A prototype for water content measurement in partially saturated soils

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Abstract. The paper presents the technological set-up and calibration of a system based on impedance spectroscopy for measuring water content in partially saturated soils. The technique adopted is relatively recent in geotechnical practice; it is used herein to characterize the electrical response of a soil specimen among two conducting electrodes upon application of an alternate voltage and the measurement of the current intensity resulting across the specimen, for frequency values in the range [500 Hz - 50 kHz]. The complex impedance of the soil specimen is due to both resistance, i.e. opposition to current, and reactance, i.e. tendency of the system to yield and retrieve energy, and it depends on the specimen water content. An on-purpose experimental plan has been conceived and is presented herein, aimed at building a calibration function for deriving the water content in pyroclastic soils from the impedance measurements. Preliminary results reveal an adequate level of repeatability of the measurements and suggest the existence of a monotonic correlation between the impedance modulus and the gravimetric water content.

1 Introduction

Partially saturated pyroclastic soil covers laying on steep bedrocks are commonly affected by flow-like landslides. These instability processes, well known for causing heavy social and economic damages and threatening human life, are generally triggered by rainfall infiltration, which leads the unsaturated slope to failure by reducing matric suction and consequently the soil shear strength (e.g. [1, 2, 3, 4]).

In hydro-geological contexts affected by this class of landslide processes, risk mitigation can be conveniently addressed through early warning systems based on monitoring of factors predisposing landslide activation, such as suction and/or water content in the slope. It follows that the geotechnical field monitoring of the slope hydraulic conditions plays a crucial role for the prediction of the landslide initiation.

In this regard, water content field measurement is less problematic than suction field measurement, as the sensor response is much faster and soils can be continuously monitored over all the range of partial saturation without any particular maintenance [5].

Among the various techniques for soil moisture measurement, dielectric based techniques as Time Domain Reflectometry, TDR, and capacitance techniques, CT, have gained much more popularity, mainly due to revolutionary developments in the field of electronics and data communication systems [6]. The TDR technique, which is a broadband -frequency method (up to units of GHz), provides highly accurate measurements but it is expensive and suffers from installation problems that make the determination of water content at relatively large depths difficult. Moreover, this technology is significantly energy-consuming.

On the other hand, CT, which is a single narrowband-frequency method (usually 70MHz), is relatively inexpensive and easy to operate, uses little power but it is less accurate for soils having relatively high bulk electrical conductivity and at high volumetric water content [7].

Within this framework, the paper presents an alternative system to measure water content in partially saturated soils, based on impedance spectroscopy, that is commonly used for investigation of electrical material properties. With respect to TDR and CT, the system proposed here results cheaper because of the electronic components involved and it works at multiple low frequencies from 500 Hz to 50 kHz. With the purpose to exploit this measuring system for field water content measurements, as an alternative to TDR and CT, an experimental programme has been developed and a correlation between the impedance measured for the specimens at assigned water content and their humidity has been built.

As first, the soil specimens were prepared following the standardized procedure of dried soil air pluviation and then wetted at different water contents. The

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experimental programme was intended to test the effectiveness and repeatability of the measuring system and to derive the device calibration function for the pyroclastic soil tested.

This system is proposed to offer support and a potential alternative to traditional water content measuring techniques (e.g. [8, 9, 10, 11]) by providing measurements of impedance over a large range of frequencies. It benefits from easy and affordable manufacturing, and allows containing costs and adapting to customization requirements as regards device geometry and long-term monitoring. Also, it can readily be designed to be coupled with suction probes.

2 Impedance spectroscopy

Impedance spectroscopy (IS) is a technique allowing to characterize most electrical properties of materials through the application of an electrical stimulus (a known voltage or current). In detail, the technique allows the measurement of the complex impedance, $Z(f)$, representing the opposition of the medium to the alternate electric current passing through it and depends on frequency, f [12]. Conventional IS consists of measuring Z as a function of f over a wide frequency range. The resulting structure of the $Z(f)$ *vs.* f response allows inferring the electrical properties of the electrode–material system.

$Z(f)$ generalizes Ohm's law to circuits in sinusoidal regime and in rectangular coordinates it is expressed as:

$$\frac{V(f)}{I(f)} = Z(f) = Z' + jZ'' \tag{1}$$

$$Re(Z) = Z' = |Z|cos\theta;\ Im(Z) = Z'' = |Z|sin\theta \tag{2}$$

The real part of impedance, Z', is associated to the dissipation process and represents the resistive component (*resistance*), while the imaginary part, Z'', corresponds to charge accumulation, hence representing the capacitive component (*reactance*).

In polar coordinates phase angle and modulus equal, respectively:

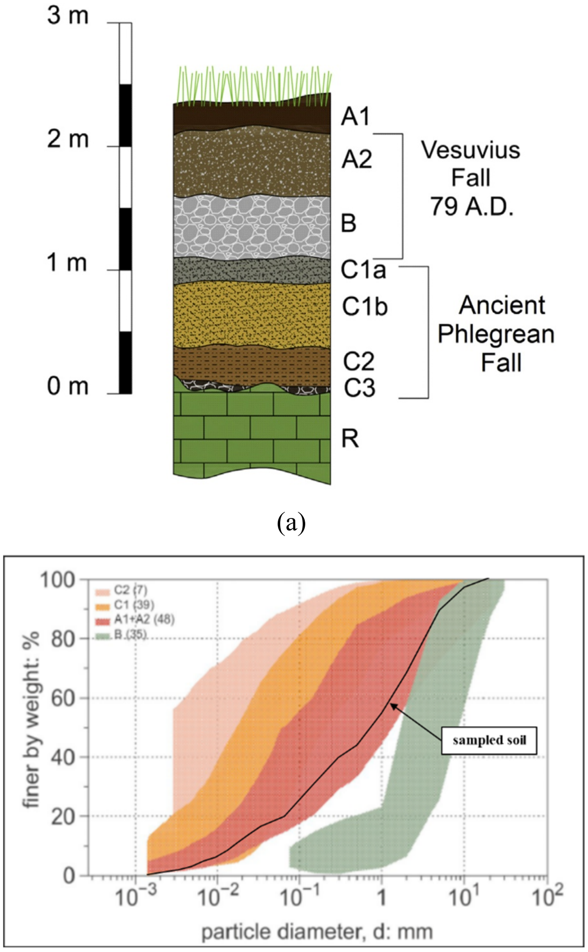
$$\theta = tan^{-1}\left(\frac{Z''}{Z'}\right) \tag{3}$$

$$|Z| = \sqrt{(Z')^2 + (Z'')^2} \tag{4}$$

3 Laboratory testing

3.1 Tested material and experimental programme

A pyroclastic soil sampled at the top soil of the site of Nocera Inferiore (SA) has been used for laboratory testing [13]. The stratigraphic sequence typical of the Lattari Mounts [14] has been recognized at the sampling site. In particular, more recent top soils, layer A, deposited after the Somma Vesuvius eruption of 79 d.C. consist of: the upper layer, A1, vegetated and affected by biogeochemical processes; the lower layer, A2, made of silty sands rich in pumices (Figure 1). The sampled soil belongs to level A and is mainly sandy (SF=49%; Figure 1b), with a significant amount of gravel (GF=31%) and silt (MF=18%). The physical properties of the tested soil are reported in Table 1.



(a)

(b)

Fig. 1. (a) Stratigraphic sequence at the sampling site (after [14]) and (b) envelopes of grading curves for the different soil layers recognized at the basin of the Lattari Mts (in parentheses the number of samples analysed).

The soil specimens were prepared layer by layer through dried soil air pluviation [15, 16, 17, 18] to reproduce the field porosity (around n=0,6; [14]), inside jars of shape and size compatible with the sensor geometry. After complete oven-drying of the material, a pyroclastic fall was generated by hand with a filling funnel. The latter was placed at a distance of 20 cm to the current layer surface. The dried specimens were then wetted using a sprinkler-like system, in order to facilitate homogeneous distribution of water and avoid volumetric collapse.

Following this procedure, triplets of specimens at 4 different gravimetric water contents, w, were obtained: w=21%, 31%, 42% and 57%, corresponding to saturation degrees: S_r=36%, 54%, 71% and 96%, respectively. The sensor operates both below and above the air entry value, which is typically recognized to correspond to values of S_r ranging between 75 and 80%. To investigate the repeatability of the measurements, each gravimetric water content was reproduced on a triplet of specimens, resulting in 12 tested specimens.

For each specimen, measurements were taken at different time intervals from wetting, up to the reach of a steady impedance measurement, as will be discussed in more detail in Section 4. After wetting, then, the specimens were sealed as to minimize evaporation losses and weighted before each measurement.

Table 1. Physical properties of the tested soil.

n **(-)**	0,6-0,7
γ_s **(kN/m^3)**	25,1
γ_d **(kN/m^3)**	10,09
IP **(%)**	n.d.

3.2 Measuring system

The measuring system consists of a prototype sensor holding the two conducting electrodes (Figure 2a) and an impedance measuring circuit (Figure 2b), equipped with an on-board signal generator and an analog-to-digital converter (Analog device: AD5943, 2017; [19]). During the impedance metering operations, the two stainless steel plates acting as electrodes are inserted in the specimen. The two electrodes (10x6x0.3 cm) are placed at a distance of 4 cm. Thus, the sampling soil volume equals 240 cm^3.

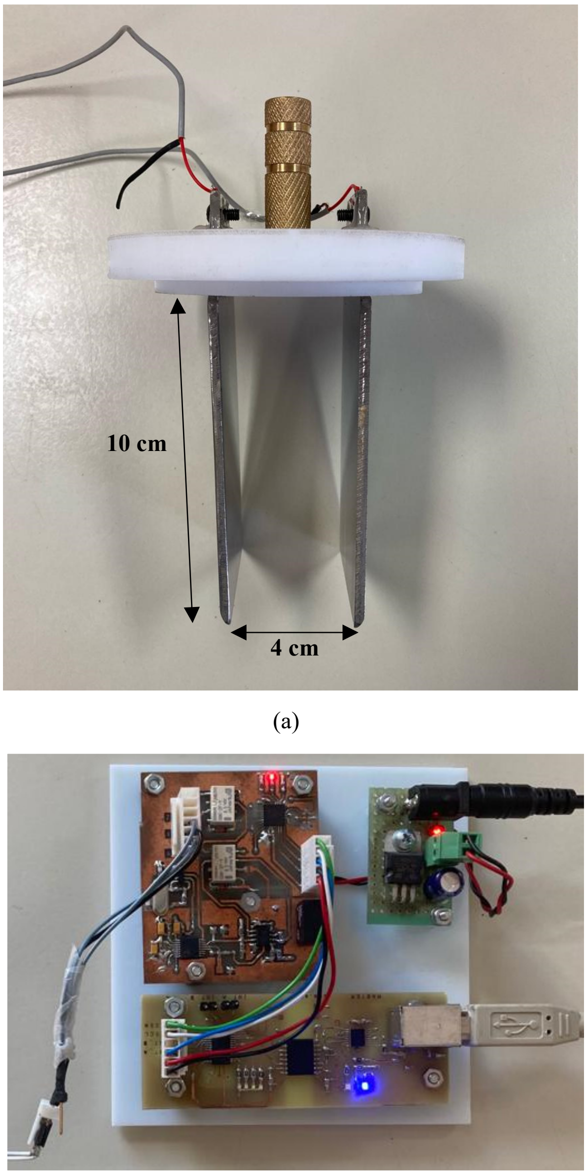
The impedance spectroscopy analysis is carried out by means of an external computer interfaced via USB.

Through the signal generator, the impedance meter applies to the electrodes within the specimen an alternate voltage, whose frequency is linearly increased over the range [500 Hz - 50 kHz]. This interval allows to minimize environmental interference affecting impedance analyses for higher frequency values. The application of a voltage between the electrodes causes a current intensity across the soil specimen, which is affected by the soil impedance. The current stemming across the specimen is then transduced, digitalized and processed by the impedance meter to obtain the impedance modulus and phase angle.

To evaluate the performance of the prototype system, an experimental setup made of a decade resistor and a sample capacitor in series has been assembled and repeated tests have been carried out on a set of nominal values of impedance, at discrete frequency values.

The procedure has proved the linearity of the prototype system and its accuracy, in terms of deviation between measured and nominal impedance values. Figure 3 illustrates the results for discrete frequency value set to 10 kHz.

Then, in order to exclude artifacts in the metering operations, the prototype impedance measurements at different water contents were compared to those of benchtop impedance meters, assumed as reference. Since the latter operates at discrete frequency values, the measuring frequency was set equal to 1 kHz.



(a)

(b)

Fig. 2. (a) Prototype sensor and (b) impedance measuring circuit.

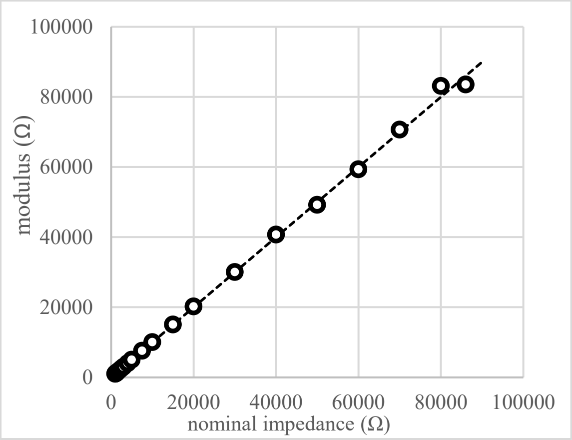
4 Preliminary results

Some preliminary results on the triplets of specimens mentioned above will be presented in this Section.

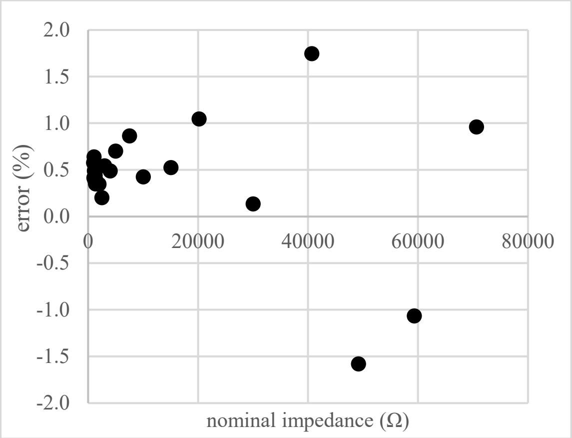
For each specimen, homogeneous distribution of water after wetting, as well as limited evaporation losses, have been verified. To this end, the impedance measurements were repeated at different time intervals from wetting (2h, 4h, 8h, 24h, 48h, 3 days, 7 days, 21 days) up to the reach of steady impedance values. The results shown in the following refer to the steady condition.

Figure 4 illustrates the impedance modulus (Figure 4a) and phase angle (Figure 4b) over the whole operational frequency range for the four triplets of wetted specimens.

For all specimens, the impedance modulus reaches a constant and frequency-independent value already at low frequencies (<1 kHz); the impedance phase, instead, varies linearly with frequency up to f=45 kHz. Apart from the triplet at water content w=21%, the impedance analyses reported show high repeatability. It is suspected that, at water contents as low as 21%, the impedance measurements are likely to be more sensitive to differences in porosity and/or soil structure among the specimens belonging to the same triplet, thus causing more pronounced dissimilarities in the measurements (Figure 4).



(a)



(b)

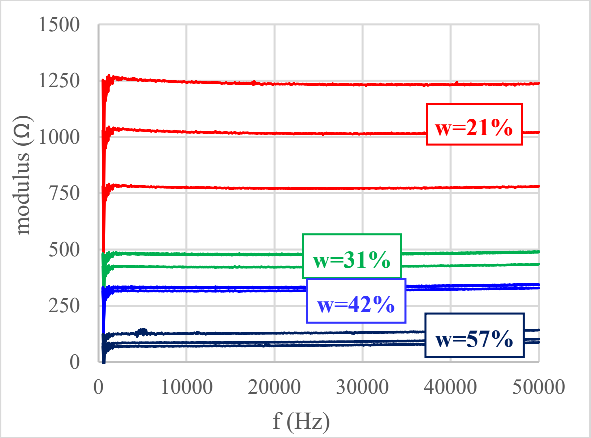
Fig. 3. (a) Linear system response and (b) measuring error against a known impedance system (f=10 kHz).

When comparing the electrical response at different water contents (Figure 4a), the impedance modulus decreases while w increases, as expected due to the highest electrical conductivity of the pore water compared to the grains (e.g. [5, 11, 12]).

Figure 5 reports, in linear scale, the values of the impedance modulus, which is frequency-independent, against the corresponding specimen water content. As the soil porosity was not controlled during the test, gravimetric water content was used as variable to be plotted against impedance modulus. The empty symbols refer to the impedance measured by the benchtop impedance meter, set at fixed operational frequency.

The impedance analyses achieved using the measuring system presented herein match well with the benchtop impedance metering results, confirming the effectiveness of the prototype.

Moreover, the results in Figure 5, although preliminary, suggest the existence of a monotonic correlation between the impedance modulus and the gravimetric water content of the specimens tested.



(a)

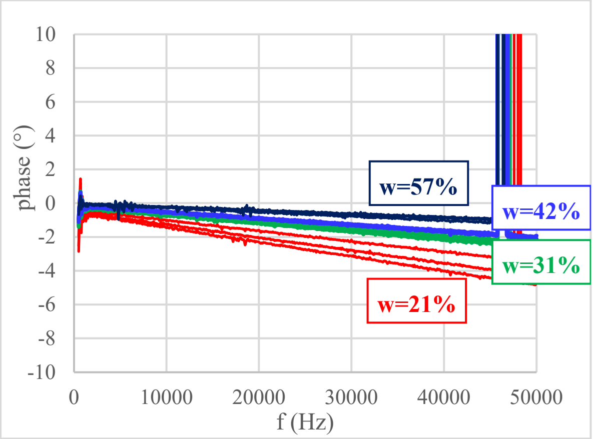


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Fig. 4. (a) Impedance modulus and (b) phase angle across the whole frequency range, for water contents ranging from w=21% to 57%.

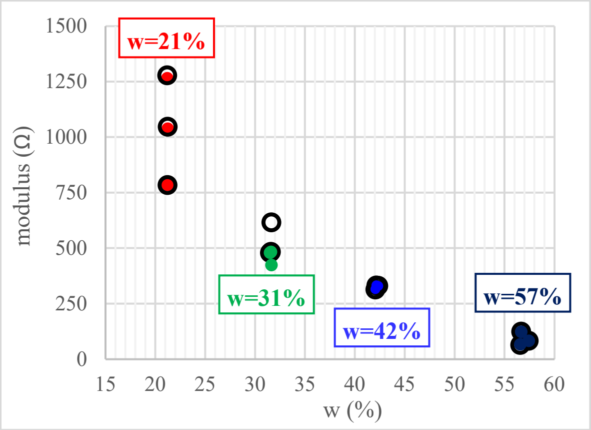

Fig. 5. Preliminary correlation between water content, w, and impedance modulus and comparison with the impedance meter measurements (empty symbols) on each specimen.

5 Conclusions

The paper presents a study on the development of a device for measuring water content in partially saturated soils, based on impedance spectroscopy. The new system is conceived for field applications in pyroclastic soils covering steep slopes susceptible to rapid flowslides [20, 21] and it may be even implemented in real-time monitoring nets within early warning strategies. The experimental activities devoted to test the efficiency of the method and to gain the calibration function of the innovative system in pyroclastic soils have been described.

Preliminary results show the efficiency of the system in characterising the electrical properties of the soil tested. Also, the system is able to describe the relation between the soil specimen response and its gravimetric water content, identifying a non-linear monotonic correlation between the impedance modulus and the specimen water content with satisfactory repeatability. The proposed methodology hence appears as a promising alternative to traditional field water content measuring techniques, with the advantage of reducing costs significantly. Applications to different lithotypes are envisaged, provided that proper calibration procedures are undertaken.

Further investigation is required at low saturation degrees, where impedance analyses provide less accurate results, although such low water contents are seldom recorded on site and might be less relevant for slope stability purposes. Then, future work shall include investigation of the correlation between water content and impedance phase angle, other than modulus, as the latter is seen to vary linearly over the wide operational frequency range investigated. Further experiments will be carried out on triplets at unexplored water contents; also, stepwise wetting will be performed on an on-purpose triplet of specimens.

Alternative sensor geometries will be manufactured and tested, to exploit the versatility of the device which allows the full customization of the system and better adapt to specific monitoring needs and field measuring operations.

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