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Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

Principles and applications of a new class of soil water matric potential sensors: the dihedral tensiometer

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Abstract

Soil tensiometers are instruments to measure directly, without calibration, the soil matric potential between zero and the barometric pressure, but in practice it is functional up to about 85 kPa, allowing monitoring continuously the soil water status for irrigation scheduling and other hydrological applications. The major drawback of these instruments is water cavitation, which causes interruption of measurements (tension breakdown) and requires instrument re-saturation. In order to avoid the major problems related with common tensiometers, a new class of instruments named dihedral tensiometers was developed at the Brazilian Agricultural Research Corporation. In this new class of instruments two rectangular hydrophilic flat glass plates or one glass plate with a fine porous flat plate are fixed in angle, defining the dihedral angle. The distance from the vertex to the water meniscus (L) formed after equilibration is linearly proportional to the soil matric potential. Using different spacer thickness between the two flat plates allows constructing sensors for different matric potential ranges and applications. Several dihedral tensiometer prototypes have been designed, constructed and tested for matric potential measurements in pot substrates and soils. Results shows linear responses between the applied water potential, using a Richards chamber as reference, and the distance L. Time responses was of few minutes to about 40 min, depending on the range of measurement, on the spacer thickness, and on the porous element properties and length. Results of experiments performed in laboratory are presented and discussed as well as the basic principles and construction details of the dihedral tensiometer are described.

Keywords: Soils water matric potential; Sensor; Laplace's law

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1. Introduction

Soil water matric potential (ψ) determinations are crucial for most of soil-water relationships and processes studies and for practical applications in different areas as agriculture, environment, civil and geotechnical engineering. Water movement in soils is driven by the gradient of the total soil water potential, which is composed of the gravitational, matric (capillary and adsorptive forces), osmotic, pneumatic and overburden potentials [1]. However, at the unsaturated and vadose zone the soil matric potential is the most important and difficult to access component of the total water potential and, therefore, great efforts and attention has been devoted to instrumentation and method for ψ measurements.

Direct measurements of ψ in the field are generally performed by soil tensiometers for the relatively low soil water tension or wet range, whereas indirect measurements can be done by thermocouple psicrometers, gypsum blocks, granular matrix sensors, filter paper method or heat dissipation sensors for the high soil water tension or dry range [1,3]. Although the tensiometric technique is straightforward, relatively easy to use and its range of measurement is adequate for most of the agronomic applications [1] it does not cover the entire range of interest and are unsuited for some applications where soil water limits plant growth, for instance [3]. Additionally, an important drawback is the continuous maintenance requirement of these apparatus (re-saturation of the porous cup) due to water cavitation (spontaneous boiling) when the soil dries to matric potentials higher than about 85 kPa or when air flows through the porous cup (soil dries to ψ values higher than the air entry value - bubbling pressure - of the ceramic porous cup). Disadvantages of the indirect methods are slow response time, hysteresis, the non-uniqueness relationships between ψ and the sensor output, and lower sensitivity and accuracy [3,4].

In order to extend the operation range of tensiometers to higher ψ values several alternative or advanced tensiometers have been developed, as self-filling, osmotic or polymer tensiometers [4,5,6,7] and improved tensiometers that uses the defervescence concept (delay in boiling) to minimize the cavitation [8,9]. However, these special tensiometers are difficult to construct and the commercial versions are expensive. They are relatively complex technologies, including temperature compensation, electromechanical components, use strongly hydrophilic and high air entry value ceramic materials or need special pressure-vacuum pre-cycling procedures to dissolve potential cavitation nuclei. These advanced tensiometers are relatively new technologies, not widely tested and, for those reasons, still restricted to some special applications [4,10].

Another sensor system developed to directly measure the soil matric potential for irrigation scheduling which is not affected by water cavitation was proposed by Calbo [11] and tested by Paschold and Mohammed [12] and Calbo and Silva [13]. The Irrigas® sensor consists of a porous cup connected to an air pressuring/measuring device and pertains to the class of sensors that uses the principle of air permeation to the porous material [14]. Operating at the discrete mode the Irrigas sensor indicates the moment to irrigate when the soil dries to matric potentials higher than the porous cup bubbling pressure (Tb) and an applied low air pressure permeates the porous cup. Working in a continuous mode the Irrigas can operate as a tensiometer with a linear response from zero to Tb [13], differently from the system proposed by Kemper and Amemya [15], in which the air permeability increases as sigmoidal function of ψ. The Irrigas system has been widely used in Brazil for irrigation management in horticulture mainly for tomato cultivation and other vegetable crops. The main drawback for field applications is the need of pressurized air source and significant amount of tubing connections.

Aiming to overcome the major problems related with common tensiometers, a new class of instruments named *dihedral tensiometers* was developed at the Brazilian Agricultural Research Corporation, Embrapa [16,17]. In this new invention two rectangular hydrophilic flat glass plates are fixed in angle, defining the dihedral angle. The system is fixed in a porous element for contact with soils or other porous material and the distance from the vertex to the water meniscus formed after equilibration is proportional to the soil matric potential (ψ). Alternatively, one glass plate and one flat porous plate can be used to form the dihedral angle. Using different spacer between the two flat plates allows constructing sensors for different matric potential ranges and applications.

In this work the general principles of the dihedral tensiometer are presented as well as different designs and construction for different applications in pot substrates, ornamental vases and field applications. Sensors time response and accuracy are evaluated using a Richard chamber as reference for varying matric potentials.

2. Material and Methods

2.1. Background and definitions

The dihedral tensiometer system is comprised of two flat glass plates attached in a dihedral configuration (two nonparallel plates) with a water film between the plates. The distance from the vertex to the water meniscus (L_i) and the distance between the plates at the meniscus position (a_i) are related by the tangent of the dihedral angle (α), as shown in Fig. 1.

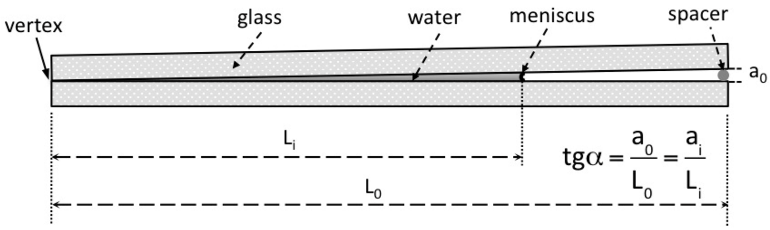

Fig. 1. Sketch of the dihedral tensiometer with a dihedral angle α.

The pressure between two nonparallel wetting plates can be derived from Laplace's law (sometimes called Young-Laplace-Gauss law) that links the curvature of a liquid-gas interface to the pressure differences across the interface. Laplace's law for the curvature of the interface in a dihedral is given by Eq. 1 and the curvature radius R can be expressed by Eq. 2 [18].

$$P_0 - P_i = \frac{\sigma}{R} \tag{1}$$

$$R = \frac{r_i}{\cos(\alpha + \theta)} \tag{2}$$

where P_i is the pressure inside and P_0 outside the liquid, R is the radius curvature, σ the water surface tension (0.0728 Nm^{-1} at 20 °C), θ the wetting angle and α the dihedral angle.

Substituting Eq. 2 in Eq. 1 and considering $P_0 = 0$ (open chamber dihedral), $\cos(\alpha + \theta) \cong 1$ (because $\alpha + \theta \cong 0$) and writing the distance $a_i=2r_i$, provides Eq. 3, which relates the pressure in the liquid-gas curvature interface with the distance between the plates at the interface position. The two plates separation distance at the liquid-air interface can be expressed as $a_i = L_i$ tg α, allowing the determination of the pressure P_i by simply measuring L_i, since α is known for a fixed dihedral angle ($tg\alpha = a_0/L_0$).

$$P_i = -\frac{2\sigma}{a_i} = -\frac{2\sigma}{L_i tg\alpha} \tag{3}$$

2.2. Dihedral tensiometers description

When a dihedral tensiometer (Fig. 1) is placed in contact with a soil porous medium by its vertex, the water film under tension inside the sensor equilibrates with the soil water matric potential (ψ) and measurements of ψ can be performed just by measuring the distance L_i at equilibrium with a rule or a caliper.

In order to favor water to enter through the sensor by its vertex, one of the glass plates needs to be scratched at the bottom to form microchannels. Nevertheless, one possible problem with this configuration (glass/glass) is contamination with chemicals dissolved in the soil water (salts, organics, pollutants) on the internal glass plates, modifying the glass hydrophilicity and therefore the wetting angle θ. One approach that minimizes this problem and increase sensor lifetime is to substitute one of the glass plates by a porous plate or connect the vertex to a porous material. In both cases the porous material can act as a filter for colloids and some chemicals.

Fig. 2 illustrates three dihedral tensiometers made of glass/gypsum block (S1), glass/ceramic (S2) and glass/glass + gypsum (S3) with spacers of 160 μm, 60 μm and 30 μm, respectively. Different spacers are used to provide various ranges of measurement for the soil matric potential. The two plates of each sensor is kept together adding small amounts of epoxy resin to their lateral openings. At the top, near the spacer, no resin is applied in about 2 mm length allowing the air to enter or escape from the dihedral cavity when the meniscus moves due to changes in ψ.

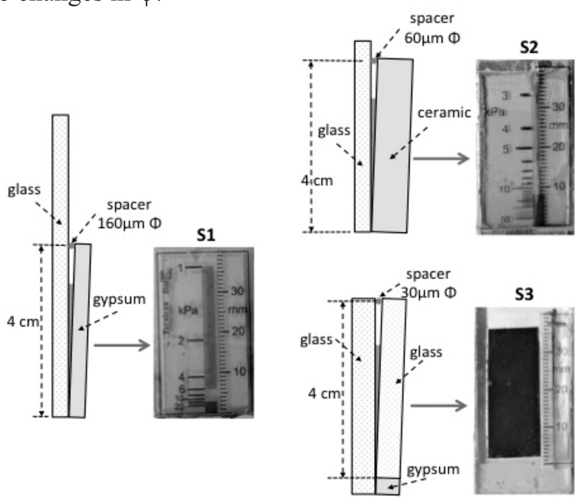

Fig. 2. Description of three dihedral tensiometer configurations named S1, S2 and S3.

The extremely plain glass surface is very suited for this kind of application (e.g sensor S3), but the gypsum block needs a prior planation process to get a very plain surface for sensor S1. The gypsum planation is obtained by pressing a clean glass plate to the gypsum/water mixture. After the gypsum setting, the glass plate is removed and a very smooth and plain surface is obtained. The same procedure is applied to obtain a plain surface in the ceramic block (sensor S2) adding a small amount of gypsum/water mixture to one of the ceramic surface and pressing it to a glass surface, resulting in a thin layer of gypsum on this ceramic face. In sensor S3 a small amount of gypsum is placed close to the vertex to allow water enter into the sensor and a black plastic tape is stick at the back external surface to improve the meniscus visualization. Before use all dihedral tensiometers are placed in a clean glass plate and water is added to saturate the porous materials and fill the dihedral cavities. Thereafter, the sensors are ready for use by just pressing slightly the porous face against the soil surface.

For measuring ψ in subsurface soil layer a sensor design as shown in Fig. 3 can be used, consisting of a gypsum porous rod protected laterally with a heat-shrink tubing and a glass/glass dihedral tensiometer (sensor S3 type) glued at the gypsum rod top with gypsum/water mixture in a 30^o inclination. The gypsum porous cylinder provides hydraulic contact between the soil in deeper layers with the dihedral tensiometer, which is positioned above the soil surface.

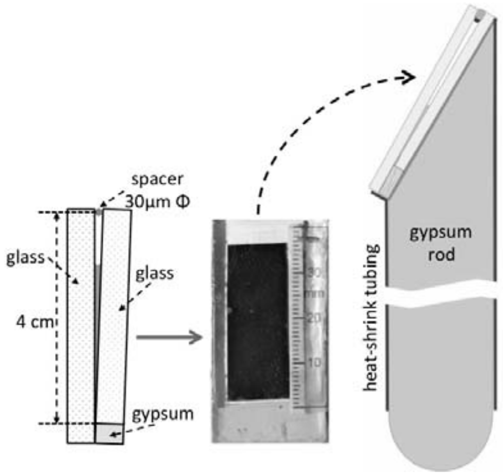

Fig. 3. Description of a dihedral tensiometer (sensor S3 set at the top of a 30 cm long gypsum rod) designed to measure ψ in subsurface soil layers.

2.3. Experimental procedure to test the dihedral tensiometers

A Richard chamber working at negative pressure (suction) mode was used to evaluate the performance of the three dihedral tensiometers S1, S2 and S3 (Fig. 2) and the tensiometer shown in Fig. 3. Fig. 4A shows the experimental setup used to test sensors S1, S2 and S3, consisting of two Richard chambers with a ceramic cup (bubbling pressure of about 50 kPa) filled with fine glass beads (particle diameters lower than 100 µm), connected to a vacuum pump and a mercury manometer. The dihedral tensiometers were placed on the Richard chamber as indicated in Fig. 4A and suctions from 0.5 to 12 kPa, 0.5 to 25 kPa and 5 to 50 kPa for tensiometers S1, S2 and S3, respectively, were applied in steps, and L_i (mm) measured after equilibrium. The procedure was repeated four times for each dihedral tensiometer. Fig. 4B presents the setup for testing the gypsum rod/dihedral tensiometer S3 (Fig. 3), where the uncovered bottom end is placed into the Richard chamber and suctions are applied similarly to the experiment described to test S1, S2 and S3.

The response time were evaluated by measuring L_i (mm) as a function of time after applying different suctions for the three dihedral tensiometers. The accuracy was accessed by the root mean square deviation (RMSD) of the measured matric potential for the applied suctions (four replications) and the measured matric potential after equilibration in a sandy soil and a pot substrate composite.

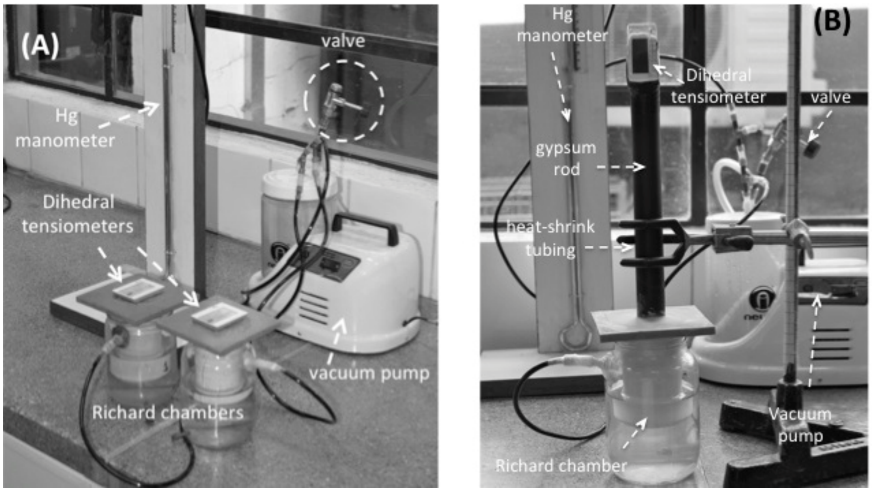

Fig. 4. Experimental setup to test the dihedral tensiometers S1, S2 and S3 (A) and the glass/glass dihedral tensiometer (S3) connected to a gypsum rod shown in Fig. 3 (B).

3. Results and Discussion

Responses of the dihedral tensiometers S1, S2 and S3 (L_i; mm) with the applied suctions in the Richard chamber ($\psi_{applied}$) are presented in Fig. 5 (graphs on left side) as well as the equivalent measured matric potentials ($\psi_{dihedral}$ obtained from measured L_i, using Eq. 3) against the applied suctions (graphs on right side). The dihedral tensiometer responses were linear at their full operational scale, but an offset (ψ_0) was observed between $\psi_{dihedral}$ and $\psi_{applied}$. The offset values varied among sensors (higher for S2 and lower for S3) and indicate an average overestimation of about 1 kPa.

The reasons for this small overestimation is not evident and must be further investigated. One possible reason is the assumption of zero wetting angle ($\cos\theta=1$) in Eq. 2. In general, reported measured water wetting angle in glass surfaces (angle θ) varies from about 10 to 50^o [19,20] with the $\cos\theta$ varying from 0.98 to 0.65 and, therefore, causing an overestimation in ψ measurements, using Eq. 3, of about 2 to 35%. For that reason it is very important to clean the dihedral internal glass surfaces prior to the sensor construction. Another aspect to be considered is that the dihedral angle α can be affected by imperfection in the rectangular dimensions of the glass or ceramic plates (arising from cutting the glass and preparing the ceramic or gypsum plates) as well as the presence of some very small particles (dust, ceramic or gypsum powder) during the sensor preparation. These imperfections cause deviations from Eq. 3.

Considering the offset observed and the aforementioned imperfections in the sensor construction, Eq. 3 can be re-written including ψ_0 as a linear term (Eq. 4) and the experimental data can be used to calculate ψ_0 and the actual distance a_0 and $tg\alpha$ by least-square fitting [21] for each sensor, as shown in Table 1.

$$\psi = -\left(\psi_0 + \frac{2\sigma}{L_i tg\alpha}\right) \tag{4}$$

Table 1. Range of measurement, root mean square deviation of ψ using Eq. 3 (RMSD#) and Eq. 4 (RMSD&) and determination coefficient (r^2). ψ_0 and a_0 were obtained fitting Eq. 4 to the experimental data presented in Fig. 5 (least-square fitting).

Sensor	range	RMSD#	r^2	ψ_0	a_0	RMSD&
	kPa	kPa		kPa	m	kPa
S1	0.5 to 12	1.0	0.98	0.67	169.7	0.4
S2	0.5 to 25	1.4	0.98	1.52	58	0.8
S3	5 to 50	1.9	0.99	0.52	30.5	1.7

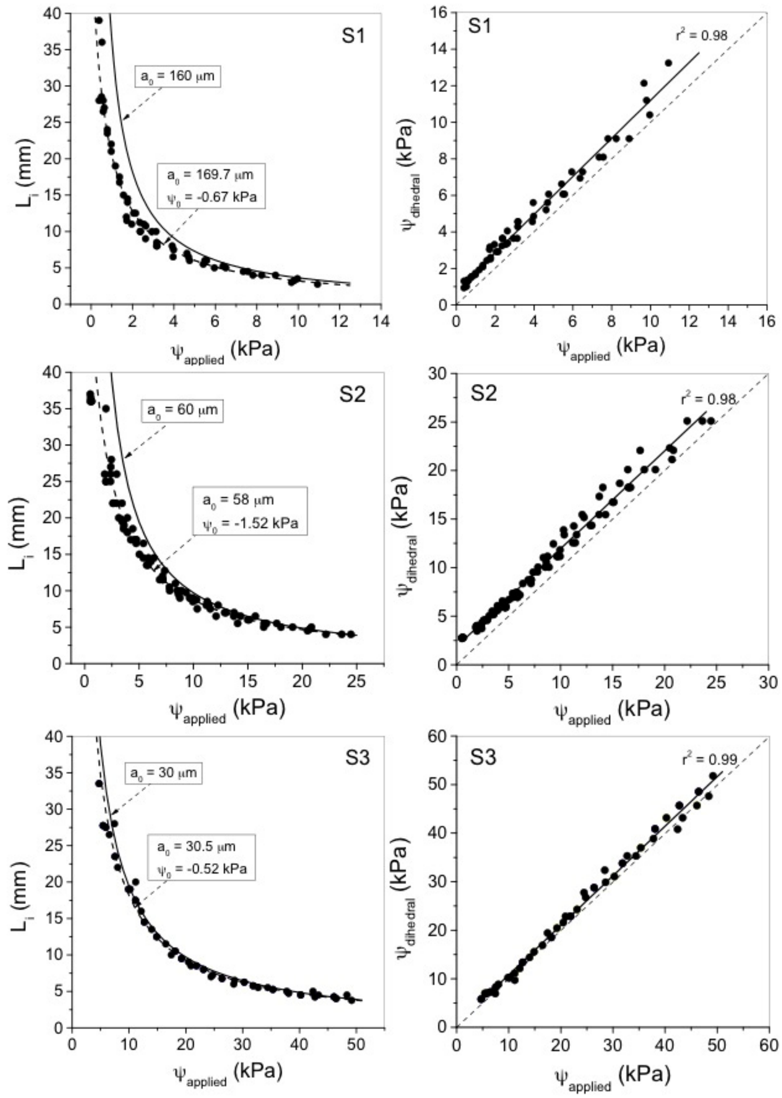

Fig. 5. Measured distance from vertex to meniscus (L_i) as function of the applied suctions ($\psi_{applied}$) (graphs on the left side) and comparison of $\psi_{applied}$ and measured matric potential with the dihedral tensiometer ($\psi_{dihedral}$) (right side), for S1, S2 and S3.

Continuous and dotted lines in the left side graphs of Fig. 5 shows the original Eq. 3 (continuous lines) and the modified equation (Eq. 4, dotted lines) fits that considers the estimated offset ψ_0 and the adjusted a_0 values for each sensor. Table 1 presents fitted ψ_0 and a_0 values and the RMSD's obtained in the estimation of the matric potential with these three dihedral tensiometers. The estimated a_0 values are very close to the values measured with micrometer caliper (varying from 2 to 6 % differences) and ψ_0 varied from -0.5 to -1.5 kPa. The combination of these two parameters affects the uncertainty in $\psi_{dihedral}$ determinations with root mean square deviations of 1.0, 1.4 and 1.9 kPa ($RMSD_1$) for dihedral tensiometers S1, S2 and S3, respectively. However, when each sensor is corrected considering the actual fitted a_0 and ψ_0 (Eq. 4) the RMSD is reduced to 0.4, 0.8 and 1.6 kPa, respectively ($RMSD_2$ in Table 1). Therefore, the average precision of these dihedral tensiometers was 1.4 kPa using Eq. 3 and reduced to 0.9 kPa when individual corrections using Eq. 4 are applied.

The response time for various suctions applied are presented in Fig. 6 for the dihedral tensiometers S1, S2 and S3 and the gypsum rod/dihedral tensiometer of Fig. 3. Results show that equilibrium is obtained in about 2, 4 and 15 minutes for tensiometers S1, S2 and S3, respectively. Sensor response for dihedral tensiometer connected to the 30 cm gypsum rod was about 40 minutes. This was caused by the relatively low water conductance of the gypsum rod and other material having higher conductance should be further selected and tested for this specific application.

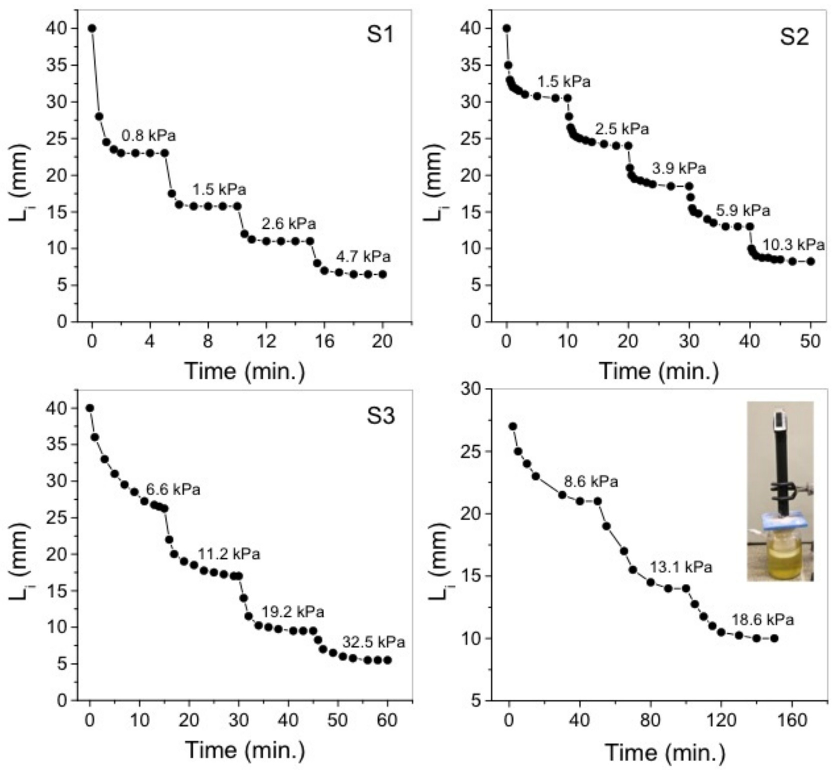

Fig. 6. Response time for various suctions applied in the dihedral tensiometers S1, S2 and S3 and the gypsum rod/dihedral tensiometer S3 shown in Fig. 3.

Results from the dihedral tensiometers application (S1, S2 and S3) in a sandy soil and a pot substrate, after parameterization of Eq. 4 (parameters ψ_0, and a_0 presented in Table 1) are depicted in Fig. 7. Data were obtained placing the dihedral tensiometers S1, S2 and S3 on the Richards chamber at a given suction and waiting 15 minutes for the sandy soil and 30 minutes for the substrate reading L_i (mm) at the tensiometer display. Sensor accuracy can be assumed as the root mean square deviation of these two experiments in sand and substrate as the average value of 1.4 kPa. For the gypsum rod/S3 dihedral tensiometer tested using an equilibration time of 40 minutes in the sandy soil the RMSD obtained was also 1.4 kPa.

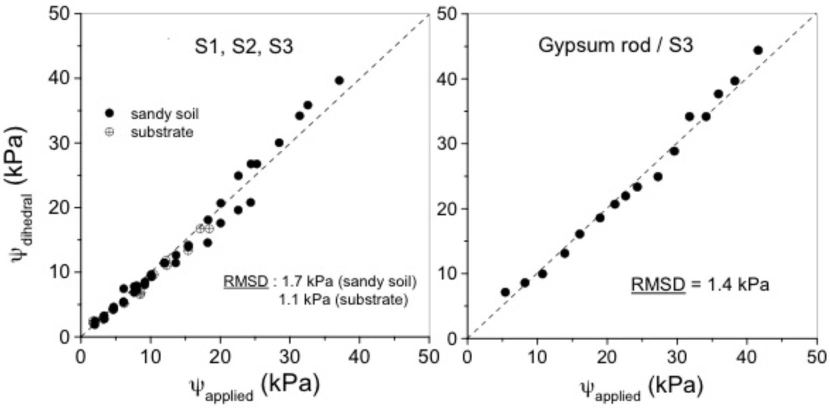

Fig. 7. Application of dihedral tensiometers S1, S2 and S3 for measuring the matric potential (corrected Eq. 4) in a sandy soil and pot substrate composite (left), and in a sandy soil with the gypsum rod/ dihedral tensiometer S3 shown in Fig. 3.

4. Conclusions

The three dihedral tensiometers constructed with glass/gypsum block (S1), glass/ceramic (S2) and glass/glass (S3) flat plates (4cm long) and spacer diameters of 160, 60 and 30 μm presented linear responses with the applied suction adjusted at a Richard chamber and monitored with a mercury manometer, at equilibrium condition.

An offset (ψ_0) of about 1 kPa between the applied suction adjusted at the Richard chamber system and the measured matric potential by the dihedral tensiometer was observed and the reasons for this behavior must be further investigated.

Equilibrium time was relatively fast, varying from 2 (S1) to 15 (S3) minutes. Equilibrium between the suction applied at the Richards chamber and the dihedral tensiometer placed on the top of the gypsum rod (Fig. 3) was obtained in about 40 minutes.

Results presented show a great potential for this new class of sensors for soil water potential determinations. Automatic readings of the dihedral tensiometers can be performed by electrical, pneumatic, optical or others and are under investigation.

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