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Reliability of water content estimation by profile probe and its effect on slope stability

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Abstract

Shallow landslide failures are distributed worldwide and cause economic losses and fatalities. A proper evaluation of the possible occurrence of shallow landslides requires reliable characterization of water content. Volumetric water content (θ) is commonly estimated using dielectric sensors, which use manufacturers' calibration curves developed for specific soil types. In this study, we present the experimental results achieved during a laboratory calibration of a capacitance probe (PR2/6 probe), tested on two sandy soils widely outcropping in Central Italy. The proposed equations demonstrate a more reliable estimation of θ with respect to the generalized soil equation provided by the manufacturer, which overestimates θ by up to 10 percentage points. Such overestimation could affect the evaluation of suction stress in partially saturated shallow soils affecting the slope stability analysis. Although the use of θ from correct calibration equations provides less precautionary factor of safety values, a reliable evaluation of the soil moisture condition is fundamental when mapping and predicting the spatial and temporal occurrence of shallow landslides. The use of the PR2/6 probe with the appropriate soil calibration equations in early warning monitoring systems will provide a more reliable forecast, minimizing the number of false alarms.

Keywords: landslides, water content, PR2/6 probe, sandy soils, suction stress.

1. Introduction

Landslide susceptibility assessments and slope stability analysis are affected by measurements, mapping, modelling errors and uncertainties (Ang and Tang, 1984; Baecher and Christian, 2003; Guzzetti et al., 2006; Rossi et al., 2010; Di Matteo et al., 2013; Jiang et al., 2015; Rossi and Reichenbach, 2016; Rossi et al., 2017). The understanding and forecasting of geohydrologic phenomena require a reliable estimation of the water content of unsaturated soils (Babu and Murthy, 2005; Zhang et al., 2011; Sahis et al., 2014). This is particularly relevant to shallow landslides, which generally involve small volumes of soil.

Although the water content by the gravimetric method (θ_g – eq. 1) is the standard to measure the water content of porous media and used to compare results from other methods (Walker et al., 2004), the volumetric water content (θ – eq. 2) is largely used in place of θ_g, particularly in slope stability analysis and numerical landslide modelling. θ can be expressed in terms of θ_g by knowing the dry unit weight of soil γ_d, eq. 3.

$$\theta_g = \frac{M_w}{M_s} \quad 1); \qquad \theta = \frac{V_w}{V_T} \quad 2); \qquad \theta = \theta_g \cdot \frac{\gamma_d}{\gamma_w} \quad 3)$$

where:

M_w = mass of water (kg);

M_s = mass of solids (kg);

V_w = volume of water (m^3);

V_T = volume of soil sample (m^3);

γ_d = dry unit weight of soil (kN/m^3);

γ_w = unit weight of water (kN/m^3).

Unlike the estimation of θ, the gravimetric method is time-consuming, requires the soil sampling (destructive method), and does not allow a continuous space-time monitoring of the water content (Rudnick et al., 2015). The latter poses important limitations when distributed modelling approaches are used, which require the knowledge of the variations of the water content in space and time. According to Chae et al. (2014), the response of θ to rainfall events is more immediate than pore water pressure changes. This indicates that observation of θ and its changes over time at shallow soil depths may be relevant for landslides monitoring. Among the field sensors for near-real-time landslide monitoring, dielectric soil-moisture probes are used in unsaturated soil conditions (Reid et al., 2008). These probes included Time Domain Reflectometers (TDR), Frequency Domain Reflectometers (FDR) and Capacitance Probes (CP). The reliability of indirect measurements by soil-moisture probes is strongly affected by the calibration procedure used for water content estimation. The use of equations provided by the manufacturer could lead to unreliable estimations of the water content, thus to improve the performance of sensors, soil-calibrations are required (Evett et al., 2006; Bogena et al., 2007; Robinson et al., 2008; Mazahrih et al., 2008). According to Kizito et al. (2008), soil water monitoring devices require a laboratory evaluation and calibration for a range of soil types prior to field deployment. Laboratory soil-column experiments can be useful to calibrate the equipment or to compare the performance of different instruments on different soil types under controlled conditions (Paltineanu and Starr, 1997; Baumardth et al., 2000; Huang et al., 2004; Irmak and Irmak 2005; Polyakov et al., 2005; Evett et al., 2006; Kim et al., 2008). As reported by Irmak and Irmak (2005), few studies have evaluated the performance of FDR and CP in coarse-textured soils under controlled experimental conditions. This critical aspect holds also for other hydrological applications, such as satellite soil moisture products and/or the use of infiltration and surface runoff models, which require reliable in situ soil moisture data (Brocca et al., 2011; Morbidelli et al., 2012).

Quantifying uncertainty of soil variables, such as θ, is necessary to evaluate hydrologically-driven processes. The investigation of the effects of non-specific soil equations for θ estimation on the suction stress is of interest, being the latter an important component of slope stability analysis of unsaturated soils. The present work aims to calibrate the PR2/6 profile probe (capacitance probe, Delta-T Devices) at laboratory scale on sandy soils. We quantify and discuss these aspects taking as reference two soils from Central Italy. Specific calibration equations to estimate θ in sandy soils are presented and compared with the default calibration equation for mineral soils provided by the manufacturer and with other equations available in the literature.

2. Material and methods

2.1 Study area

Two sampling sites characterized by sandy deposits widely outcropping in Central Italy were selected: the alluvial plains of (A) Nera and (B) Tiber rivers (Fig. 1). The mineralogy of the two soils is different: soil S_A (Conca Ternana alluvial plain) is mainly composed by carbonates, while soil S_B (Tiber River alluvial plain) is a typical flyschoid sand being composed by micas, pyrite, and quartz. The two sites have been chosen because they are easily accessible to soil sampling and the mineralogical characteristics of the materials can be considered as representative of recent and ancient fluvial-lacustrine deposits (Fig. 1) widely outcropping along alluvial plains and hill slopes in Umbria Region and in other places in Central Italy.

FIG. 1

2.2 Soil characteristics

For each soil, particle size distribution (ASTM D422-631998), specific gravity G_s (CEN ISO/TS 17892-3 2004), Atterberg limits (CEN ISO/TS 17892-12 2004), compaction properties (standard Proctor test, ASTM D698 - 12e2), and organic matter (ASTM D2974 - 14) were determined in laboratory.

Table 1 summarizes the main geotechnical properties of soils. Compaction behaviour of Soil S_A is typical of poorly-graded sands (coefficient of uniformity, C_u = 3): the presence of large amounts of voids leads to lower Maximum Dry Density (MDD) with respect to Soil S_B which contains about 18% of fines (Table 1).

TABLE 1

2.3 Experimental setup

Laboratory investigations were carried out in order to determine the specific soil equations to estimate θ of the two selected sandy soils. Soils were mixed with tap water and left for 24 hours to moisten at controlled temperature conditions (T = 22±1 °C). The procedure was repeated several times in order to obtain soils with different θ_g values. Then, the soils were placed and manually compacted in a cylindrical PVC container (soil column, diameter 0.50 m and height 1.30 m, Fig. 2a). Compaction was conducted repeatedly by dropping a cylindrical hammer (used to drive the core cutter system into the soil as standardized by BS 1377-9:1990, mass = 13.5 kg; diameter = 0.15 m) from a height of about 0.20 m. In order to make the procedure repeatable, approximately 0.10 m of damp sand was laid and compacted using 25 blows, as for the standard Proctor test (Fig. 2b). The compaction procedure allowed analysis of the soils over a wide range of water content and degree of saturation values. Thanks to the compaction procedure, the water content was homogeneously distributed in each soil column (this was verified on soils sampled at different depths). The compaction was carried out all around an access tube, placed at the centre of the soil column. The profile probe PR2/6 (Delta-T Devices, Cambridge, UK) was placed in the access tube allowing the estimation of θ at different depths (0.10, 0.20, 0.30, 0.40, 0.60, and 1.00 m) by measuring the dielectric constant (ε) of the damp soil. In the PR2/6 probe, a signal of 100 MHz is applied to six pairs of stainless steel rings, which transmits an electromagnetic field extending about 0.10 m into the soil (Fig. 2a). The change in the circuit output (in Volts - V) is related to the square root of soil permittivity (√ε) by a sixth-order polynomial fit (eq. 4, Delta-T Devices Ltd, 2016). Topp et al. (1980) showed that there is a simple linear relationship between the complex refractive index (similar to √ε) and θ. The generalized equation given by the manufacturer for mineral soils, meant as generic soils having low organic matter, is shown in eq. 5. Information on characteristics of mineral soils (are available from Van Bavel and Nichols (2002) and Delta-T Devices Ltd (2016). The default parameters a_0 (soil offset) and a_1 (slope) suggested by the manufacturer for mineral soils (Delta-T Devices Ltd, 2016) are 1.6 and 8.4.

$$\sqrt{\varepsilon} = 1.125 - 5.53 \cdot V + 61.17 \cdot V^2 - 234.42 \cdot V^3 + 413.56 \cdot V^4 - 356.68 \cdot V^5 + 121.53 \cdot V^6 \qquad 4)$$

$$\sqrt{\varepsilon} = a_0 + a_1 \cdot \theta = 1.6 + 8.4 \cdot \theta \qquad 5)$$

The permittivity of the soil measured by dielectric sensors (ε) is given by the sum of soil real (ε’) and imaginary (ε”, dielectric loss) permittivity (eq. 6), where j is the imaginary constant, which is equal to √−1 (Robinson et al., 1999):

$$\varepsilon = \varepsilon' + j \cdot \varepsilon'' \qquad 6)$$

Muñoz–Carpena et al. (2005) state that, soil temperature (T), salinity of the effluent pore fluid, and operating frequency affect ε”. According to Scudiero et al. (2012), the contribution of ε” in saline soils cannot be ignored especially when sensors working at low frequencies (<1 GHz) are used. Laboratory experiments using the 100 MHz PR2/6 were carried out with tap water as pore fluid (Electrical Conductivity, EC = 400 μS/cm). Additionally, EC of the water from saturated soil-pastes was determined. The soil-paste was saturated by adding distilled water to 200 g of air dry soil and left 24 hours to permit the soil to fully imbibe the water and the readily soluble salts to fully dissolve (Rhoades et al., 1999). The EC values of the effluent fluid were then measured resulting 416 μS/cm for soil S_A and 444 μS/cm for soil S_B. As investigated by Rüdiger et al. (2010) and Sevostianova et al. (2015) - depending on the dielectric sensor used - the effect of pore water salinity on θ is appreciable for values higher than 1500-5000 μS/cm. In this study, the values of salinity of the effluent pore fluid are an order of magnitude lower, thus the effect of salinity on PR2/6 output is negligible.

During the experiments, two series of readings, of three measurements each, were made by rotating the PR2/6 profile probe of 120°. This allowed to obtain by eq. 4 an average value of √ε. In order to obtain representative measures of θ_g and γ_d – necessary for the computation of θ with the eq. 3 – three soil samples were collected within the soil-column around the PR2/6 access tube. For the calibration purposes, all the measurements (√ε with PR2/6 probe and θ from soil sampling) are taken at a depth of 0.4 m (Fig. 2a, 2b). This procedure was applied to both soils, S_A and S_B, taking into account several degree of saturation (S_r) from “quasi” dry (S_r = 5%) to wet (S_r = 92%).

3. Results

The calibration procedure required the comparison of the dielectric properties of the damp soil ($\sqrt{\varepsilon}$), measured by the PR2/6 profile probe, and θ from soil sampling. Figure 3 shows the plot of experimental data for soils S_A and S_B (θ vs $\sqrt{\varepsilon}$): regression lines of these soils allowed to obtain the specific parameters (a_0 and a_1) for both soils (eqs. 7 and 8).

$$\sqrt{\varepsilon} = a_0 + a_1 \cdot \theta = 1.7 + 9.5 \cdot \theta \qquad (S_A, R^2 = 0.995) \qquad 7)$$

$$\sqrt{\varepsilon} = a_0 + a_1 \cdot \theta = 1.9 + 10.6 \cdot \theta \qquad (S_B, R^2 = 0.997) \qquad 8)$$

The two equations differ from that suggested for mineral soils by the manufacturer (eq. 5). The use of eq. 5 produces an overestimation of θ, particularly appreciable for $\sqrt{\varepsilon}$ higher than 3. As an example, for $\sqrt{\varepsilon} = 4.5$, the eq. 5 overestimates θ values of about 5 and 10 percentage points for soil S_A (calcareous sand) and soil S_B (flyschoid sand), respectively.

The comparison with literature data indicated that the calibration curve for calcareous sands (soil S_A) could also be used for quartz sands (Fig. 3). Comparison has been carried out with the calibration line (θ vs $\sqrt{\varepsilon}$) of Theta probe device presented by Robinson et al. (1999). The principles of Theta Probe are similar to those of profile probes, such as the PR2/6 probe (cf. Cooper, 2001). Both devices measure, at the same frequency of 100 MHz, the same physical parameter, the dielectric constant ($\sqrt{\varepsilon}$).

FIG. 2

FIG. 3

4. Discussion

Erroneous estimate of θ by PR2/6 profile probe may derive from the use of manufacturer's equation in place of soil-specific calibration equations. Reliable θ values are fundamental for a proper estimation of the suction stress (σ^s). According to Lu and Likos (2004), suction stress can be expressed in terms of normalized volumetric water content (eq. 9).

$$\sigma^s = -\frac{\theta - \theta_r}{\theta_s - \theta_r} \cdot (u_a - u_w) \qquad 9)$$

Where:

σ^s = suction stress (kN/m^2);

θ = volumetric water content (dimensionless);

θ_r = residual volumetric water content (dimensionless);

θ_s = saturated volumetric water content (dimensionless);

u_a = pore air pressure (kN/m^2);

u_w = pore water pressure (kN/m^2);

u_a-u_w = matrix suction (kN/m^2);

The Soil Water Characteristics software (version 6.02.75) available from https://hrsl.ba.ars.usda.gov/soilwater/Index.htm is a useful tool for hydrological soil properties estimations. The software allows the estimation of soil water tension, conductivity and water holding capability based on the soil physical properties of texture, organic matter, gravel, salinity, and compaction (Saxton and Rawls, 2006). Based on soil physical properties of both soils summarized in Table 1, the model developed by Saxton et al. (1986), implemented in the software, allowed the estimation of the Soil Water Characteristic Curve (SWCC). SWCC parameters (θ_r and θ_s) are related to the matrix suction (u_a-u_w) by the volumetric water content (θ). Table 2 summarizes the main SWCC parameters and suction stress values for θ values calculated by the manufacturer equation (eq. 5) and the specific-soil calibration curves provided by the present work (eqs. 7 and 8). In the calculation a $\sqrt{\varepsilon}$ by PR2/6 equal to 4.5 was used, corresponding to S_r higher than 50%, regardless the calibration lines used (Fig. 4).

TABLE 2

FIG. 4

As reported by Lu and Likos (2004, 2006), the generalized effective stress that unifies both saturated and unsaturated conditions can be expressed by eq. 10, where σ is the total stress.

$$\sigma' = (\sigma - u_a) - \sigma^s \qquad 10)$$

The suction stress is an important component in evaluating the Factor of Safety (FS) for shallow slope failures occurring within the vadose zone under partially saturated soil conditions (Wolle and Hachich, 1989; de Campos et al., 1991; Godt et al., 2007; Lu and Godt, 2008). For simplicity and wide usage, the limit equilibrium method can be used to evaluate the stability of landslides with longitudinal dimensions much larger than failure plane depth (Doglioni et al., 2013). For uniform homogeneous and unlimited slopes with inclination β characterized by cohesionless soil and groundwater table parallel to the slope, FS can be calculated using eq. 11 (Lu and Godt, 2008). Such approach account for θ variations in the unsaturated zone.

$$FS = \frac{\tan\phi'}{\tan\beta} - \frac{\sigma^s}{\gamma \cdot H_{ss}} \cdot (\tan\beta + \cot\beta) \cdot \tan\phi' \qquad 11)$$

where:

ϕ' = friction angle (°);

β = slope angle (°);

γ = unit weight of soil (kN/m^3);

H_{ss} = depth of sliding surface (m).

The findings of the present study show how the use of calibration equations allows a proper estimation of θ and then σ^s. According to eqs. 9, the overestimate of θ from manufacturer's equation results in an error of suction stress by up to about 2.7 kPa. As a consequence, the effective stress (σ', eq. 10) reduces. Referring to eq. 11 and assuming constant values of ϕ', β, and γ, for a given depth of sliding surface (H_{ss}) this error also causes inevitably a reduction of the FS value. As an example, Fig. 5 shows the differences when calculating FS at two depth of sliding surface (H_{ss} = 0.6 and 1.0 m) considering the error of θ and σ^s estimation for the different soils (Table 2) and assuming ϕ' equal to 34° (value suggested by Hoek and Bray 1981 for homogeneous sands having γ_d of 14.0 kN/m^3). Such FS differences due to the use of inappropriate PR2 probe empirical equations (θ vs √ε) may affect the modelling of spatial and temporal occurrence of landslides.

FIG. 5

5. Conclusions

The work discusses the reliability of volumetric water content estimation using the PR2/6 probe on two sandy soils widely outcropping in Central Italy and its effects on suction stress estimation and slope stability analysis. The results confirm that - in order to have reliable measurements - specific soil calibration equations are required. The use of manufacturer's equation brings to errors in θ estimation, which inevitably affect the evaluation of S_r for the unsaturated region (by up to 22 percentage points for a given dry unit weight). Overall, the results here presented indicate that the overestimation of θ values decreases the effective stress and hence reduce the shear strength, which causes a lower FS. In other words the overestimation of θ produces more precautionary (i.e., lower) FS values. Since the θ time-space evolution of the unsaturated region influences the initiation of shallow landslides, the use of reliable θ values is fundamental to model their spatial and temporal occurrence (Glade et al., 2000; Alvioli et al., 2014; Raia et al., 2014; Cullen et al., 2016). The use of such probe with the appropriate soil calibration equations in early warning monitoring systems will provide more reliable forecast, minimizing the number of false alarms.

Given these results, further studies devoted to the calibration of dielectric sensors on other types of soil should be carried out. In addition, the identification of landslide forecasting and susceptibility modelling approaches that accounts for the uncertainty and reliability of water related parameters should be encouraged.

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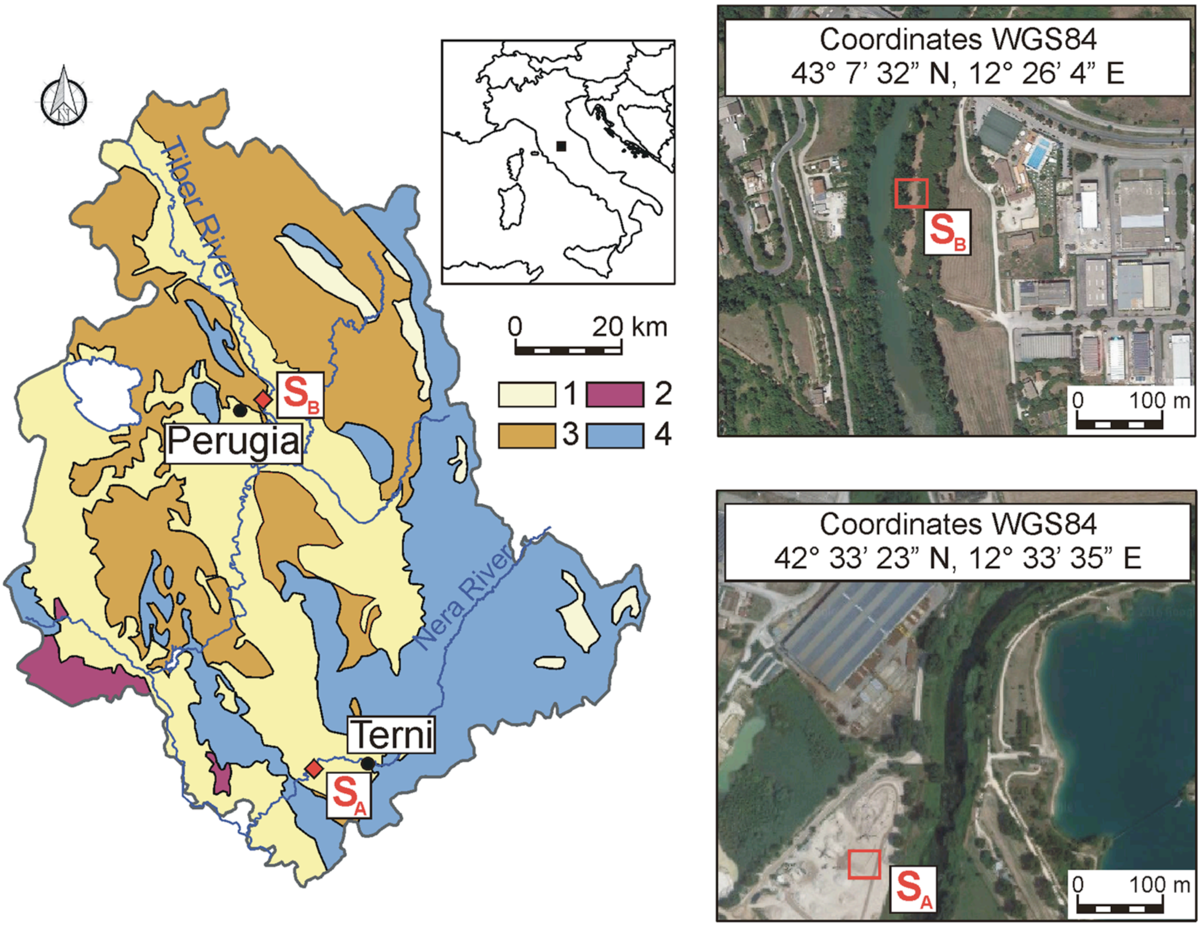

Fig. 1 Lithologic map of Umbria Region (Central Italy) with location of soil sampling sites (S_A – Conca Ternana alluvial plane – Nera River, S_B – Tiber River alluvial plane). 1) recent and ancient fluvial-lacustrine deposits; 2) volcanic deposits; 3) flyschoid rocks; 4) calcareous and marly-silici-calcareous rocks.

Soil	Grain size (%)			G_s	Compaction properties		PI (%)	OM (%)	Mineralogy
	Fines	Sand	Gravel		MDD (kN/m^3)	OMC (%)			
S_A	4.75	94.95	0.30	2.67	14.8	20.0	N.P.	0.37	Carbonates with subordinate minerals (muscovite, gypsum)
S_B	17.59	82.41	–	2.66	17.5	13.2	N.P.	1.53	Quartz, biotite, muscovite, pirite, biotite, carbonaceous frustules

Table 1 – Geotechnical e mineralogical properties of soils. G_s – specific gravity; MDD – Maximum Dry Density; OMC – Optimum Moisture Content; OM – Organic Matter.

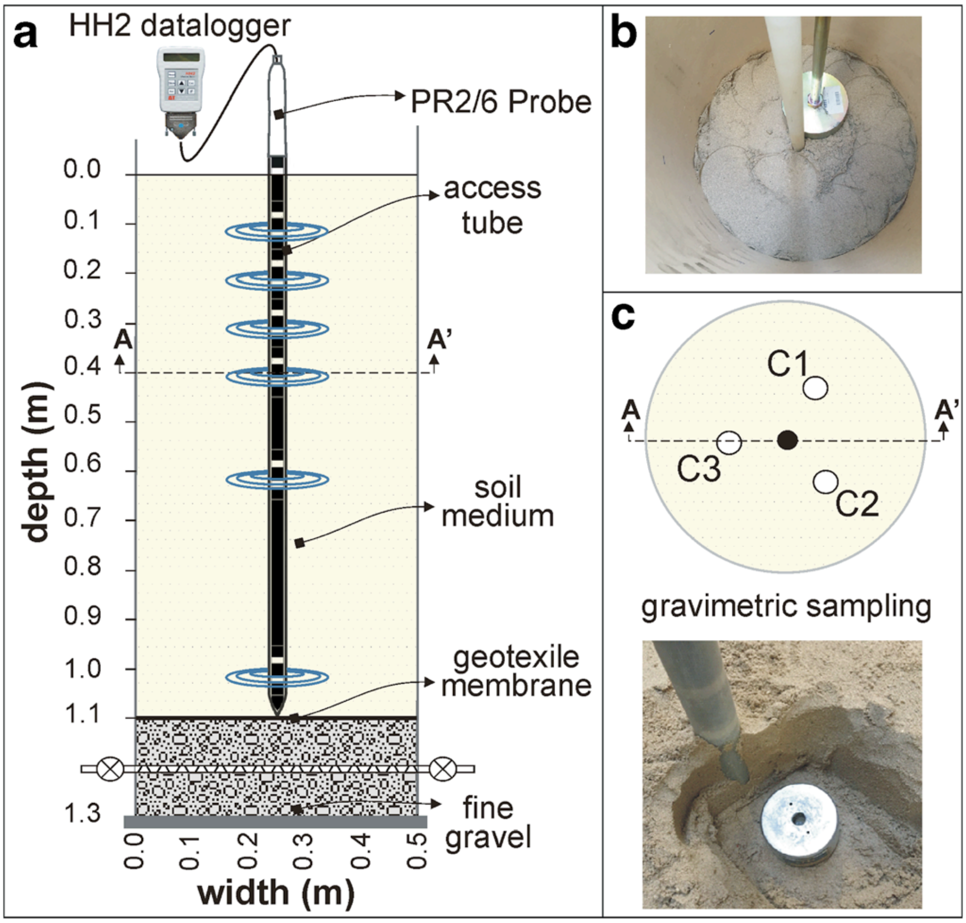

Fig. 2 a) Soil column (not to scale) used to calibrate the PR2/6 probe; b) Detail of compaction procedure; c) Gravimetric sampling for the measurements of θ_g used to calculate θ values by eq. 3.

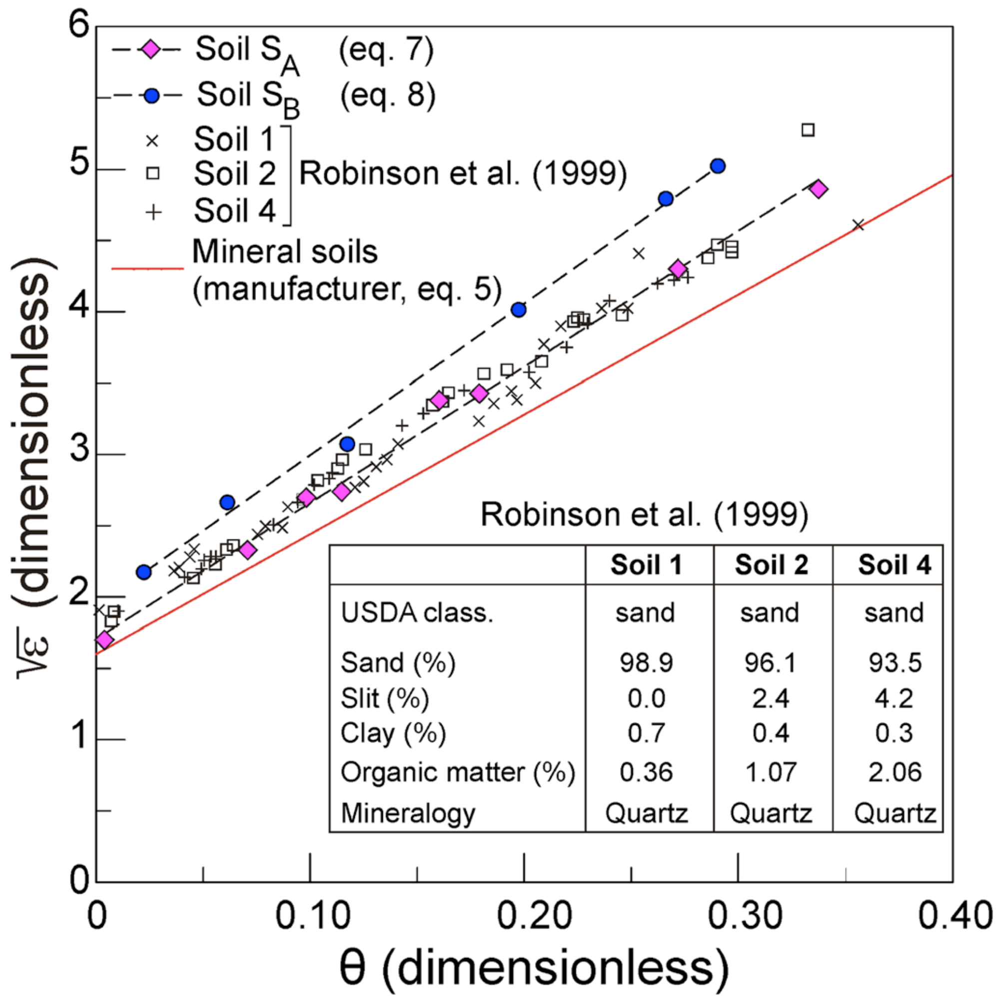

Fig. 3 Laboratory relationship between the square root of dielectric constant - as measured by PR2/6 probe - and θ values obtained by soil sampling (Fig. 3c). Data are compared with those obtained with Theta probe (based on same principles of PR2/6 device) on quartz sands by Robinson et al. (1999).

Soil	θ_r	θ_s	SWCC properties u_a-u_w (kPa): θ by eqs. 7 or 8 (calibration equations)	SWCC properties u_a-u_w (kPa): θ by eq. 5 (manufacturer equation)	σ^s (kPa): Using SWCC properties and θ from calibration equations	σ^s (kPa): Using SWCC properties and θ from manufacturer equation
S_A	0.032	0.451	18 (θ = 0.25)	9 (θ = 0.35)	− 8.67	− 6.74
S_B	0.033	0.452	15 (θ = 0.29)		− 9.41	

Table 2 SWCC parameters estimated for S_A and S_B by the Saxton et al. (1986) model and suction stress values according to eq. 9.

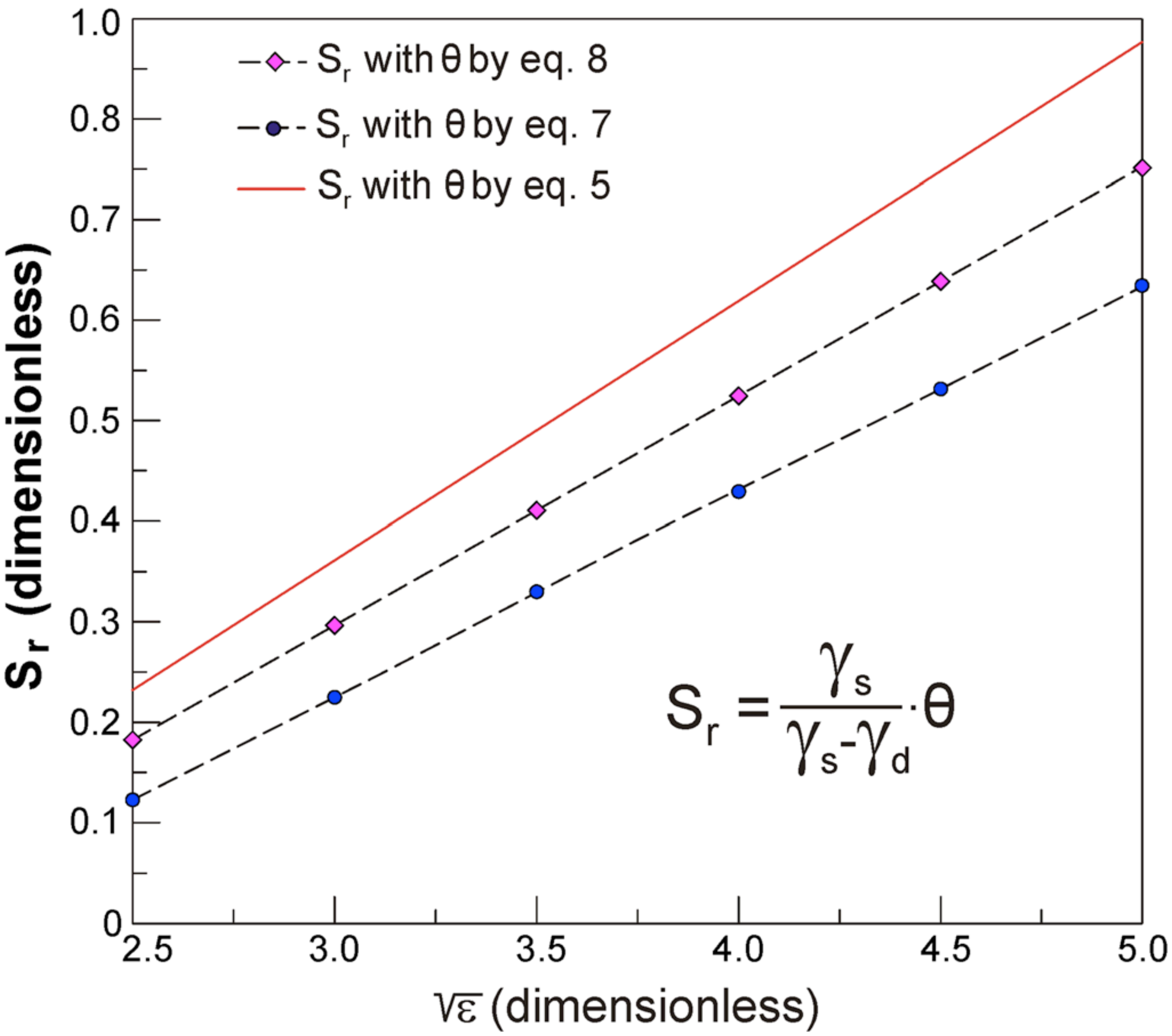

Fig. 4 Relationship between the degree of saturation (S_r) and square root of dielectric constant ($\sqrt{\varepsilon}$) measured by PR2/6 probe. Values are calculated by considering γ_d = 14.0 kN/m^3, γ_s = 26.0 kN/m^3, and θ computed by using the specific soil calibration (eqs. 7-8) and the generalized equation by manufacturer (eq. 5).

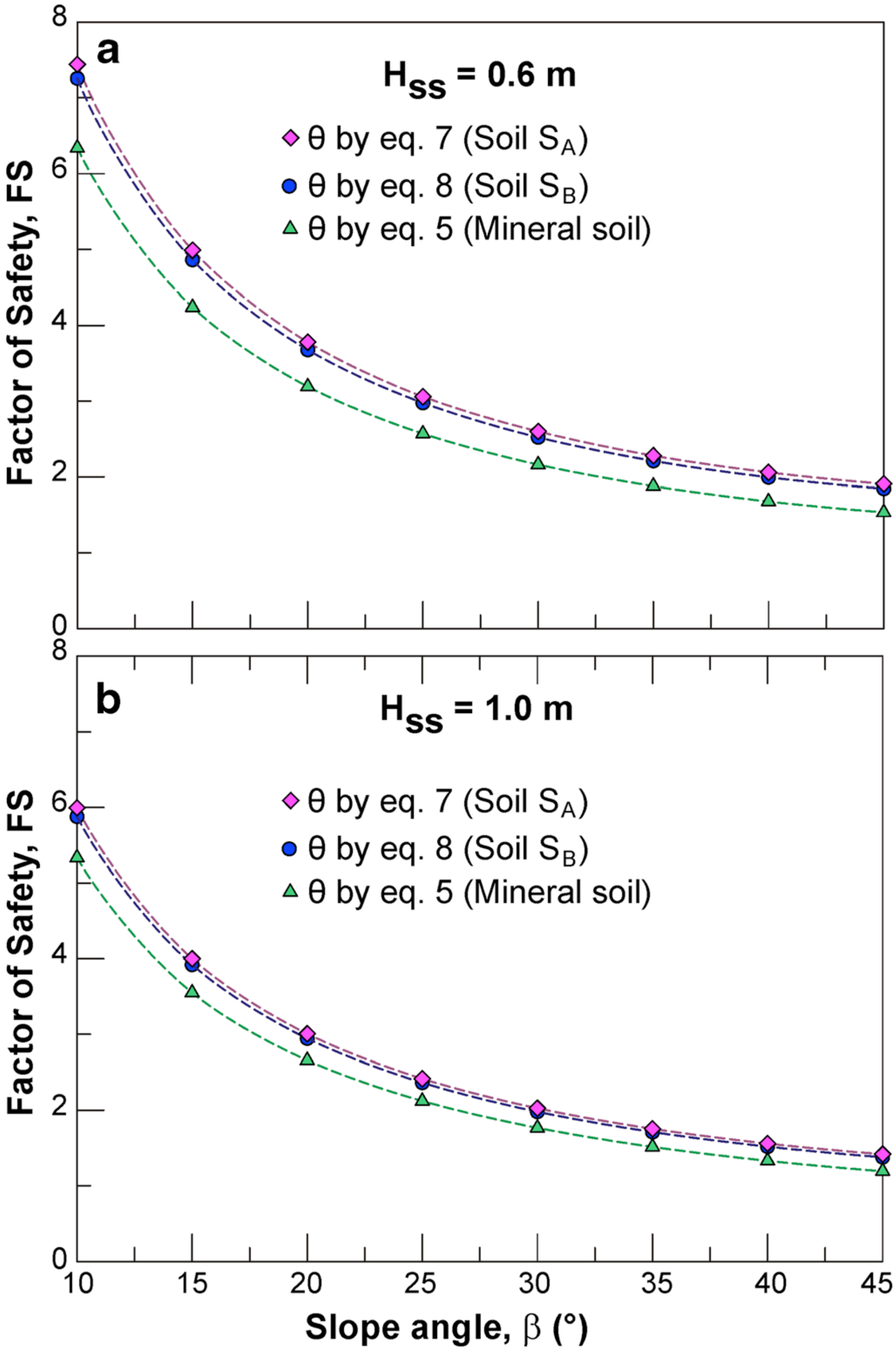

Fig. 5 FS values computed by eq. 9 as a function of slope angle. Values are calculated by considering γ_d = 14.0 kN/m^3, γ_s = 26.0 kN/m^3, ϕ' = 34° and $\sqrt{\varepsilon}$ = 4.5. a) depth of sliding surface (H_{ss}) equal to 0.6 m; b) depth of sliding surface (H_{ss}) equal to 1.0 m.