Calibration of a granular matrix sensor for suction measurements in partially saturated pyroclastic soil

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Abstract. Field monitoring of soil moisture and matrix suction is a useful tool for the implementation of a reliable early warning system against rainfall-induced landslide occurrence. Several test fields have been set up in Campania region (southern Italy), frequently affected by flow-like landslides involving pyroclastic soil cover. In particular, at the Mount Faito test site (Lattari Mountains, southeast of Naples), field matric suctions were measured over two years by conventional jet-fill tensiometers and granular matrix sensors (Watermark, Irrometer®) at different depths. Granular matrix sensor is a resistive device that is more and more spread in agriculture applications and that may also be used for geotechnical purposes thanks to a suitable calibration. In order to gain the calibration curve of the Watermark sensor, two small tip tensiometers (STT) and one High Capacity Tensiometer (HCT) were installed at the same depth of the Watermark sensor in the partially saturated pyroclastic soil sampled at the topsoil of the Mount Faito test site. Tests were carried out in the laboratory by performing drying and wetting phases on undisturbed soil sample. By coupling resistance measurements by Watermark and matrix suction provided by the reference tensiometers, it was possible to derive the non-linear relationship between these two quantities. The soil retention curve was also determined thanks to the installation in the soil sample of a decagon probe previously calibrated in the same pyroclastic soil.

1 Introduction

Flow-like landslides are usually rainfall-induced events and represent a major natural hazard worldwide, occurring widely in many geological settings [1,2,3,4]. These types of landslides are particularly dangerous because characterized by a pre-failure evolution hard to recognise and by a fast propagation of the mass involved in the post-failure phase. Once the shear failure occurs, basal and lateral soil is eroded during the propagation and incorporated into the landslide body due to the avalanche effect. The debris mass involved into the landslides can reach high volume (up to 100000 m^3) and high velocity of propagation (up to 30-40 km/h) [5], causing a lot of damage to structures and fatalities when it arrives at the foot of the slopes [6, 7]. The Campania region (southern Italy) is frequently affected by flow-like landslides, involving pyroclastic shallow deposits resting on fractured limestone, usually in unsaturated condition [1, 2]. Slopes susceptible to the occurrence of flow-like landslides are characterised by an average slope angle generally greater than the friction angle of pyroclastic soil, so the equilibrium of steep slopes is guaranteed by the contribution to the shear strength offered by matrix suction [8, 9]. During autumn, winter and spring, rainwater infiltration causes an increase in soil moisture and a decrease in matric suction and, consequently, a reduction in soil shear strength.

Field monitoring of soil moisture and matric suction is a very useful tool for the implementation of a reliable early warning system against flow-like landslide occurrence. In this regard, several test fields have been set up in Campania region (southern Italy) [10, 11]. In particular, field matric suctions were measured by both conventional jet-fill tensiometers and granular matrix sensors (Watermark, Irrometer®) at different depths over two years (from 2017 to 2019) at the test site of Mount Faito, located at the Lattari Mountains, southeast of Naples [12, 13, 14, 15, 16].

The granular matrix sensor is an electrical resistance-based sensor and represents the simplest type of indirect sensor for the measurement of suction [17]. This type of sensor is more and more widespread in agriculture for irrigation management and is produced in large quantities by industry, making it inexpensive. It has been adopted in this research because of the following features: a) it can measure suction over 200 kPa (situation that actually occurs in dry periods); b) the equilibrium time is estimated in some hours for matric suction not greater than 50 kPa; c) it is cheaper than the traditional tensiometers, thus, making it possible to monitor large critical sloping areas. An appropriate calibration is required for geotechnical use.

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This paper deals with the calibration of the Watermark sensor for suction measurements in the partially saturated pyroclastic soil of the test site of Mount Faito. Tests were carried out in the laboratory by performing drying and wetting phases on an undisturbed soil sample of silty sand sampled at the topsoil (first meter) of the test site. Starting from the natural water content, first the soil sample was saturated, then was subjected to drying path. Once the upper limit of the range of the Watermark was reached, a wetting path was performed. In order to gain the calibration curve, two small tip tensiometers and one High Capacity Tensiometer were installed in the soil sample at the same depth of the Watermark sensor. During the experimentation, the soil moisture was monitored by means of decagon probes (MAS-1, METER Group) installed at the same depth of the other instruments. A thermometer was also used to monitor the air temperature of the room test. By coupling resistance measurements provided by the Watermark sensor and matrix suction measurements provided by the reference tensiometers at fixed time interval, it was possible to derive the non-linear relationship between these two variables.

2 Material and methods

2.1 The Mount Faito test site

From 2015 to 2019, the Mount Faito test site, located in the municipality of Castellammare di Stabia (Naples), was extensively investigated through boreholes to collect undisturbed soil samples for laboratory testing [14, 15] and trenches to reconstruct the stratigraphic setting [16]. To monitor matric suction and volumetric water content in the pyroclastic cover, two parcels were selected to install equipment. A total of 40 tensiometers, 42 TDR probes, 8 Watermark sensors and 8 Decagon sensors were installed in situ at different depths to monitor matric suction and volumetric water content [12].

The stratigraphy recognized at this site is mainly composed of three pyroclastic soil layers (A, B and C, in Figure 1a) resting on limestone, originated from two different volcanic eruptions.

The results of the grain size analyses (Figure 1b) show that A1 is a silty sand with gravel and A2 is a silty gravel with sand. Layer B can be classified as a sandy gravel, while the two layers C1 and C2 can be classified as sandy silt, although C2 is finer than C1 due to the presence of a clayey fraction [16].

2.2 Soil sample

To collect undisturbed soil samples, a PVC hollow cutter with an internal diameter of 19.2 cm and height of 30 cm was horizontally inserted by hand into the top soil A1 (first meter) of a trench at the Mount Faito test site. A Plexiglas base was attached to the hollow cutter and each soil sample was sealed with paraffin in order to preserve its natural water content. The physical properties of the tested soil are summarised in Table 1.

Table 1. Properties of the tested samples

Sample height h (cm)	Dry density G_s (-)	Dry unit weight γ_d (kN/m^3)	Porosity n (-)
20.2	2.649	7.67	0.71

The grain size curve obtained from laboratory test on the sample used for the calibration was superimposed to the envelopes of grain-size distributions of samples collected at different depths during different campaigns carried out at the Lattari Mountains [16] (Figure 1b). The results shown that the grain size curve of the soil sample is contained in the envelope of the grain size distribution of A1 and A2 soils. In detail, the soil sample is composed by 22% of gravel, 68% of sand and 10% of silt.

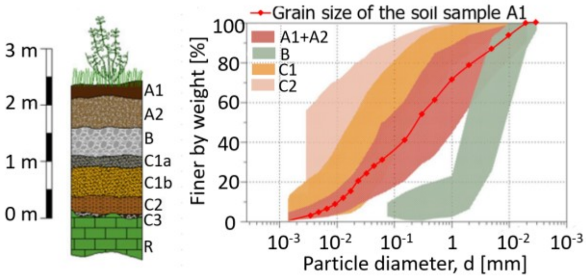

Fig. 1. a) stratigraphic sequence of the Lattari Mountains [16]; b) grain size curve of the soil sample (red line) superimposed to the envelopes of grain-size distribution of samples collected at different depths during different campaigns on the Lattari Mountains (modified from [16]).

2.3 Equipment

In the centre of the soil sample, at a depth of 8 cm, a granular matrix sensor (Watermark, Irrometer®) was installed. At the same depth and at a distance that does not interfere with the equipment, two small tip tensiometers (STT) (2100F SoilMoisture® Probe), a High Capacity tensiometer (HCT) and a Decagon probe (MAS-1, Meter Group) were installed (Figure 2).

2.3.1 Granular matrix sensor (Watermark, Irrometer®)

The granular matrix sensor is an electrical resistance-based sensor constituted by a porous block containing two metal electrodes imbedded. The matric suction of the surrounding soil is inferred from the water content of the porous block through a calibration process. In the field, the block has to be installed in a hole at contact with the soil, so that its water moisture changes with water conditions (water content and matrix suction) in the surrounding soil. The moisture of the porous block is measured by the difference in electrical resistance between the two internal electrodes.
This sensor is equipped with an electronic sensor adapter, that translates the resistance value into a linear voltage output.

These types of sensors are inexpensive, easy to install and use, are not affected by freezing temperatures and no maintenance is required. Therefore, they could be installed in large quantities in shallow soils susceptible to flow-like landslides, at low cost. On the other side, these sensors have a long response time (2 days) for matric suction higher than 100 kPa. Last, these suffer from hysteresis, thus, an appropriate calibration curve is required for field applications [17, 18].

The manufacturer provides the measurement range between 0 and 2800 mV. If the linear relationship between the voltage output and the soil matrix suction is adopted as suggested by the manufacturer, these values correspond to 0 and 239 kPa, respectively:

$$s = V \cdot 239/2800 \quad (1)$$

where s is the matrix suction [kPa] and V is the output voltage [mV].
Granular matrix sensor was installed inside small boreholes at the same diameter as porous block in order to guarantee the close contact with the soil around. The borehole was realized by means of a thin-walled copper cylinder. The head of sensor was carefully sealed with the dug soil.

2.3.2 Small tip tensiometer, SST (2100F SoilMoisture® Probe)

Two STTs were installed at the same depth of the Watermark sensor. This model is suitable for investigation of soil suction in such small range (0-80 kPa) and include a porous ceramic cup, a vent tube, a plastic body tube, and a vacuum gauge. The ceramic cup is placed in hydraulic contact with the surrounding soil. Transfer of water into and out of the vent and body tubes is allowed, depending on the difference in hydraulic load, up to attaining equilibrium between the soil pore water and the water inside the instrument; this latter is measured by the dial gauge. The SST has an accuracy of +/- 1.5% full scale.

As for granular matrix sensor, the SSTs were installed inside small boreholes at the same diameter as porous ceramic cup.

2.3.3 Decagon probe (MAS-1, Meter Group)

The decagon is a capacitive probe (MAS-1, Meter Group). The system supplies a 70 MHz oscillating wave to the sensor prongs that induces an electromagnetic field in the soil surrounding the sensor; a current intensity from 4 to 20 mA is returned. The microprocessor makes a dielectric measurement and updates the transmitted current once per second. The transmitted current can be converted to the water content of the soil using a simple function calibrated for the tested soil in previous researches:

$$\theta = 0.0038 \cdot I^2 + 0.0244 \cdot I + 0.1843 \quad (2)$$

where θ is the volumetric water content and I is the current intensity [mA]. Its accuracy is ± 0.015, the resolution is 0.001. The probe was vertically positioned inside boreholes that was, then, backfilled around with the dug soils.

2.3.4 High capacity tensiometer

The HCT is a prototype developed at University of Naples Federico II using a design layout similar to that initially proposed at the Imperial College of London [19]. The instrument was composed of: an interchangeable filter cup containing a HAEV ceramic disk of 6.0 mm in height inserted into a stainless-steel housing; a water reservoir of 3 mm^3 in volume; an integral strain-gauged diaphragm embedded in a brass housing (Figure 2) [20].

The water in the ceramic disk and in the measuring chamber reaches the hydraulic equilibrium with the surrounding soil. A pore water pressure variations in the soil determines a change in the deflection of the strain-gauge diaphragm, resulting in a change in voltage. An acquisition unit measures the dimensionless output voltage, that can be converted to the pore water pressure of the soil using a function calibrated for the tested soil:

$$u = -(-1322.3 \cdot V - 473.66) \quad (3)$$

where u [kPa] is the soil pore water pressure and V is the dimensionless output voltage [mV/V].

Depending on the strain-gauge deformation direction, it is possible to measure either negative or positive pore water pressure (from -750kPa to 750 kPa).

Also, HCT was installed by doing a hole of the same diameter of stainless-steel housing.

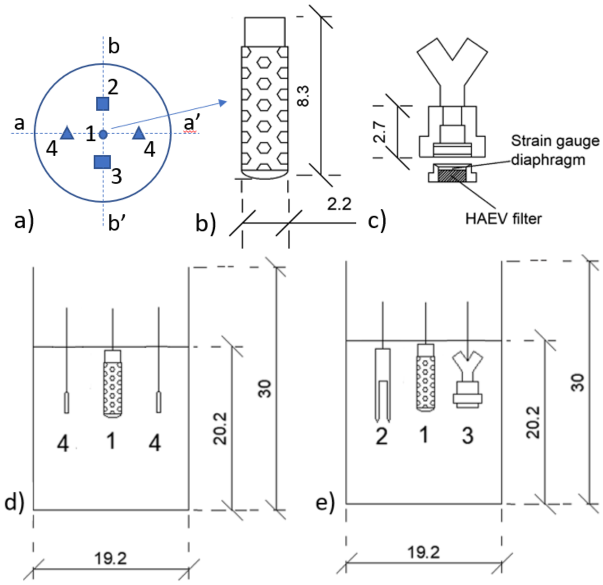

Fig. 2. a) Plan section of the soil sample and position of the equipment installed 1: Granular matrix sensor; 2: Decagon probe; 3: High capacity tensiometer; 4: Small tip tensiometer); Details and dimensions [cm] of the equipment installed: b) Granular matrix sensor; c) High capacity tensiometer; d) Longitudinal section a-a'; e) Longitudinal section b-b'.

2.4 Experimental procedure

Tests were carried out in laboratory by performing drying and wetting phases on the undisturbed soil sample. Starting from the natural water content, the first step consisted of the soil saturation by wetting the sample from the top by sprinkler; then a drying path was carried out until the upper limit of the measurement range of the Watermark sensor was reached. At the end of the drying phase, the soil sample was saturated again (wetting path). In the drying phase, the water was lost through forced evaporation while in the wetting phase distilled water was added to soil sample. Both the drying and wetting phase were carried out by discrete steps: after varying the hydraulic condition on the upper boundary, the soil sample was covered in order to reach the hydraulic equilibrium. Once the instrumentation provided a time-stable value of water content and suction, indicating that hydraulic equilibrium had been reached in the soil sample, the next step was carried on. All details about the number, type of each step and the measurements read by all the sensors are reported in Table 2 and Table 3.

Table 2. Details about the number and measurements read by all sensors during the drying path.

Drying path				
Step	STTs	HCT	Watermark	Decagon
	s	s	V	θ
[-]	[kPa]	[kPa]	[mV]	[m³/m³]
0	3.25		73.91	0.52
1	5.25		73.76	0.51
2	6.25		79.58	0.50
3	11.25		222.38	0.46
4	12.25		264.75	0.44
5	14.25		279.94	0.42
6	17.25		302.63	0.40
7	19.75		340.31	0.39
8	22.25		353.06	0.38
9	23.25		366.11	0.37
10	25.25		385.21	0.36
11	30.75		419.81	0.34
12	34.25		426.92	0.33
13	36.75		440.39	0.32
14	39.25		458.36	0.32
15	41.25		471.68	0.31
16	45.25		493.16	0.31
17	52.25		530.96	0.30
18	54.25	54.78	540.13	0.30
19	68.25	66.39	616.77	0.30
20	78.25	79.61	703.45	0.28
21		112.67	800.60	0.27
22		133.83	932.83	0.27
23		287.22	1333.47	0.25
24		365.23	1587.72	0.24
25		652.17	2721.94	0.23

During the experimentation, all measurements were acquired automatically every 10 minutes by an acquisition unit. Only small tip measurements were acquired manually every two hours during the test. Up to a value of suction equal to 60 kPa, suction measurements were provided by the small tip tensiometers; above this value the reference measurements were performed by the high-capacity tensiometer. By looking the Table 2 and 3, it is useful to note that the measurements provided by the SST and the HCT, when both are available, are almost equal.

At the end of the tests, the samples were dismantled in order to determine the grain size curve, the dry unit weight and the porosity.

Table 3. Details about the number and measurements read by all sensors during the wetting path.

Wetting path				
Step	STTs	HCT	Watermark	Decagon
	s	s	V	θ
[-]	[kPa]	[kPa]	[mV]	[m³/m³]
0		652.17	2730.31	0.23
1		344.13	1970.80	0.23
2		169.53	1791.64*	0.24
3		111.35	1454.25	0.25
4	58.00	61.10	726.19*	0.26
5	26.25		526.49	0.28
6	20.75		392.96	0.32
7	18.75		393.04	0.35
8	16.75		363.19	0.36
9	14.75		343.56	0.37
10	13.75		325.28	0.38
11	10.25		300.26	0.40
12	8.25		242.06	0.42
13	7.25		200.89	0.46
14	5.25		95.48	0.51
15	3.25		471.68	0.52

*: the sensor did not reach the equilibrium because of low response time at high matric suction

3 Results

By coupling resistance measurements and matrix suction provided from the reference tensiometers when the hydraulic equilibrium was attained in the soil sample, it was possible to gain the calibration curve (see Figure 3). According to the results, the relationship between sensor resistance and matrix suction is not linear. In particular, the data are best fitted by the equations (4) and (5), along the drying and the wetting paths respectively:

$$s=7\cdot 10^{-5}\cdot V^2+0.0808\cdot V \quad (4)$$

$$s=7\cdot 10^{-5}\cdot V^2+0.0127\cdot V \quad (5)$$

The coefficient of determination, R^2, is 0.9682 for drying curve and 0.9688 for wetting one.

By looking at the Figure 4 representing a zoom of Figure 3 for matric suction between 0 and 200 kPa, it is clear that the experimental points obtained in drying and wetting path are below the manufacturer curve up to a matrix suction value equal to 30 kPa. On the contrary for higher suction value the experimental points obtained in laboratory test lie above. For a given output voltage value, the difference between the suction value given by the reference tensiometers and the one given by the manufacturer relationship is not negligible for high range of suction (higher than 80 kPa).

For the manufacturer, at the maximum output voltage value a suction of 239 kPa corresponds. This value was exceeded in this laboratory test, attaining a suction of 648 kPa. For high range of suction a hysteretic behaviour is observed according to outcomes of [18]. Then, along wetting path the sensor did not reach the equilibrium because of low response time of porous stone at high matric suction (see the values with asterisks in Table 3).

Inevitably, the hysteretic behaviour of porous block in combination with low response time at high values of suction limits the accuracy, thus, the use, of such sensors.

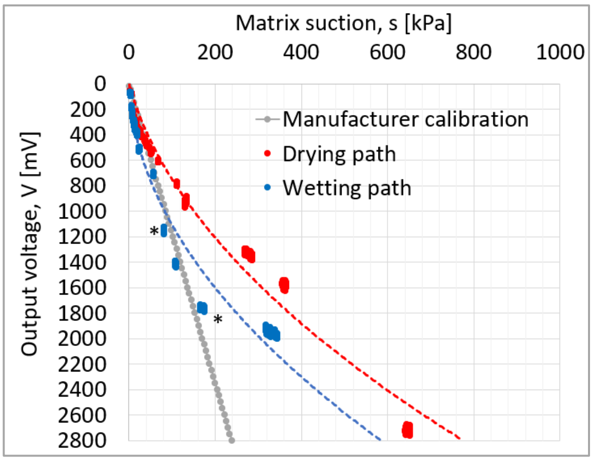

Fig. 3. Drying and wetting path: couple of measured matrix suction and output voltage compared with manufacturer calibration. The calibration curves for both the paths are overlapped.

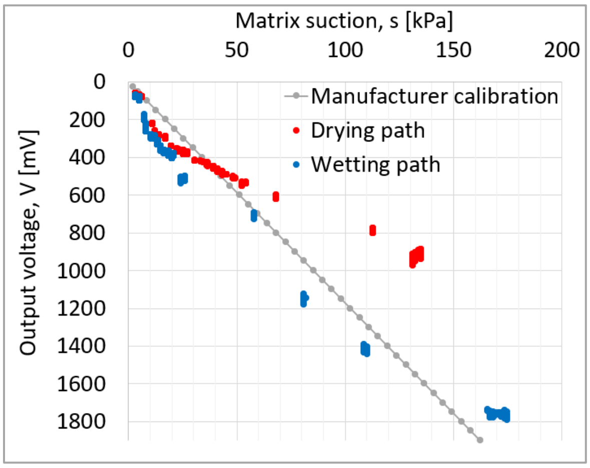

Fig. 4 Detail of Figure 3 for matrix suction between 0 and 200 kPa.

For the same time interval, couple of suction and volumetric water content values provided by the reference tensiometer and the decagon probe respectively have been used to obtain the water retention curve of the soil both in wetting and drying paths (Figure 5). The results show that the drying curve obtained here overlaps the envelope of the main drying curve obtained by [12] on undisturbed A1 soil sampled at the Mount Faito test site. This confirms that the coupling of the two instruments fulfils the aims of the research.

The first couple of matric suction and volumetric water content, equal to 3.25 kPa and 0.52, measured along the drying path (Figure 4), points out that the soil specimen was not fully saturated at the beginning of the experimentation. Therefore, taken a soil porosity of 0.71, the initial degree of saturation amounted to 73%. This might be due to a significant amount of air bubbles that got trapped at low matric suction [21].

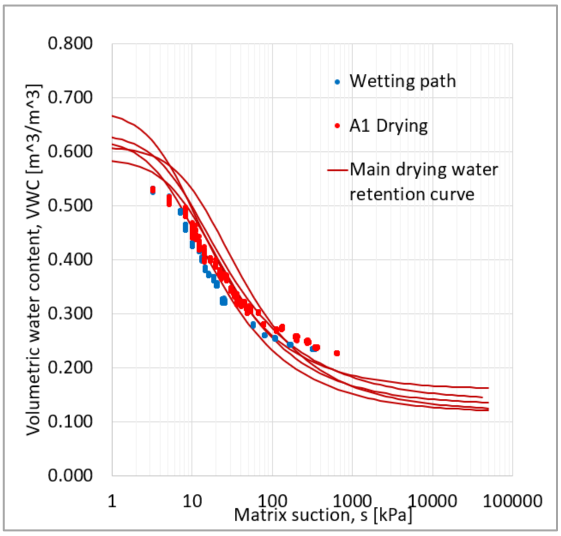

Fig. 5. Couple of measured matrix suction and volumetric water content compared with main drying water retention curves carried out by [15] on soil A1.

4 Conclusion

Granular matrix sensors are devices that provide an indirect measure of matrix suction in unsaturated soils. They are unexpensive and no maintenance is required as opposed to traditional tensiometers, therefore they may be suitable to be installed in large quantities at slope susceptible to flow-like landslides, at low cost. Nevertheless, a proper calibration curve has to be necessarily determined at lab as the linear relationship suggested by the manufacturer over/underestimates the suction for values lower/higher than 90 kPa. Moreover, a hysteresis between the output voltage and suctions has been identified for suction values higher than 100 kPa. This result can be explained by the fact that the sensor responds to a change in water content which notoriously exhibits hysteresis when related to suction. Then, some limitations for field application result the hysteresis and the low response time at high level of matric suction (>100kPa). On the other hand, it returns values even higher than 100 kPa up to 600 kPa, as opposed to traditional tensiometers, allowing to capture the

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seasonal trend in suction at shallow deposits susceptible to shallow landslides.

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