Long-term suction measurements in Greece & Cyprus. A continuous update.

Michael Bardanis^{1,*} Dimitrios Loukidis²

¹EDAFOS Engineering Consultants S.A., 10558 Athens, Greece

²Univeristy of Cyprus, Nicosia, Cyprus

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 are presented in the paper. From these -admittedly few- measurements until today, the large magnitude of suction that may occur both during summer and winter is presented, along with the possibility of long periods of these suctions being maintained. Another consequence is the range of suction values that sensors should be able to measure in regions of similar climatic conditions in order to cover the range of expected values as obtained from the measurements available so far.

1 Introduction

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. The climate in Cyprus is subtropical Mediterranean to Mediterranean. Some areas in both countries have a climate close to semi-arid. 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: strength increases, compressibility decreases, micro-permeability decreases, fissures and cracks appear in fine-grained soils causing macroporosity 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 higher than the angle of repose, large loads will be transferred to the ground without failures, swelling will take place, especially in Cyprus, where expansive soil formations outcrop in many parts of the island. This observed behaviour is perceived by the engineering community as

a 'dry' state in many parts of the two countries 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. The paper presents some long-term measurements of the other property allowing along with the water content (and degree of saturation) a better description of the soil conditions relative to its partial saturation: soil suction. The measurements come from various locations in Greece and Cyprus and include measurements of both soil suction and volumetric water content allowing an understanding of "how dry is dry" or perhaps not. 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. The results presented in the paper may by no means be considered typical or representative of hydraulic conditions in the vadose zone in the two countries. Still they constitute initial evidence of the range of soil suction that should be expected, the 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.

* Corresponding author: mbardanis@edafos.gr

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] 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 [5]. This paper presents an update of these measurements and gives the range of expected values. 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 maximum 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. Examples of stations of the first two categories are presented in the paper. Currently one large depth station is planned but not yet installed.

3 Shallow depth stations

3.1 Artemis station, Attica, Greece

Artemis, Attica, is a seaside resort close to the capital of Greece, Athens, with typical Mediterranean climate and low annual rainfall typical of central Greece and Athens itself. A first, temporary, array was installed in the garden of a private property during August 2013, one of the driest, warmest and most windy months of the year for the particular area. The objective then was to obtain an idea of the magnitude of expected suction and volumetric water content values at shallow depths during summer. Additional objectives were the identification of

Table 1. Properties of soils at suction monitoring stations.

Station	w _L (%)	I _p	% Passing No 200	USCS class/tion	Void ratio
Artemis, Attica, Greece	NP		32-33	SM	0.45- 0.55
Maritsa, Rhodes island, SE Aegean, Greece	33- 35	9-11	32-35	SM	0.45- 0.55
Bassales, Skiros island, N Aegean, Greece	41- 50	21- 24	53-78	ML-CL	0.80- 0.90
Aglantzia, University of Cyprus, Nicosia, Cyprus	39- 54	19- 29	78-83	CL-CH	0.65- 0.80

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, Greece	Meter TEROS21	Meter TEROS10 & Decagon GS3	0.15 & 0.30m
Maritsa, Rhodes, SE Aegean Sea, Greece	Decagon MPS2	Decagon GS3	0.30m
Bassales, Skiros, N Aegean Sea, Greece	Decagon MPS2	Meter TEROS10 & Decagon GS3	0.60, 1.10 & 1.70m
Aglantzia, Univ. of Cyprus, Nicosia, Cyprus	Decagon MPS6	Decagon GS3	0.75 & 1.50m

trends of suction and volumetric water content changes, and temporal responses to major changes like complete wetting. In order to obtain more information and have the ability to cross-check measurements, more types of sensors were installed. Also two arrays were placed, the main one containing most sensors where a complete wetting test took place, and a second one, called the reference array which was used only for reference of continuously acting climatic conditions after wetting took place at the main array. The results monitored and already presented in [3, 5] constitute an interesting addition to the list of references with field measurements of suction and volumetric water content from various locations around the world, especially given the magnitude of suctions measured. Maximum suction values reach well beyond 3 MPa in Autumn and are practically instantly lost at 0.15m depth after 22mm of rainfall on 31/10/2019 (Fig. 1 & 2) and approximately a week after this event at 0.30m depth, though signs of change were evident within hours. Summer values of suction from 2019 and 2013 compare fairly with August 2013 recording higher values at 0.30m depth even after equilibrium following the 2013 wetting test. After the start of rainfall incidents in 2019, suction begins to

Fig. 1. a) Suction with time, and b) volumetric water content with time at Artemis station, Attica, Greece. 2019 wetting and cover periods bounded by dashed vertical lines. August 2013 measurements added for comparison.

Fig. 2. a) Suction with time, and b) volumetric water content with time at Artemis station, Attica, Greece, after the beginning of the rainy season in Autumn 2019. Dashed curves are daily precipitation from the nearby Rafina meteorological station.

increase again after each incident but decreases rapidly to the lowest value TEROS21 sensors can measure (approx. 10 kPa) after all daily rainfalls exceeding 10mm. Both suction and volumetric water content sensors respond quickly as has already been documented for the particular station and soil found on the spot [3, 6].

3.2 Maritsa station, Rhodes island, Greece

This station was a temporary station installed in the garden of an one-storey country house exhibiting signs of strains due to cycles of swelling and shrinkage of soils under its footings. Measurements took place during August 2018 and although limited to a fairly short period, they were very useful for understanding the effect of temperature on cables and the importance of cables and logger thermal insulation. Suction with time is presented in Fig. 3a. It seems to have a daily fluctuation in the range of 300-350 kPa around a practically constant average value and within a constant range (unlike for instance Artemis station measurements where average suction was not constant). One could argue that this is the actual effect of daily fluctuation of temperature and relative humidity in the area and a result of the smaller time period of recordings. Still, as shown in Fig. 3b, daily fluctuations of temperature measured by the sensors' thermometers range between 27 and 35 °C, coinciding practically with atmospheric temperature (whereas at Artemis station for the same period temperature at 0.30m depth fluctuated between 20 and 30 °C, well below atmospheric temperature). This indi-

Fig. 3. Measurements from Maritsa station: a) suction, and b) temperature of sensor in the ground.

Fig. 4. Maritsa station: a) MPS2 suction sensor temperature with time of the day, b) suction with time of the day, and c) suction with temperature.

cates that, as cables of sensors had not been thermally insulated, the sensors simply recorded the actual effect of temperature on their readings. Sensor temperature and suction with time are presented in Fig. 4a and 4b respectively, indicating a temporal variation following daily fluctuations of atmospheric conditions. If suction is plotted against sensor temperature, a very strong relation between the two is noticed (Fig. 3c). 1 °C causes 45 kPa smaller recorded suction. These observations indicate that suction at Maritsa was practically constant at 1200 kPa during the period of measurements. These measurements emphasize the need for thermal insulation of cables of sensors coming out of the ground to loggers.

4 Medium depth stations

4.1 Bassales station, Skiros island, Greece

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. 5a, and volumetric water content with time in Fig. 5b. 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, 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.

Fig. 5. a) Suction with time, and b) volumetric water content with time at Bassales station, Skiros island, Greece. Daily precipitation for Skiros island also plotted.

4.2 Aglantzia station, University of Cyprus Campus, Nicosia

Aglantzia station in Nicosia is a station installed in the campus of the University of Cyprus. For the time being

this is the longest recording station, with recordings spanning more than 4 years. Sensors were installed in the khaki Nicosia Marl, an expansive, often very high plasticity formation, outcropping in Nicosia and other parts of Cyprus. At the particular location and depths where the sensors were installed, Nicosia marl ranges between CL and CH with a maximum liquid limit of only 53% [4]. Suction at 0.75m depth ranges (after equilibrium from the initial wetting test was achieved in April 2016) between 200 and 1100 kPa (Fig. 6a). At the same period, suction at 1.5m ranges between 10s of kPa to 400 kPa. The most important observation at the particular station is that suction remained above 200kPa for two winter seasons (2016-2017 and 2017-2018 of 250-300mm rainfall). Only during the wet winter of 2018-2019 (600mm of rainfall) the suction was lost, within hours to days at 0.75m depth and within 2 months at 1.50m depth. Another interesting observation is that the suction time history for 0.75m depth shows every year a distinctive “break” of continuity at around mid-May, lasting until early January. During this time range, which encompasses the dry season, the suction measurements become noisier and exhibit a depression in suction values, despite the fact that no increase in volumetric water content θ is recorded (Fig. 6b). This observation is most likely caused by partial loss of hydraulic contact of the shallow suction sensor with the ground during the dry season due to the opening and propagation of desiccation cracks (evident on the ground surface every summer) down to the depth of the sensor, allowing more interaction with air temperature and humidity. The hydraulic contact is re-established during the following wet season as the soil swells and the cracks close. Finally, it should be noted that the water content measurements of Fig. 6b are based on the factory calibration of the sensors. The θ values for 1.5m depth, which are unrealistically high (>50%), corresponding to degree of saturation well above 100% (for the porosity of around 0.4 of the given marl), stress the fact that factory calibration is not always suitable, especially in the case of mineralized ground, such as Nicosia marl which contains several horizons with Fe and Mn stained fissures.

5 Conclusions

The measurements for four suction and volumetric water content monitoring stations in Greece and Cyprus were presented. Maximum values of suction ranged between 3 and 4 MPa during dry seasons. The response of the soil down to 0.30-0.50m was measured in the range between minutes and hours during rainfall and days to months at greater depths down to 1.5m. At large depths and in low permeability soils like those at the Aglantzia station in Cyprus it took an extremely wet winter like that of 2018-2019 to observe actual loss of suction. It seems that suction sensors in areas like Greece and Cyprus must be able to measure throughout the whole range from 0 to 4-5 MPa, so that all anticipated suction values can be measured using one type of sensor.

Fig. 6. a) Suction with time, and b) volumetric water content with time at Aglantzia station, Nicosia, Cyprus, c) cumulative monthly rainfall data from the nearby Athalassa meteorological station.

References

1. R. Geiger, *Klima der Erde*. (Wandkarte 1:16 Mill.) – Klett-Perthes, Gotha (1961)
2. "Climate Atlas of Greece". Hellenic National Meteorological Service (2019) (in Greek)
3. M. Bardanis, *Proc. Int. Symp. Shrink-Swell Processes in Soils, Climate & Construction*, 18-19, Marne-la-Vallée, France, pp. 463-472, June (2015)
4. G. Lazarou, D. Loukidis, M. Bardanis, *Geotech Geol Eng J.* **3** (2019)
5. M. Bardanis, D. Loukidis, *Proc. One-day Workshop of the Hell. Soc. SMGE on Unsaturated Soils*, 1st July 2019, Athens, Greece (2019) (in Greek).
6. Bardanis, M., *Proc. 3rd Eur. Conf. on Unsaturated Soils*, Paris, France, 12-14 September (2016) DOI: 10.1051/e3sconf/20160910005