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Giovanni Rallo, PhD, Fellowship researcher; Giuseppe A. Provenzano, PhD, Associate Professor

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--Manuscript Draft--

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Discussion
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Discussion of "Laboratory and field calibration of the Diviner 2000 probe in two types of soil" by J. Haberland, PhD, R. Galvez, C. Kremer, PhD, and C. Carter.

2014. J. Irrigation and Drainage Eng. ASCE. DOI: 10.1061/(ASCE)IR.1943-4744.0000687

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Comments to the paper

The authors deal with the quite interesting and actual problem of Diviner 2000 capacitance probe calibration and present some field and laboratory data obtained on two different layers (0-0.26 cm and 0.26-0.50 cm) of the same soil profile, characterized by different textural class. The importance of site-specific calibration of sensors used to monitor soil or plant water status assumes a particular relevance in semi-arid environments where the application of precision irrigation represents an appropriate management strategy aimed to achieve high values of water use efficiency (Cammalleri et al., 2013). Moreover in clay soils, physical properties are strongly influenced by soil water content (Provenzano et al., 2013), so that the correct measurement of this variable plays a key role to increasing crop yield and preserving water.

However, these discussers would focus on some significant points to be corrected in the manuscript and some others that AA. should have been specified in the methodology and considered in the final discussion, as following specified, for the benefit of potential readers.

The need to install adequately the access tube, aimed to ensure the contact between the tube and the surrounding soil, is not only to avoid preferential flow of water down the walls of the tube, as considered in the paper, but also to reduce air gap around the tube and to avoid rough measurements of scaled frequency, used to estimate soil water contents, whose values depend on the mutual proportion of soil, water and air in the soil volume investigated by the sensor.

With reference to the second part of eq. (2) it is necessary to precise that the function $\theta_w(SF)$ correctly results:

$$\vartheta_w = \sqrt[B]{\left(\frac{SF}{A}\right)} \qquad (1)$$

or

$$\vartheta_w = aSF^b \qquad (1a)$$

in which θ_w is the volumetric soil water content, SF is the scaled frequency, $a=\left(\frac{1}{A}\right)^{\frac{1}{B}}$ and $b=\left(\frac{1}{B}\right)$ are two empirical coefficients, generally used when the calibration equation is expressed in terms of $\theta_w(SF)$ function.

Regarding the methodology, field calibration considered by the AA. followed the general procedure proposed by the manufacturer. When describing the related methodology, AA. should have been specified some soil physical parameters (texture, organic matter, bulk electrical conductivity, etc.) as well as the two depths, in each soil layer, at which they acquired the scaled frequency and then collected the undisturbed soil samples. Moreover, the dimension of the cylindrical samples, used to determine soil bulk density, should have been provided in the manuscript.

On the other hands, when referring to the laboratory calibration procedure, samples were prepared by using sieved soil collected in the same layers where field calibration was carried out. After sieving at 5,0 mm and air-dry the soil, three samples of not specified weight, corresponding to a volume of 20 l, were brought to volumetric soil water contents of about 5%, 15% and 35% by adding different amounts of water and then compacted in the plastic container, later on used for laboratory calibration of the sensor. Despite the similar compaction method applied to fill all the containers, these discussers consider questionable the adopted methodology, believing that soil should have been moistened only after filling the container and not before. Actually, the different initial water content characterizing the soil used to fill the containers, could have determined values of soil bulk density different between the samples, and also dissimilar from the actual value measured in the field.

In fact, if considering the standard protocol of compaction ASTM D698 (2005), by using a Proctor hammer, it is possible to achieve different values of bulk density depending on the water content of the sieved soil used to fill the containers. Fig. 1a,b shows the values of bulk density obtained in laboratory by applying the standard ASTM D698 protocol of compaction to two sieved soils, i.e. a sandy (PAR) and a clay loam (CAS), prepared at different gravimetric soil water contents (personal unpublished data). As can be observed, in both cases it is possible to detect an optimal value of gravimetric water content to which corresponds a maximum soil bulk density. Of course, considering that the values of bulk density in the soil volume investigated by the sensor, as well as the corresponding variability, were not provided in the manuscript, it is not possible to quantify in which proportion this variable could be responsible of the observed differences between field and laboratory calibration equations, whose coefficients are indicated in table 1 of the original paper.

Basically, soil bulk density must be essentially considered a source of uncertainty in estimation of volumetric soil water contents, because it affects the soil dielectric permittivity (Gardner et al., 1998) and also because it governs the relationship between gravimetric and volumetric soil water contents (Geesing et al., 2004).

In the following paragraph these discussers will present some unpublished experimental data, demonstrating the effects of soil bulk density on the scaled frequency and consequently on the estimated values of volumetric soil water content.

In addition, it is necessary to underline that the parameters *A* of the default calibration equation proposed by the manufacturer and indicated in the original table 1, must be corrected to 1.263 if soil water content is expressed in cm^3/cm^3; in fact, the value *A*=0.2746, obtained on different Australian soils (sands, sandy loams and organic potting), as specified in the Sentek Pty manual (2001), is referred to soil water content expresses in mm (Sentek Environmental Technologies, 2001) and therefore unit transformation must be considered to compare the different calibration equations presented in the original table 1.

These discussers strongly believe that in fig. 4a,b, the experimental points and their variability should have been indicated together with the regression functions, in order to recognize the dispersion characterizing the measurements and also to identify the limits of validity of the proposed equations.

The following fig. 2, rearranged from fig. 4a,b to adjust the inexistent curves' knee showed in the original version, also illustrates the dimensionally corrected default equation proposed by the manufacturer, whose actual trend, as a consequence, induces to reconsider most of the results presented and discussed in the paper.

Moreover, with reference to the misleading figs. 5 and 6, in which it is not clear the meaning of the represented continuous functions, AA. should have been represented the volumetric soil water contents estimated with the different equations versus the corresponding measured in laboratory (fig. 5) or in the field (fig. 6), together with the 1:1 best fitting line, in order to give a more comprehensible representation of the observed differences.

The comment on the error of 176% for the highest soil water content (P3) determined according to field experiments in the upper clay loam horizon (probably referred to the original fig. 6a and not to fig. 5, as indicated), attributed to the circumstance "that was not possible to dry the soil sufficiently to obtain a good dispersion of points during the field calibration process", seems to be in contrast with the following sentence evoked by AA. in which, according to Vera et al. (2010), they declared that significant errors could occur when soil water content is estimated "in areas not accounted for during the calibration process".

Anyway, the difficulty to dry the soil below certain water content evidenced by AA., has been also observed in field experiments carried out by these discussers, whose results have not been published yet.

In particular, field calibration of Diviner 2000 sensor was carried out in two layers (0-40 cm and 40-80 cm) of the same soil profile, by acquiring measurements every 10 cm, from 5 cm to 75 cm depth, according to the procedure suggested in the manufacturer's manual (Sentek Pty manual, 2001). Six 1.20 m long access tubes were installed in order to explore different soil water status, i.e. wet (P1), moist (P2) and dry (P3), during three different periods of the year, i.e. winter (P1), spring (P2), late summer (P3). According to USDA textural soil classification, the upper layer is classified as clay-loam, with a sand, silt and clay content equal to 42.4%, 18.9% and 38.7%, whereas the lower layer is sandy-clay with sand, silt and clay content equal to 45.3%, 18.0% and 36.7%, respectively.

Fig. 3a,b shows, for each considered soil layer, the experimental $SF(\theta_w)$ data pairs as well as experimental (dashed line) and manufacturer's (solid line) calibration equations. Standard deviations of scaled frequency and volumetric soil water content are also indicated. The former was obtained by considering two measurements acquired at each depth, whereas the latter was evaluated taking into account the values of θ_w

determined on three undisturbed soil samples (8.0 cm diameter, 5.0 cm high) collected at the different depths. For each soil sample, the value of θ_w was obviously calculated multiplying the gravimetric water content by the soil bulk density, ρ_b, evaluated on the same undisturbed sample.

As can be observed, if in the upper layer it was possible to explore a wide interval of volumetric soil water contents, variable between 0.05 cm^3/cm^3 and 0.33 cm^3/cm^3, in the lower layer the variations of θ_w resulted more limited and ranging between 0.20 cm^3/cm^3 and 0.31 cm^3/cm^3. Of course, the calibration equation identified for the lower layer cannot be considered valid for values of volumetric soil water content lower than 0.20 cm^3/cm^3. Moreover, observing fig. 3 a,b it is also possible to notice the great variability of volumetric soil water contents measured at each depth of the soil profile, as a consequence of its spatial variability as well as of the different bulk density characterizing the collected soil samples.

For upper and lower layers, fig. 4a,b shows the soil bulk density measured in the field as a function of depth, evidencing that at increasing depth, soil bulk density tends to rise and also that, for a fixed depth, the values of ρ_b are largely variable around their average value justifying, at least in part, the recognized variability of the measured volumetric soil water contents.

Finally, considering the quite high clay content characterizing either the soil investigated by these discussers than (probably) those examined in the original paper, another crucial aspect to be investigated should have been related to the shrinkage and swelling phenomena consequent to variations of soil water content that, depending on the clay mineralogy, could have affected both the original field and laboratory $\theta_w(SF)$ relationships.

Effect of soil bulk density on Scaled Frequency measured by Diviner 2000 probe

With the aim to evaluate the effect of soil bulk density on scaled frequency measured by Diviner 2000 probe, experiments were carried out on different agricultural soils collected in western Sicily, two of which will be presented in this discussion (a sandy soil, PAR and a clay loam soil, CAS). For each investigation site, the collected soil was air-dried, sieved at 5 mm and then used to fill two plastic cylinders (diameter and height equal to 25.0 cm), after placing in axial position a 30 cm long access tube. In order to achieve two quite different values of bulk density, a preliminary analysis on soil compaction properties was carried out by applying the standard D698 ASTM protocol (fig. 1a,b), so to assess the initial soil water content necessary to reach a pre-fixed value of bulk density. Then, two samples were prepared: the first by using air-dried soil (gravimetric water content $U \approx 0.05$) according to which a low bulk density was obtained (MIN), whereas the second was initially moistened to the optimal water content, variable between soils, allowing to reach the maximum bulk density (MAX). After filling the containers, soil was saturated and then the sensor calibration procedure was applied following an air-drying process. For each soil water content from saturation to oven dry, values of scaled frequency, sample weight and heights, the latter measured on eight points on the soil surface, were registered. At the same time, the lateral contraction was determined with analysis of the images captured on the soil surface. In this way it was possible to evaluate, at the end of the experiment, the gravimetric water contents and the corresponding actual values of soil bulk density.

Fig. 5a,b shows for both the considered soils the measured scaled frequency as a function of gravimetric soil water content, whereas fig. 5c,d illustrates the soil shrinkage characteristic curves, expressed in terms of variations of soil bulk density with gravimetric soil water contents. In particular, for the sandy soil (PAR), the values of bulk density are almost constant whatever is the gravimetric water content (rigid soil); on the other hands both samples of clay loam soil (CAS) evidenced reductions of bulk density at increasing water content even if, as visible, the extent of reductions is greater for sample with a lower bulk density (MIN). This circumstance is a natural consequence of shrinking phenomena occurring in soils containing a certain percentage of swelling clay.

Moreover, as can be observed in fig. 5a,b, for each gravimetric soil water content, greater the soil bulk density higher the scaled frequency measured by the probe. The diverse response of the sensor is an obvious consequence of the different contribute of soil, air and water to the soil dielectric permittivity.

When observing the graphs of fig. 6a,b, in which the values of scaled frequency are expressed against volumetric soil water content, it is possible to notice that for the sandy soil (PAR, fig. 6a) two quite different relationships $SF(\theta_w)$ can be identified, whereas for the clay loam soil (CAS, fig. 6b) a certain overlapping of the experimental points obtained in the two samples, as well as a lower variability of the $SF(\theta_w)$ relationships are visible for the higher water contents. This result is consequent to the compensative effect ascribable to the higher values of soil bulk density corresponding to the lower gravimetric water content, as determined according to the soil shrinkage characteristic.

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FIGURE CAPTIONS

Fig. 1a,b – Values of bulk density obtained applying the standard D698 ASTM compaction protocol to a sieved sandy soil (a, PAR) and to a clay loam soil (b, CAS) prepared at different gravimetric soil water contents.

Fig. 2 – Relationships $SF(\theta_w)$ presented in fig 4a,b of original paper and corrected Diviner 2000 manufacturer's calibration equation

Fig. 3a, b – Comparison of field calibration equations in two layers (0-40 cm and 40-80 cm) of a Sicilian soil (CAS) with calibration curve provided by manufacturer.

Fig. 4a,b – Values of soil bulk density measured at the different depths, for layers 0-40 cm and 40-80 cm.

Fig. 5a,d - Experimental $SF(U)$ and $\rho_b(U)$ data pairs and corresponding regression curves, obtained on samples prepared at different values of bulk density for a sandy (PAR) and a clay loam (CAS) soils

Fig. 6a,b - Experimental $SF(\theta_w)$ data pairs and corresponding regression curves, obtained on samples prepared at different values of bulk density for a sandy (PAR) and a clay loam (CAS) soils

Figure 1
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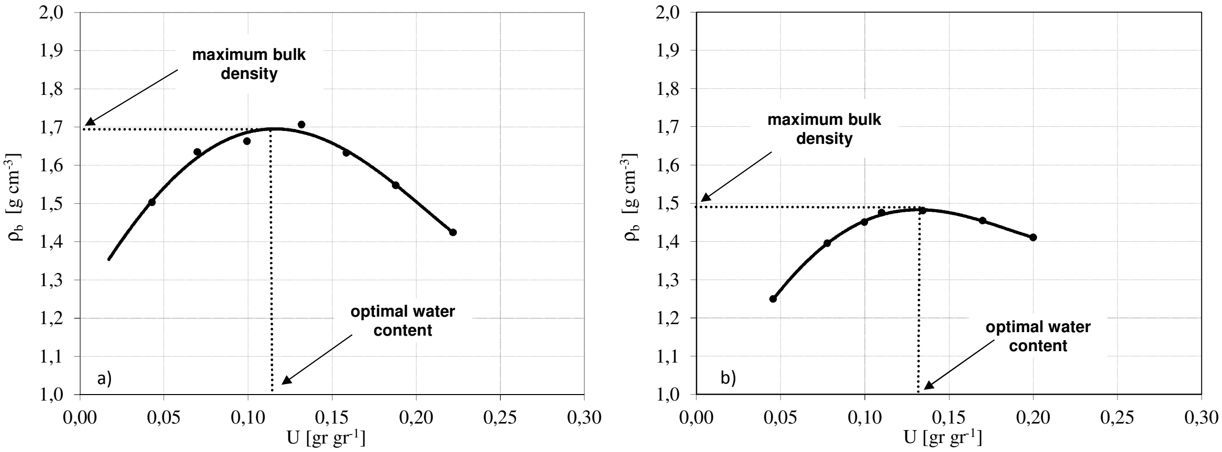

Fig. 1a,b – Values of bulk density obtained applying the standard D698 ASTM compaction protocol to a sieved sandy soil (a, PAR) and to a clay loam soil (b, CAS) prepared at different gravimetric soil water contents.

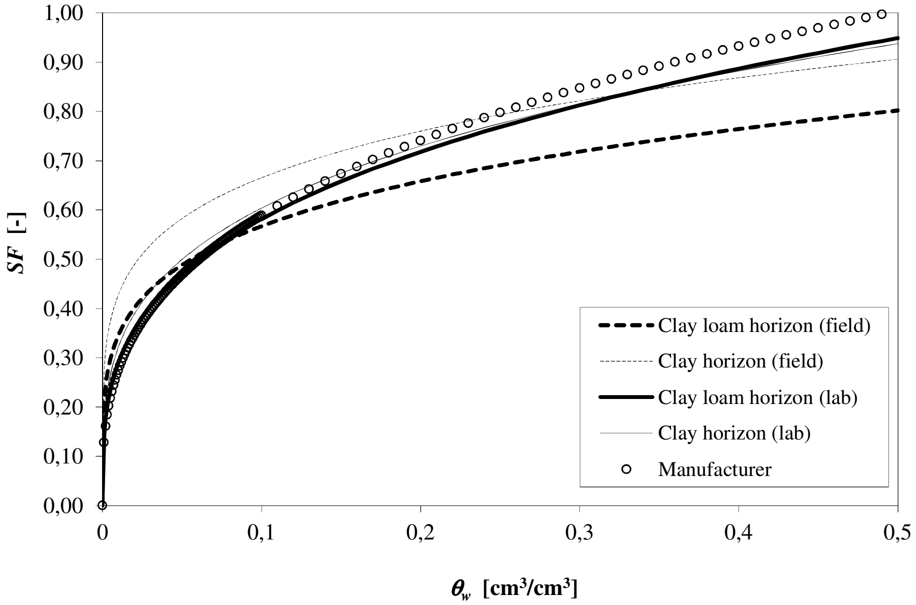

Fig. 2 – Relationships *SF(θ_w)* presented in fig 4a,b of original paper and corrected Diviner 2000 manufacturer's calibration equation

Figure 3

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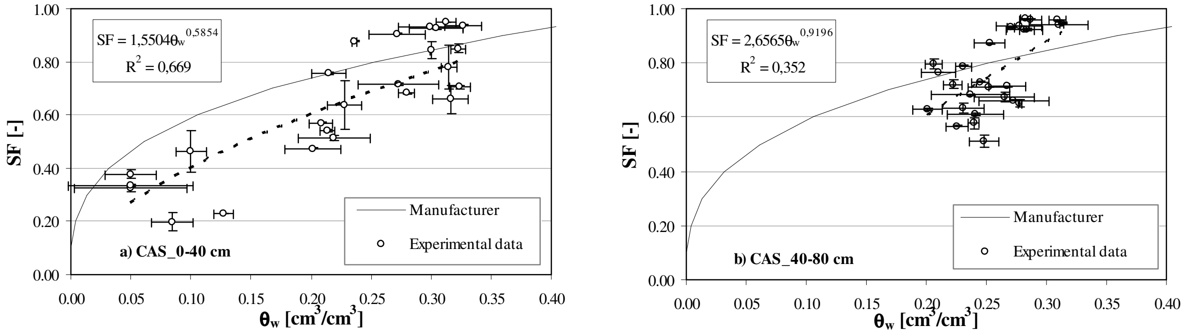

Fig. 3a, b – Comparison of field calibration equations in two layers (0-40 cm and 40-80 cm) of a Sicilian soil (CAS) with calibration curve provided by manufacturer.

Figure 4
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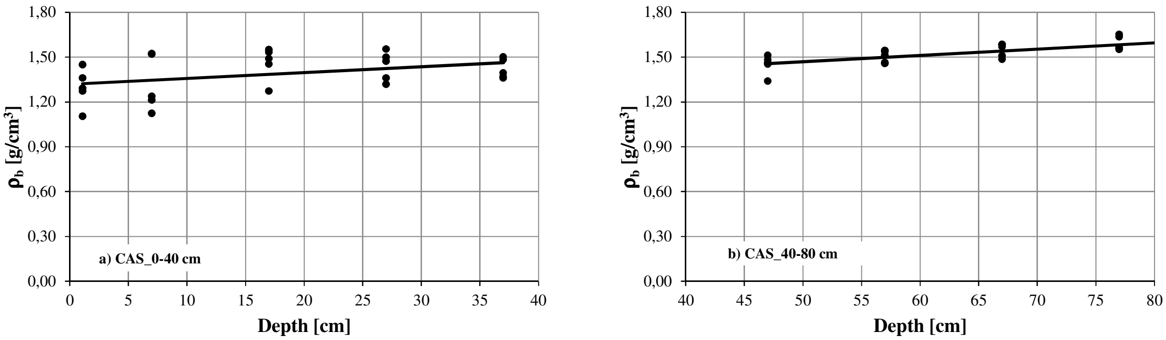

Fig. 4a,b – Values of soil bulk density measured at the different depths, for layers 0-40 cm and 40-80 cm.

Figure 5
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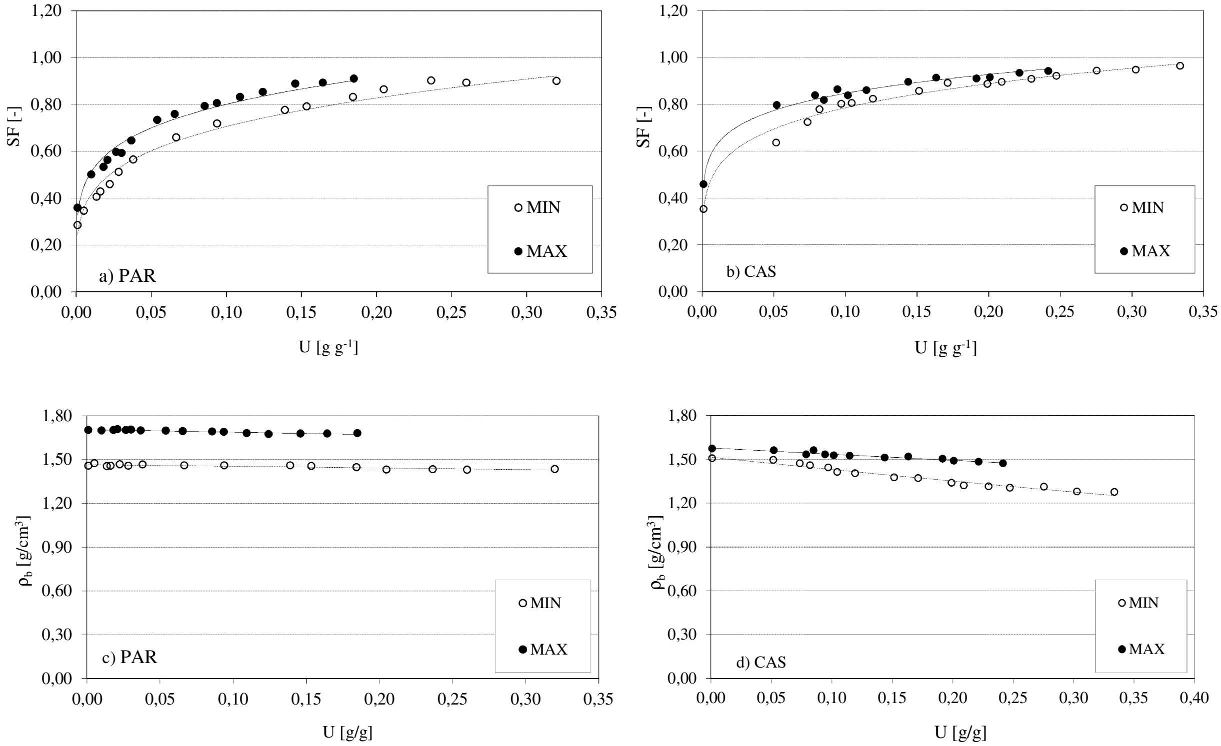

Fig. 5a,d. Experimental *SF(U)* and $\rho_b(U)$ data pairs and corresponding regression curves, obtained on samples prepared at different values of bulk density for a sandy (PAR) and a clay loam (CAS) soils

Figure 6

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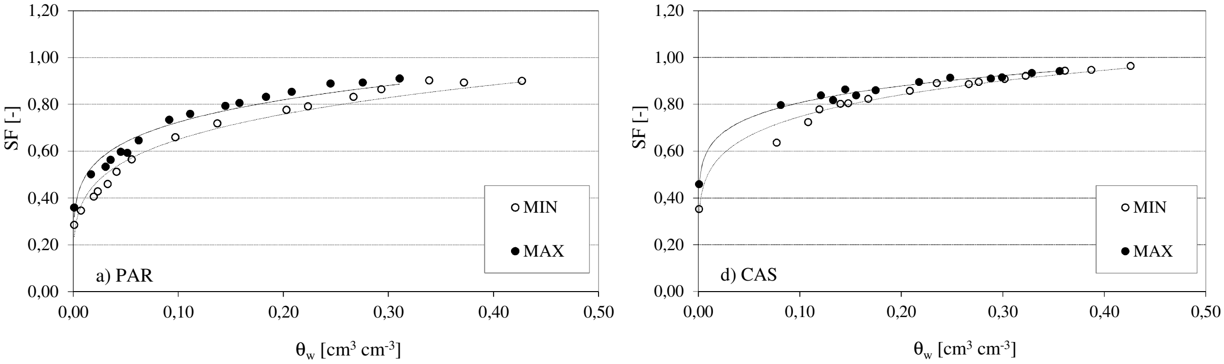

Fig. 6a,b. Experimental *SF(θ_w)* data pairs and corresponding regression curves, obtained on samples prepared at different values of bulk density for a sandy (PAR) and a clay loam (CAS) soils