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The laboratory calibration of a soil moisture capacitance probe in sandy soils

MARINA CAMPORA¹, ANNA PALLA^{2*}, ILARIA GNECCO²,
ROSSELLA BOVOLENTA², ROBERTO PASSALACQUA²

¹Genoa, Italy

²Department of Civil, Chemical and Environmental Engineering, University of Genoa, Genoa, Italy

*Corresponding author: anna.palla@unige.it

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Abstract: Determining and mitigating landslide risk is a technical-scientific objective, particularly for the protection and proper territorial management and planning. The slope stability depends on the pore pressure distribution, which is influenced by the saturation front propagation through the unsaturated zone, whose monitoring is useful to understand any possible instabilities. Such monitoring may be undertaken by sensors based on the measurement of the relative dielectric permittivity. Reliable relationships between the measurement and the soil moisture are necessary. The main objective of this study is to assess a laboratory calibration protocol for a specific capacitance sensor (Drill & Drop, Sentek Sensor Technologies). Two monogranular sands have been selected for the calibration purpose. The laboratory tests were performed under three relative density values (D_R equal to 40%, 60% and 80%) for seven volumetric water content values (θ_v ranging from 0.00% to 36.26%). Based on the experimental measurements, the soil-specific calibration curves were determined at an assigned relative density value; in particular, a simple power law is adopted to describe the probe's reading as a function of the volumetric water content. The results point out that the relative density values slightly affect the tests, thus, the soil-specific calibration curves are derived based on a simple regression analysis fitting the whole set of the laboratory tests validated for each sand. The calculated coefficient of determination ($R^2 = 0.96 \div 0.99$) and root mean square error ($RMSE = 1.4\% \div 2.8\%$) values confirm the goodness of fit. In order to propose more general fitting curves, suitable for both the investigated sands, multiple linear regressions are performed by considering θ_v and the mean grain size, D_{50} as independent variables; again, the R^2 and RMSE values equal to 0.97 and 2.41%, respectively, confirm the suitability of the calibration curve. Finally, the laboratory calibration curves are compared with the manufacturer-supplied curves, thus, enhancing the need for the soil-specific calibration.

Keywords: particle size distribution; regression analysis; relative density; soil water monitoring; volumetric water content

Since a great number of landslides affecting Italian territories are triggered by rainfall, the installation of sensor networks, able to monitor significant parameters from the hydrological and geotechnical points of view, may provide useful support to both the land-planning, the design and management, and the maintenance of slopes.

Two examples of monitoring sensor networks are TELLME (The Eledia LandsLide Monitoring System) and LAMP (LAndslide Monitoring and Predicting). For instance, LAMP (Bovolenta et al. 2016) proposes the use of a dense, low-cost and self-sufficient network of sensors, disseminated on the ground, coupled with a cognitive/predictive hydrological-geotechnical

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(IHG) model, to monitor and predict landslides triggered by rains. The sensor network monitors the local hydrogeological conditions. The adopted IHG model (Federici et al. 2015; Passalacqua et al. 2015) analyses, in real time, the propensity of different portions of the territory to collapse, by establishing a cause-and-effect relationship between the rainfall and occurrence of the landslide.

Soil moisture sensors can be used to analyse areas where there is a high risk of landslide, since the increase and/or variation in water content in the soil is one of the main triggering factors. In order to achieve soil moisture monitoring, several techniques and devices for measuring the water content have been developed.

In general, for environmental monitoring, many water content sensors have been adopted. They can transmit information to a main server with wireless communication (Bogena et al. 2007). Several factors have to be considered when selecting a sensor for network applications: in order to maximise the lifetime of a sensor network, the sensors have to be economic on the energy demand and should be reasonably robust. Because of the multitude of the soil water content measurements within the network, interpretation of the sensor signal has to be straightforward and unambiguous. Finally, yet importantly, in order to maximise the number of sensor nodes, the soil water content sensors have to be as inexpensive as possible.

Nowadays, the most common technique is the one relying on the dielectric properties of the soil (Wang & Schmugge 1980). Electromagnetic sensors measure the relative dielectric permittivity of the bulk soil and use that measurement to infer the volumetric water content (θ_v). The relative dielectric permittivity of the bulk soil is defined as the permittivity of a given material relative to that of the permittivity of a vacuum and it also names the dielectric constant. They are becoming increasingly popular and several experimental studies have been carried out since the day they were launched (Gaskin & Miller 1995). Two classes of dielectric sensors are available. The first class includes the so-called Time Domain Reflectometry (TDR) sensors, which measure the time taken for an electrical impulse to traverse a transmission line of fixed length in the soil. The second class includes the Frequency Domain Reflectometry (FDR) sensors, which typically operate at a fixed frequency; they are often referred to as capacitance sensors (Campbell et al. 2009).

Since capacitance sensors are relatively inexpensive and easy to operate, they seem to be a promising choice for soil water content measurements with sensor networks (Bogena et al. 2007) and that is the reason why this study is focusing on such a type of sensor.

In particular, a multi-sensor capacitance probe allows different depths to be investigated at a time. Though working at low frequencies (thus, being quite unsuitable for fine-grained soil material), it allows for the multi-depth installation with the minimum disturbance of the soil. On the contrary, a TDR probe requires a hole to be realised at each installation depth. Besides this, it has to be considered that the capacitance probes are very cost effective, when compared to most TDR probes (Tarantino & Pozzato 2008; Tarantino et al. 2008). Therefore, the capacitance probes are more suitable for the environmental monitoring, provided an appropriate soil-dependent calibration is made.

Obviously, it is of primary importance in the use of such probes to have a reliable relationship between the measured value and the volumetric content of the water in the soil. A series of calibration curves, often based on the soil texture alone, are generally provided by the instrument manufacturers themselves. However, several studies have shown that the calibration equations provided by the manufacturers could not effectively describe the measured data, in particular for a high moisture content and for materials that are not among those studied in the calibrations offered by the producers (De Carteret et al. 2013).

For this reason, in this work, we focused on the research of specific soil calibration equations, in order to improve the accuracy and performance of the monitoring devices of the soil water content. The capacitance multi-sensor probe tested in the present study is the Drill & Drop (Sentek Sensor Technologies, Stepney, Australia). Tests were carried out on samples of either coarse or fine sand. In order to define the practical planning for such networks, the first step is to find the relationship between the sensor measurement and θ_v .

The main goal of this work is to define a laboratory calibration protocol for a specific capacitance sensor and soil type, that can be later adopted for other capacitance sensors and soils. Two specific objectives are defined: the first one is to determine the soil-specific regression curves. To this aim, the results of the laboratory measurements have been analysed and processed in order to obtain the differ-

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ent calibration curves. The second specific objective is to investigate whether the relative density and the particle-size distribution influence the probe output measurements. The relative density (D_R) is defined as the ratio of the difference between the void ratios of a cohesionless soil in its loosest state and existing natural state to the difference between its void ratio in the loosest and densest states. Finally, a comparison with the manufacturer-supplied calibration curves has been made.

MATERIAL AND METHODS

Sand samples. The experiments were carried out on sand samples. The media selection is motivated by the fact that its physical characteristics are easy to analyse, it is a permeable material and does not contain any organic matter (Fares et al. 2016). These properties are effective to create homogeneous and uniform samples, in terms of dry bulk density (i.e., the weight of the dried soil per unit volume of the material including voids and water contained in it) and the water content. Two types of sand are tested: a coarse sand (hereinafter named Ticino sand) and a fine sand.

At first, the laboratory tests were performed to determine the main physical parameters of such materials. A typical sieve analysis is carried out on the samples of both sands. Three different samples per sand type were tested. The derived particle-size distributions are reported in Figure 1, confirming that the selected materials are monogranular sands. According to the soil classification system proposed by the United States Department of Agriculture

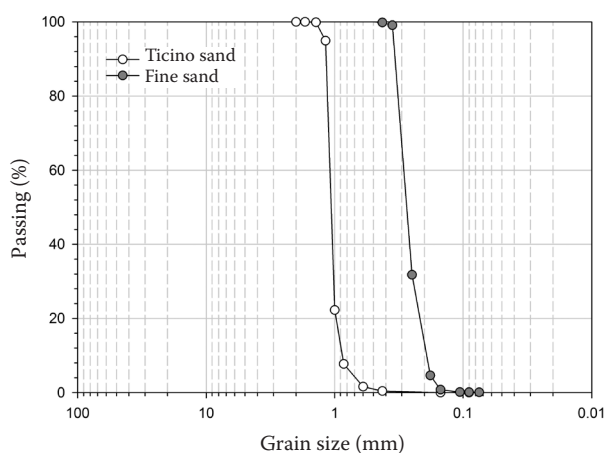


Figure 1. The particle-size distribution curves for the tested sand materials

(USDA), the investigated soils are a coarse sand and a medium-fine sand, with no traces of loam or clay. Table 1 reports some derived quantities, such as the mean grain size, D_{50} , and the uniformity coefficient, C_U . Other standard tests have been carried out in order to determine the particle density, ρ_s (provided by the pycnometer method), and the minimum and maximum void ratios, e_{\min} and e_{\max} .

Capacitance probe. The Drill & Drop (Sentek Sensor Technologies) is a fully encapsulated probe, provided with nine moisture and nine temperature sensors coupled and placed along the probe, with a 10 cm spacing in between.

The probe cable plugs to a proprietary data logger (EnviroSCAN Solo probe, Sentek Sensor Technologies, Stepney, Australia) which allows for the connection to a laptop for the data retrieval. The output value is the Scaled Frequency (SF (–)), expressed as:

$$SF = \frac{F_A - F_S}{F_A - F_W} \quad (1)$$

where:

F_A , F_W , F_S – the raw counts of the probe while suspended in the air, in a demineralised water bath and in the soil, respectively

F_A and F_W are the so called “normalisation values” and are recorded at the beginning of each measurement session. The calibration equations provided by the manufacturer have the following form:

$$SF = a \times \theta_v^b + c \quad (2)$$

where:

θ_v – the volumetric water content (%)

a , b , c – the calibration equation coefficients

The test is only performed with respect to the bottom sensor in order to limit the soil sample volume, indeed the final aim is to guarantee its homogeneity

Table 1. The main properties of the sands selected for the laboratory tests

Material	D_{50} (mm)	C_U (–)	ρ_s (g/cm ³)	e_{\min} (–)	e_{\max} (–)
Ticino sand	1.070	1.22	2.69	0.663	0.661
Fine sand	0.275	1.49	2.75	0.951	0.968

D_{50} – the mean grain size; C_U – the uniformity coefficient; ρ_s – the particle density; e_{\min} , e_{\max} – the minimum and maximum void ratios

both in terms of the dry bulk density and water content; moreover, such a limited volume contributes to guarantee a negligible water migration due to the effect of gravity.

Experimental setup. The tests are carried out using a cylindrical container, consisting of a PVC pipe for the sidewalls and a plastic plate for the bottom; in particular, the container is characterised by an internal diameter of 31.6 cm and a height of 16 cm. Such dimensions comply with the single sensor's sphere of influence, as stated in the calibration manual (Sentek Technologies Inc. 2014): it extends 14 cm radially from the external surface of the probe, 6 cm axially both above and below the centre of any sensor. The container is 4 cm higher than the soil sample, in order to facilitate the preparation of the sample itself. A second container is made in order to perform the water normalisation.

As the probe cannot be installed following an in-field procedure, an access tube is placed in the centre of the container before filling it with the soil, then this is removed after the insertion of the probe, to ensure the minimum disturbance of the sample around the probe surface (De Carteret et al. 2013). The access tube is a 14 cm long plastic tube (an internal diameter of 30 mm, an outer diameter of 32 mm).

Finally, the water content and relative density uniformity were guaranteed by the use of a professional mixer and soil pestles.

Laboratory test programme. Before of every test session setup, the probe is normalised by recording the readings in the air and in the demineralised water while the soil to be used is oven-dried at 105°C for 12 h, then cooled to room temperature. The cylindrical container has to be clean and dry and the access tube is placed in the centre of the container. In order to run the laboratory tests, the relative density has to be defined (thus, allowing one to calculate the corresponding weight of sample), then different water content values are taken into consideration (starting from the dry condition) to calculate the corresponding water volume for each test. The following steps describe the experimental procedure:

- (1) a quarter of the weighed grams of sand is poured into the mixing bowl with a quarter of the grams of the water that are necessary to obtain a certain volumetric water content; the mixer is left to work for five minutes;
- (2) the wet sand is poured into the cylindrical container and compacted to a thickness of 3 cm, by using soil pestles;

- (3) the sample is prepared by repeating steps 1 and 2 four times, since the sample has to be 12 cm high; this guarantees higher uniformity inside the sample, in terms of both the relative density and the water content;
- (4) when the sample is complete, the probe is inserted into the access tube, which is then removed, being careful to ensure the minimum disturbance of the soil;
- (5) the surface of the sample is covered with plastic wrap to avoid water losses due to evaporation; the testing period and the sampling interval are set to 10 min and 1 min, respectively, so 10 values of SF per test are finally available;
- (6) when the data acquisition is ended, the probe is removed and the container is weighed on a precision scale, in order to record the wet weight for the gravimetric test. Indeed, the gravimetric method is used to determine the effective volumetric water content inside the sample, in order to validate the test. Indeed, it has to be noticed that many factors (including the mixing and pouring phases) may help determine the water losses during the sample preparation procedure.

For each investigated sand, the tests are carried out for three relative densities and seven volumetric water contents; each test with an assigned D_R and θ_v , is repeated three times. In particular, the characteristics of the performed tests can be summarised as follows:

D_R : 40%, 60%, and 80%;
 θ_v : 0.00%, 1.97%, 3.96%, 9.89%, 19.8%, 29.7%, and 36.3%

It has to be noticed that the established dry bulk density values result in 1.47, 1.51 and 1.56 g/cm³ for the Ticino sand, and 1.49, 1.54 and 1.60 g/cm³ for the fine sand. Each test was carried out on the samples of either Ticino or the fine sand.

Data analysis. The first step of the data analysis is the validation of the experimental data obtained for each test; in particular the validation criteria are based on the temperature of the sample and on the water content values. Since the temperature affects the response of the capacitance sensors used to measure the relative dielectric permittivity of the soils (Iezzoni & McCartney 2016), it is assumed that the temperature of the sample measured during the test needs to be close to room temperature. Therefore, if the sample temperature ranges from 17 to 23°C the test is validated. Secondly, the difference in the water content of the sample between the nominal

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value (i.e., θ_v , calculated a-priori) and the effective value (i.e., $\hat{\theta}_v$, determined with the gravimetric test) is taken into account in the validation procedure. When the relative percentage error between the nominal and the measured values of the volumetric water content, defined as:

$$\varepsilon_{\theta_v} = \frac{\theta_v - \hat{\theta}_v}{\theta_v} \times 100 \quad (3)$$

is greater than 6%, the related test result is neglected. There are several reasons why the measured water content can differ from the nominal one, for example, water losses during the preparation of the sample and the test execution, or the way in which the sample is collected for the gravimetric check.

After the validation criteria have been applied to the data sets, a linear regression analysis is performed on them. A regression analysis is widely used for the predictions, to understand which of the independent variables are related to the dependent variable, and to explore the forms of these relationships. At first, a simple linear regression is performed, in order to derive the soil-specific calibration curves, each referring to a specific material and a relative density value. Secondly, the multiple linear regression is aimed at investigating whether some physical parameters (i.e., the relative density and particle-size distribution) influence the results of the regression analysis.

Referring to the calibration equation provided by the manufacturer (see Eq. (2)), several authors state that the additive constant of the equation can be assumed to be equal to zero (Provenzano et al. 2016). In fact, for θ_v tending to be zero, the corresponding SF values suddenly decrease and, for practical applications, the related errors can be neglected. Therefore, in the present study, the following expression of the regression curve is adopted:

$$SF = a \times \theta_v^b \quad (4)$$

The goodness of fit of the derived regression curves is evaluated with reference to the coefficient of determination, R^2 , and the root mean square error, RMSE, both calculated on θ_v .

RESULTS AND DISCUSSION

The laboratory tests were performed for two sands, thus, resulting in six data sets in total: three for the Ticino sand and three for the fine sand. Referring to a specific sand type, each set reports the experimental

Table 2. The validated data set with respect to the type of sand and the value of the relative density (D_R)

Material	D_R (%)	No. of validated data
Ticino sand	40	21
	60	19
	80	21
Fine sand	40	21
	60	21
	80	21

results of the tests carried out on the samples with the assigned relative density at seven values of the volumetric water content. Since each test is repeated three times, each data set is formed by 21 data sets.

Data validation. By adopting the validation criteria as previously illustrated, only in the first data set (i.e., the tests carried out on the samples of Ticino sand with $D_R = 60\%$) two measurements are not validated, thus, only nineteen data sets are used in this particular regression analysis. Table 2 reports the number of validated data points, with reference to the type of sand and the relative density.

Calibration curve. A simple linear regression is performed on the validated data. Figure 2 shows the regression curves derived for the Ticino sand at the assigned values of the relative density. Similarly, to Figure 2, Figure 3 illustrates the regression curves derived for the fine sand. It can be seen that, in both cases, the three curves almost overlap, especially

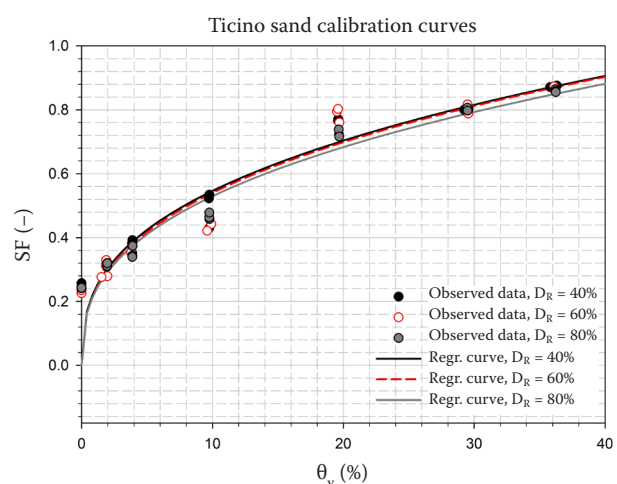


Figure 2. The scaled frequency (SF) vs. the volumetric water content values (θ_v) observed for the Ticino sand samples with respect to the three investigated relative densities (D_R); the corresponding regression curves are also reported

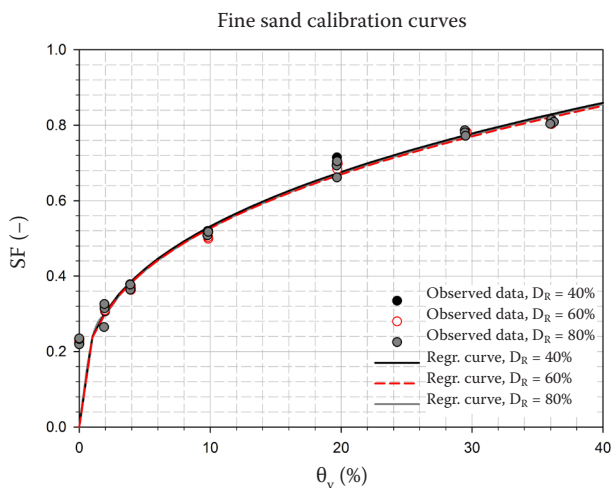


Figure 3. The scaled frequency (SF) vs. the volumetric water content values (θ_v) observed for the fine sand samples with respect to the three investigated relative densities (D_R); the corresponding regression curves are also reported

those derived for the fine sand. The calibration curves reported in Figures 2 and 3 suggest that the influence of the relative density may be negligible.

Table 3 reports the results of the linear regression analysis performed for each soil type at the assigned relative density, the number of validated data points used for fitting the curve and the coefficients of the regression curves are shown. The corresponding R^2 and RMSE values are reported for each calibration curve. It has to be noticed that since the calibration curve is a simple power law, the measurements obtained at the dry condition ($\theta_v = 0$) are not taken into account to estimate the coefficients of the calibration curve, while the RMSE values are calculated based on the validated data available for each data set.

Influence of the relative density and the particle size distribution. In order to assess the effect of the relative density on the calibration curve, a multiple linear regression analysis has been performed on the data of both the Ticino sand and the fine sand, using

Table 3. The coefficients of the soil-specific calibration curves ($SF = a \times \theta_v^b$), with reference to the type of the sand and the value of the relative density (D_R); the number of data points (N) used for fitting each curve and the corresponding coefficient of determination (R^2) and the root mean square error (RMSE) values are also reported

Material	D_R (%)	N	a	b	R^2	RMSE (%)
Ticino sand	40	18	0.2359	0.3648	0.966	2.51
	60	16	0.2303	0.3705	0.947	3.58
	80	18	0.2273	0.3674	0.966	2.03
Fine sand	40	18	0.2400	0.3458	0.992	1.49
	60	18	0.2379	0.3456	0.991	1.38
	80	18	0.2361	0.3491	0.987	1.36

θ_v and D_R as independent variables. Then, a simple linear regression has been performed on the two data sets, including the whole tests performed for each soil irrespective of the relative density values, thus, including 52 measurements for the Ticino sand and 54 for the fine sand.

Table 4 summarises the calibration curves based on the multiple and simple linear regression approach with respect to each investigated soil. The number of data points N used for fitting each curve and the corresponding R^2 and RMSE values are also reported. By comparing the values of the RMSE, reported in Table 4, it emerges that, for both soils, this remains fairly constant when D_R is ignored. Therefore, the results point out that the influence of the relative density is fairly limited. Furthermore, the values of the b_1 exponent (related to D_R) are one order of magnitude less than those of b for both of the sands (see Table 4), thus, confirming that the relative density does not seem to affect the calibration curve. The regression curves associated with the univariate functions that have been derived for each sand are named, hereinafter, Ticino sand and fine sand curves.

Table 4. The values of the coefficients of the calibration equations based on the multiple ($SF = a \times \theta_v^b \times D_R^{b_1}$) and simple ($SF = a \times \theta_v^b$) linear regression obtained for each type of sand; the number of data points (N) used for fitting each curve and the corresponding coefficient of determination (R^2) and the root mean square error (RMSE) values are also reported

Equation	Material	a	b	b_1	R^2	RMSE (%)
$SF = a \times \theta_v^b \times D_R^{b_1}$	Ticino sand ($N = 52$)	0.2760	0.3676	-0.0439	0.959	2.80
	fine sand ($N = 54$)	0.2512	0.3468	-0.0133	0.990	1.41
$SF = a \times \theta_v^b$	Ticino sand ($N = 52$)	0.2311	0.3676	–	0.958	2.82
	fine sand ($N = 54$)	0.2380	0.3468	–	0.990	1.41

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Another multiple linear regression analysis has been performed, including the whole set of measurements using θ_v and D_{50} as independent variables. The D_{50} value is chosen as the parameter which represents the particle-size distribution of a monogranular sand. The goal of this analysis is to derive a multi-variate calibration equation, called the Sand curve, that is suitable for monogranular sands, with a D_{50} value in the range of the investigated sands.

Based on the validated data set ($N = 106$), the sand calibration curve was obtained:

$$SF = 0.2365 \times \theta_v^{0.3574} \times D_{50}^{0.0147} \quad (5)$$

The associated R^2 and RMSE are 0.972 and 2.44%, respectively.

Finally, the Ticino sand, fine sand and sand curves have been compared to the manufacturer-supplied calibration equations provided in Appendix II of the Sentek calibration manual (Sentek Technologies Inc. 2011). In particular, the curves selected as a means for comparison are named the Sentek Default curve, derived for sand, clay and loam, therefore, suitable for both the Ticino and fine sand; furthermore the named coarse sand (1.3 g/cm^3) curve and the named Florida sand curve are considered as reference curves for coarse and fine sands, respectively. Note that, the named coarse sand (1.3 g/cm^3) curve

is pertinent to coarse sands with a dry bulk density equal to 1.3 g/cm^3 .

Figure 4 shows the comparison between the Ticino sand regression curve fitting the whole set of Ticino sand samples and two manufacturer-supplied calibration curves: the Sentek Default and the coarse sand (1.3 g/cm^3) curves. Similarly, Figure 5 reports the comparison between the fine sand regression curve, fitting the whole set of fine sand samples, and two manufacturer-supplied calibration curves: the Sentek Default and the Florida sand curves. The results point out that the Sentek Default curve can be suitably adopted as the calibration curve for the Ticino sand, while, for the fine sand, it properly describes the volumetric water content for values below 20% only.

Similar to Figures 4 and 5, Figures 6 and 7 compare the manufacturer-supplied curve with the Sand curve that is obtained for both the investigated soils by assigning the mean grain size D_{50} associated to each sand to the generic fitting curve.

Table 5 reports the values of the coefficients of the calibration curves considered for the comparison purposes: the Ticino sand, fine sand and sand curves representing the fitting curve based on the laboratory data set and the manufacturer-supplied curves. The corresponding RMSE values that are calculated with respect to the corresponding available data, are also reported.

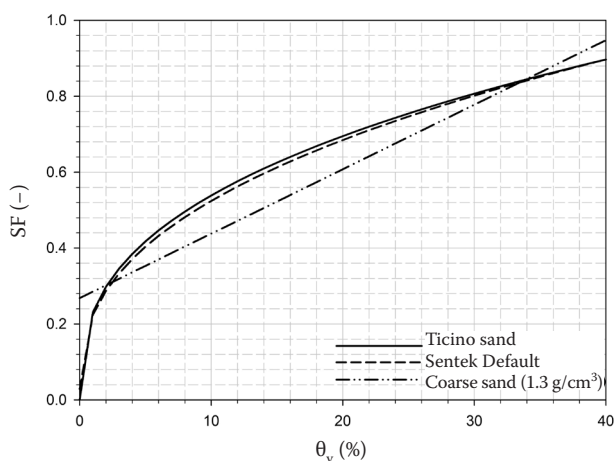


Figure 4. The comparison between the Ticino sand regression curve fitting the whole set of Ticino sand samples and two manufacturer-supplied calibration curves: the Sentek Default and the coarse sand (1.3 g/cm^3) curves; the parameters of the named Sentek Default and the coarse sand (1.3 g/cm^3) curves are listed in Appendix II of the Sentek calibration manual (Sentek Technologies Inc. 2011)

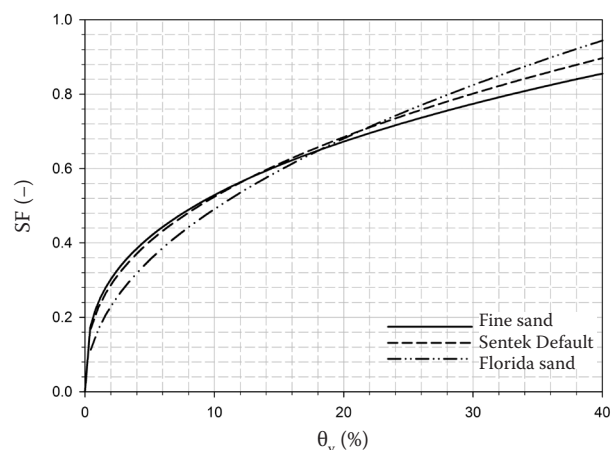


Figure 5. The comparison between the fine sand regression curve fitting the whole set of fine sand samples and two manufacturer-supplied calibration curves: the Sentek Default and the Florida sand curves; the parameters of the named Sentek Default and the Florida sand curves are listed in Appendix II of the Sentek calibration manual (Sentek Technologies Inc. 2011)

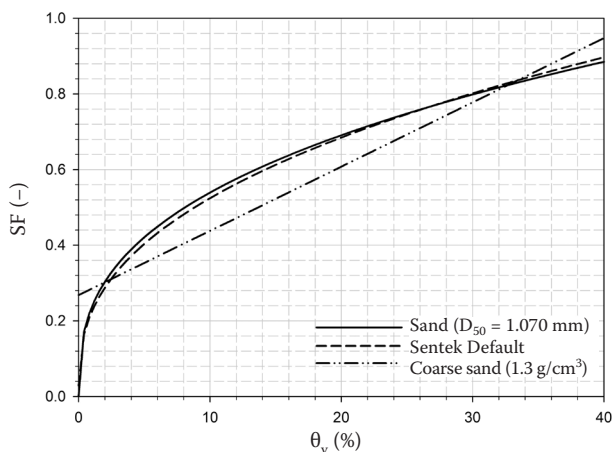


Figure 6. The comparison between the multiple regression curve named sand and two manufacturer-supplied calibration curves: the Sentek Default and the coarse sand (1.3 g/cm^3) curves; the sand curve reported in the graph is obtained setting the D_{50} value equal to 1.070 mm; the parameters of the named Sentek Default and the coarse sand (1.3 g/cm^3) curves are listed in Appendix II of the Sentek calibration manual (Sentek Technologies Inc. 2011)

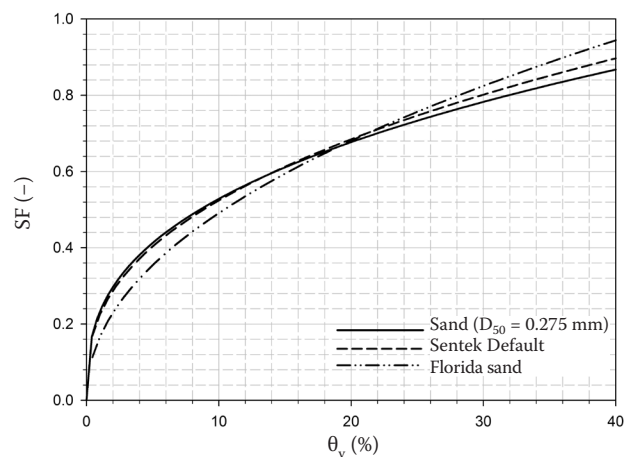


Figure 7. The comparison between the multiple regression curve named Sand and two manufacturer-supplied calibration curves: the Sentek Default and the Florida sand curves; the sand curve reported in the graph is obtained setting the D_{50} value equal to 0.275 mm; the parameters of the named Sentek Default and the Florida sand curves are listed in Appendix II of the Sentek calibration manual (Sentek Technologies Inc. 2011)

With reference to Table 5, it can be noted that, for both sand types, the manufacturer-supplied calibration curves result in the highest RMSE. In general, the fitting regression curves are the best choice, thus, confirming that a soil-specific calibration curve is necessary every time the characteristics of the soil differ from the ones for which the provided calibration equations have been derived. The fitting regression curves provide a better performance when compared to the curves provided by the manufacturer, mainly for the fine sand. The exception occurs for the manufacturer-supplied Sentek Default

curve, which has a related RMSE that is comparable to that of the Ticino sand curve.

CONCLUSION

This study explores the suitability of the Drill & Drop probe for small-scale laboratory studies of sand materials by assessing a laboratory protocol. To this aim, the sandy samples were prepared to perform the laboratory test, since the characteristics of the sands are quite easy to determine. Due to its high permeability, it is

Table 5. The comparison between the root mean square error (RMSE) values with reference to the fitting regression curves ($SF = a \times \theta_v^b$) and the manufacturer-supplied (indicated in *italics*) curves ($SF = a \times \theta_v^b + c$); the number of data points (N), used for fitting each curve and the corresponding coefficients of the calibration equations are also reported; the parameters of the named Sentek Default and the Coarse Sand (1.3 g/cm^3) curves are listed in Appendix II of the Sentek calibration manual (Sentek Technologies Inc. 2011)

Material	Equation	N	a	b	c	RMSE (%)
Coarse sand	Ticino sand	52	0.2311	0.3676	0	2.82
	sand ($D_{50} = 1.070 \text{ mm}$)	106	0.2368	0.3574	0	3.11
	coarse sand (1.3 g/cm^3)	–	0.0170	1	0.2680	4.02
	Sentek Default	–	0.1957	0.404	0.0285	2.96
Fine sand	fine sand	54	0.2380	0.3468	0	1.41
	sand ($D_{50} = 0.275 \text{ mm}$)	106	0.2321	0.3574	0	1.54
	Florida sands	–	0.1659	0.4715	0	3.25
	Sentek Default	–	0.1957	0.404	0.0285	2.25

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easy to create a sample with a uniform water content. Moreover, the absence of any organic matter ensures the stability of the sample during the drying process. In order to set up a laboratory procedure characterised by high test repeatability, a uniform soil type was adopted.

The adopted laboratory protocol set up in the present study is found to have a good repeatability. Moreover, the same method could be adopted using different soil materials and different capacitance sensors, so that a wide range of calibration equations could be developed.

Data analysis has been carried out using a linear regression analysis, due to the limited available database. At first, a simple linear regression analysis is performed on a single sand type with an assigned relative density. Based on the results of such an analysis, a multiple linear regression analysis is then applied, in order to investigate whether a unique curve could be fitted with respect to each soil type. The results of the multiple regression analysis confirm that the influence of the relative density is negligible, thus, two calibration curves are developed, each referring to a single type of sand. It is important to underline that the above consideration is strictly limited to the set of relative density values that have been investigated, although it covers a range of values that are frequent in real field conditions.

A multiple regression analysis is performed on the whole data set, including D_{50} of each soil type as the second independent variable. The results of the regression analysis show that the influence of D_{50} (chosen as a representative parameter for identifying a monogranular sand with a certain particle-size distribution) is more marked than that of the relative density. A more general curve is fitted on the whole database, expressing SF as a function of θ_v and D_{50} . It is important to highlight that the multi-variate regression curve is suitable for monogranular sands with a D_{50} that varies between the values considered (i.e., 0.275 mm and 1.070 mm). There is no evidence that the equation may be applied for other types of sand.

Another important objective of this work was to investigate whether the fitting regression curves are better than the manufacturer-supplied ones, in terms of RMSE. In fact, as reported in several scientific papers, manufacturer-supplied calibration equations are not suitable for scientific utilisation, though providing quite reliable information for other purposes (e.g., irrigation). Then, a comparison between the fitting regression curves and the manufacturer-supplied calibration curves is carried out. Two curves per sand type are considered as a basis for comparison: a general

curve and a soil-specific curve. In general, the fitting regression curves are the best fitting curves, thus, confirming that calibration is necessary every time the characteristics of the soil differ from the ones for which the provided calibration equations have been derived. It is concluded that soil-specific calibration is essential for use with the Drill & Drop probe with fine-grained materials and recommended for use with the coarse-grained materials, thus, supporting the adopted methodology.

Once again, it is important to underline that the information gained through the tests carried out on the samples of the coarse and fine sand is not general. Other monogranular sands (e.g., sands with different D_{50} values) should be tested, in order to verify whether the multi-variate equation obtained in this study can be extended to the monogranular sands in general. Other future perspectives include the testing of fine-grained materials (i.e., loams or clays), or even samples of undisturbed natural soil.

Finally, the calibration can be performed for field applications where the moisture content of the sandy materials is of interest. For field applications, the procedure needs to be changed and adjusted. Samples of undisturbed soil in-situ have to be collected in order to determine the particle-size distribution, particle density and dry bulk density. The gravimetric check has to be made on small samples collected at different depths, in order to refer the reading of each sensor to a proper water content.

In this work, sensors that can be used in environmental monitoring networks have been considered. In particular, they can be installed to control areas where there is a high risk of landslides, since the variation in the water content in the soil can significantly affect the stability conditions (e.g., Godt et al. 2009; Bordoni et al. 2015).

As outlined in this paper, it is of primary importance to have a reliable relationship between the measurement of the specific sensor and the volumetric content of the water in the soil. This work has illustrated a laboratory protocol adopted for the calibration of the soil moisture capacitance probes in a sand that can be extended to other types of soils.

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