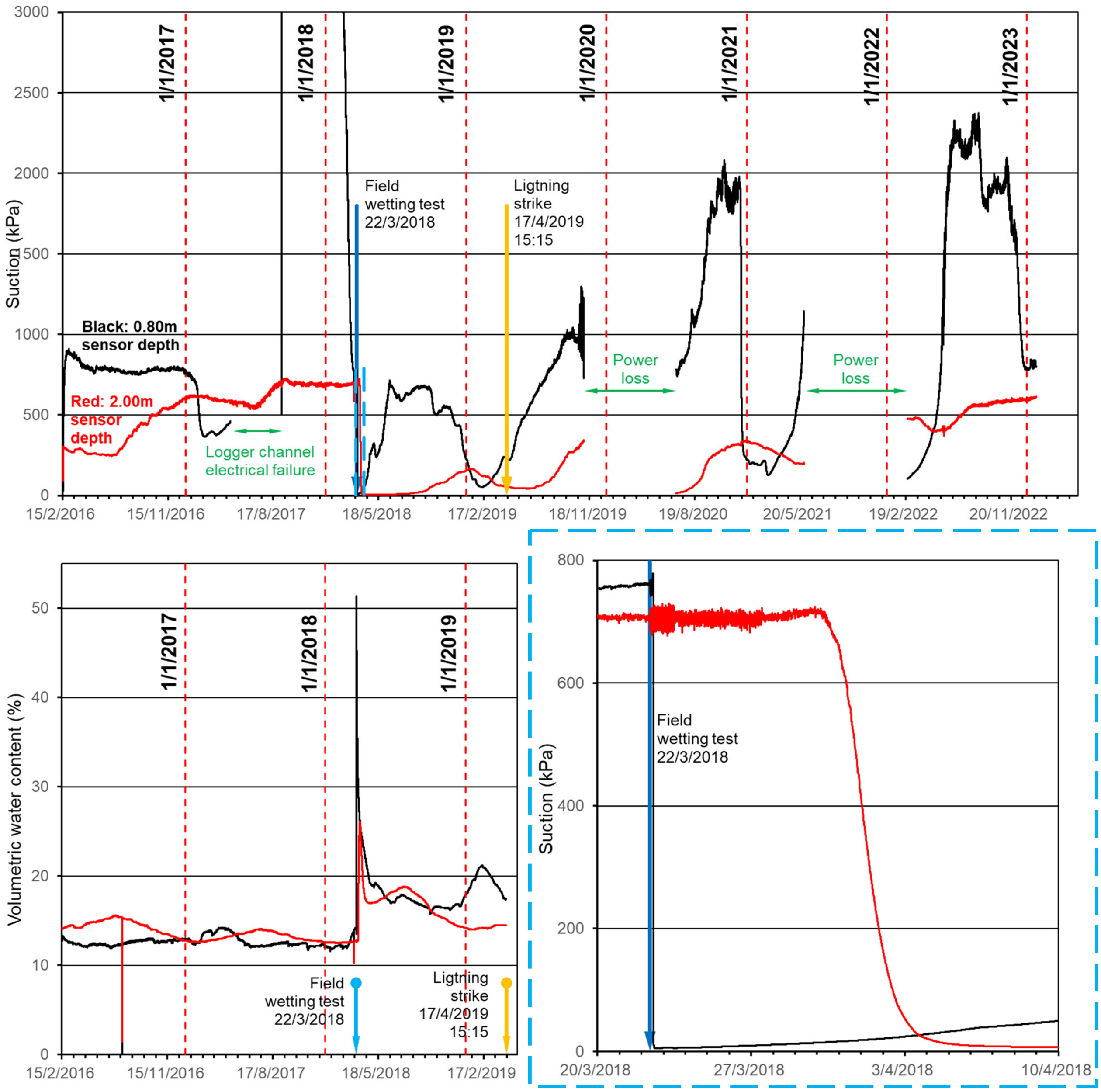

Fig. 1. Acropolis station: a) Suction evolution with time. Black solid lines correspond to 0.80m of depth and red solid lines to 2.00m of depth. Dashed light blue rectangle indicates detail in Fig. 1c. b) Volumetric water content evolution with time until the lightning strike of April the 17th 2019 when the sensors failed. c) Detail of suction evolution with time little before until 19 days after the wetting test of March the 22nd 2018.

Fig. 2. The wetting test of March the 22nd 2018 at the Acropolis station.

showcasing practically all possible problems associated with long-running monitoring schemes with continuous measurements:

- Electrical failures. Modern field sensors and loggers have come a long way and are generally fairly robust instruments, especially regarding their electrical parts. Still electrical failures are and will be a possibility and this is what happened in one of the logger channels. Abundance of channels is something that should generally be incorporated in the design of monitoring schemes (although it increases the cost) as in this case that it allowed simply changing channel for the particular sensor on the channel that failed electrically.
- Contractual problems. A smooth contractual procedure ensuring continuous involvement of specialised personnel guarantees maintenance of stations (cleaning, changes of batteries etc). Gaps in contracts often leave stations without basic maintenance that may result in loss of data. On the other hand, very long-running monitoring schemes may outlast contracts initially scheduled for a limited time on the basis of anticipated data gathering duration or budget restrictions.
- Natural phenomena. The Acropolis station "survived" the April the 17th 2019 lightning strike north-east of the Erechtheion. Although not something common, especially in Athens, a lightning did actually strike and led to the electrical failure of the volumetric water content sensors installed in the ground, despite the presence of lightning rods. Suction measuring sensors and the logger itself survived electrical loading of the ground during the strike and continue to take measurements to this day.

These problems taken into account, the Acropolis station with its 7 year long-running measurements of suction offers perhaps the most important information from the stations installed so far. First it is affected by the microclimate of Athens, which similarly affects practically half of the economic and engineering activities in Greece due to the size and population concentration of its capital, Athens. Second, it records suction evolution in a relatively free draining material, that is a material that normally would not be expected to be able to develop and maintain high values of suction. Still, as data show in Fig. 1a, suction can indeed be considerably high in this material and on top of that it can be maintained for a very long time. Suction remained very high at both depths during the wet seasons of 2016-2017 and 2017-2018 (400-450mm of cumulative rainfall with some very high intensity incidents) and it took the very rainy wet season of 2018-2019 (580mm of cumulative rainfall) for suction values to decrease to 30-40 kPa. Following that, for the wet seasons of 2020-2021 and 2022-2023 that full data for each period are available, again suction was not lost especially at the depth of 2m where practically negligible changes seem to have taken place. Corrected values of suction for temperature reached and exceeded 2000 kPa at 0.80m and 600 kPa at 2.0m. Volumetric water content followed a similar trend matching suction evolution (Fig. 1b). In this particular station, a wetting test was performed on the 22nd of March 2018 (Fig. 2). It allowed the study of the response of the sensors at the two depths (Fig. 1c) indicating a response within 3.5 hours for the depth of 0.80m (after providing a total of 738lts of water from the surface) but a response after 9 days for the depth of 2.0m (which itself lasted 3 days until suction dropped to zero). The total supply of water reached 2177 lts and was completed in the morning of the 23rd of March 2018. Recovery of "normal" field suction values took approximately 3 months for the depth of 0.80m and 9 months for the depth of 2.0m. The drying stage was used to estimate field evolution of permeability of the material with suction. The water front diameter at the ground surface was 75cm (Fig. 2).

3.2 Bassales station, Skiros island, North Aegean Sea

Bassales area on Skiros island is the location of a major palaeolandslide in marls currently under monitoring of various variables including field suction and volumetric water content as well as landslide movements measured on inclinometers and surface markers. The landslide has a long record of movements triggered by rainfall with major movements (in the order of meters) taking place during extremely wet winters (February 2004 and February 2019). After the February 2019 movements, a new geotechnical investigation was performed as part of which a suction/volumetric water content station was installed. Suction with time is presented in Fig. 3a, and volumetric water content with time in Fig. 3b. Suction values are notably lower than those recorded in other stations during summer time (given the observations of a very "wet" area at the particular location close to the scarp of the landslide). Given that the station will be dismantled as it is in an area where unloading excavations are going to take place, the older (and in the particular case re-used) MPS2 suction measurement sensors have been installed. These values therefore may be actually recording longer time-lag of the particular sensors [10], although the effect of autumn rainfall seems to be adequately monitored as shown by the suction decrease after the first continuous rainfalls of late November 2019, winter 2020-2021 and 2021-2022.

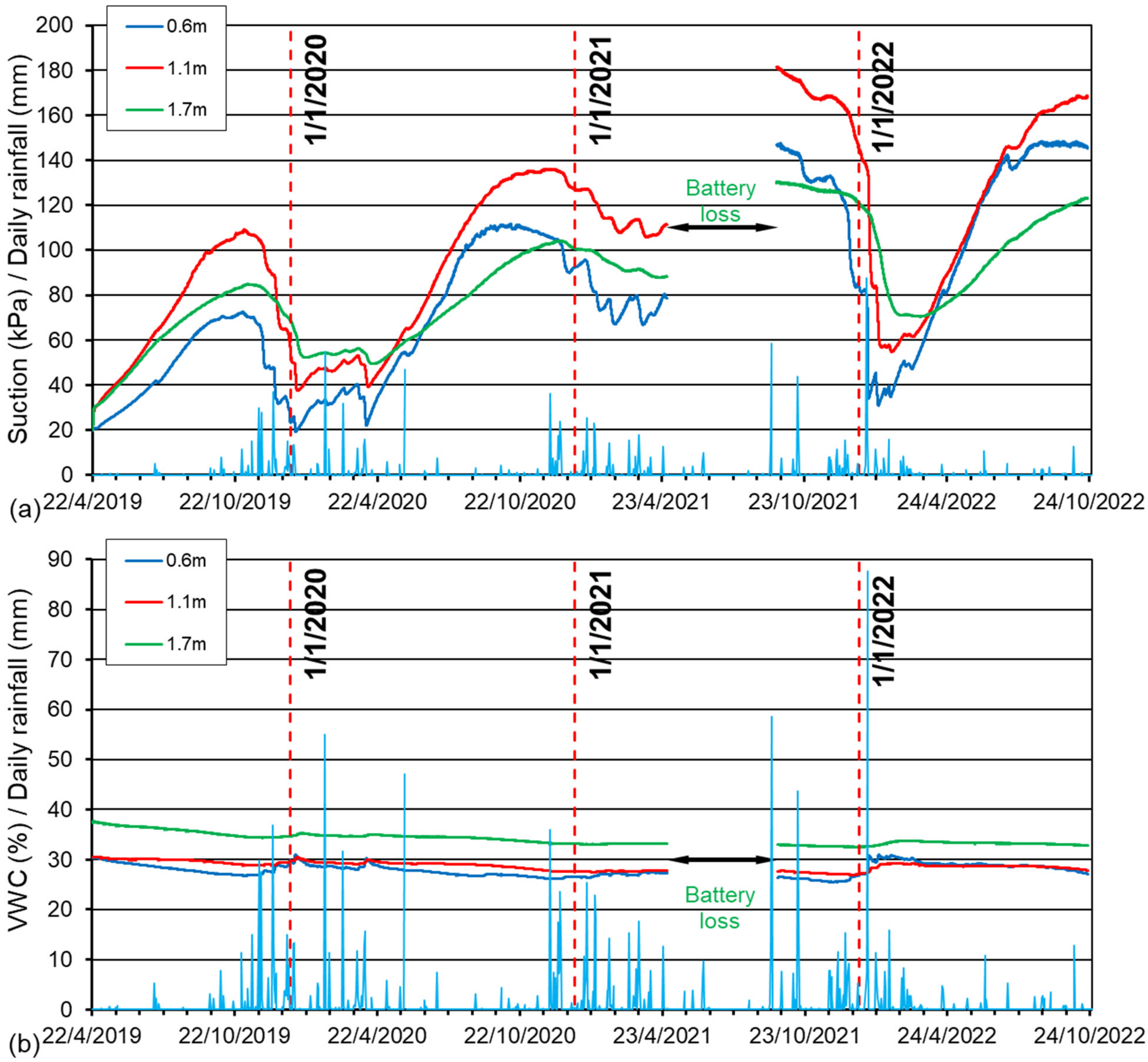

Fig. 3. Bassales station: a) Suction evolution with time. b) . b) Volumetric water content (VWC) evolution with time. Light blue solid line in both diagrams corresponds to daily rainfall.

3.3 Polyrracho station, Kozani, western Macedonia

The area close to Polyrracho village near Kozani in Western Macedonia is the location of a landslide in high plasticity clayey formations currently under monitoring of various variables including field suction and volumetric water content as well as landslide movements measured on inclinometers. The landslide has a long record of movements evidenced in the continuous need for repairs of the National Road passing through the landslide. This new station was long anticipated as it is one installed in very high plasticity clayey soils and also north in the country (it is the northernmost station of the network so far) and at the same time the station at the longest distance from the sea and the station at the highest altitude (approximately 690m).

Installation of sensors took place in September 2022 and the installation of the logger on the 1st of November 2022. Sensor readings were corrected for temperature using correction equations available in the literature [8] and are shown for the three depths in Fig. 4a along with daily rainfall with time. Despite the fact that continuous monitoring started on November the 1st 2022, very high values of suction are recorded: approximately 850 kPa at 0.55m, 1250 kPa at 1.20m and an impressive 600 kPa at 2.20m. The very high suctions up to 1.20m were maintained until the 1st of December (Fig. 4a & 4b) when suction was practically decreased to zero within a matter of hours as a result of 22m daily rainfall on the previous day. Daily rainfalls up to 18mm before the particular incident had not been able to make suction change, yet this rainfall incident seems to have caused such a large decrease (apparently with the effect of cumulative rainfall from previous incidents playing also a role). This response comes in stark contrast to that of the sensors in the Acropolis station in silty sandy gravel.

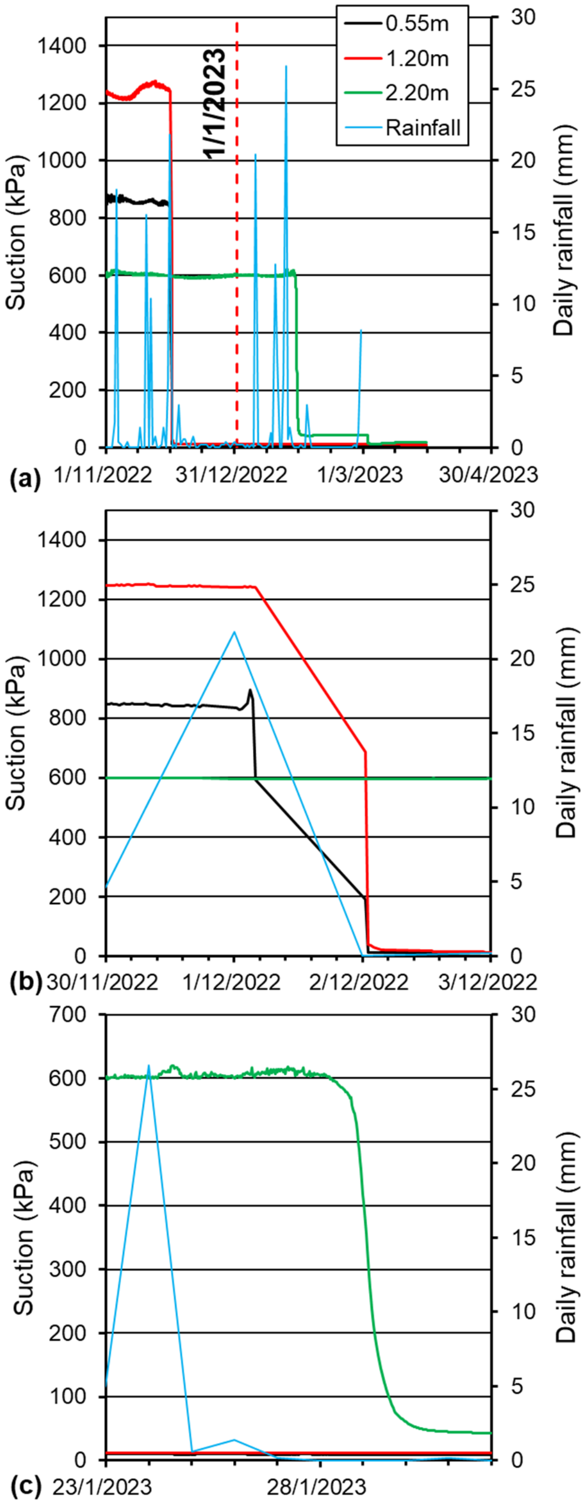

Fig. 4. Polyrracho station: a) Suction evolution with time at the three depths where sensors are installed along with daily rainfall with time. b) Detail of Fig. 4a at the time of 0.55m and 1.20m decrease in suction, and c) detail of Fig. 4a at the time of 2.20m decrease in suction.

Similar cumulative or daily incidents there were unable to cause the suction to decrease so rapidly, whereas here, in a station in high plasticity clay, this happened not only down to 1.20m but also down to 2.20m after a 28mm daily rainfall on 24/1/23 causing suction to decrease to zero after 5 days (Fig. 4a & 4c). This general behaviour is currently attributed to deep shrinkage cracks in the high plasticity clays, observed during the excavation of the particular trial pit and the other trial pits excavated in the area, as has been observed in other cases of high plasticity clays and marls [9].

4 Conclusions

The measurements from three suction and volumetric water content monitoring stations in Greece were presented as part of the continuous update presentation from the network of monitoring stations in Greece. Maximum values of suction were considerably high and generally maintained in materials without deep shrinkage cracks. More stations and measurements are obviously needed with efforts in densifying the network of stations now focusing in parts of the country in the north and in high plasticity clays with shrinkage cracks in order to investigate their effect on the time rainfall causes suction to decrease.

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6 References

1. R. Geiger, 1961. Klima der Erde. (Wandkarte 1:16 Mill.) – Klett-Perthes, Gotha.
2. "Climate Atlas of Greece" 2019. Hellenic National Meteorological Service (in Greek).
3. M. Bardanis, Proc. Int. Symp. Shrink-Swell Processes in Soils, Climate & Construction, 18-19 June 2015, Marne-la-Vallée, France, pp. 463-472.
4. M. Bardanis, D. Loukidis, Proc. One-day Workshop of the Hell. Soc. SMGE on Unsaturated Soils, 1st July 2019, Athens, Greece (in Greek).
5. M. Bardanis, D. Loukidis, *Long-term measurements of suction in the field*, Proc. 8th Hellenic Conference on Soil Mechanics & Geotechnical Engng, 6-8 November 2019, Athens, Greece (in Greek).
6. M. Bardanis, D. Loukidis, Proc. 4th Eur. Conf. on Unsaturated Soils, Lisbon, Portugal, 19-21 October, 2020, https://doi.org/10.1051/e3sconf/202019501023.
7. M. Bardanis, *Experiences from the long-term measurement of soil suction in the field*, Invited Lecture for Imperial College MSc Course in Soil Mechanics, 23rd June 2021.
8. L. Walthert, P. Scleppi, J. Plant Nutr. Soil Sci. 2018, 000, 1–11 (https://doi.org/10.1002/jpln.201700620).
9. G. Lazarou, D. Loukidis, M. Bardanis, Geotech Geol Eng J, 3/2019, https://doi.org/10.1007/s10706-018-0709-2.
10. Bardanis, M., Proc. 3rd Eur. Conf. on Unsaturated Soils, Paris, France, 12-14 September, 2016, DOI: 10.1051/e3sconf/20160910005.