XXXV CONVEGNO NAZIONALE DI IDRAULICA E COSTRUZIONI IDRAULICHE
Bologna, 14-16 Settembre 2016

DEVELOPMENT OF AN OPEN HARDWARE PORTABLE DUAL-PROBE HEAT-PULSE SENSOR FOR MEASURING SOIL THERMAL PROPERTIES AND WATER CONTENT

G. Ravazzani[1]

[1]Politecnico di Milano, Dipartimento di Ingegneria Civile e Ambientale, giovanni.ravazzani@polimi.it

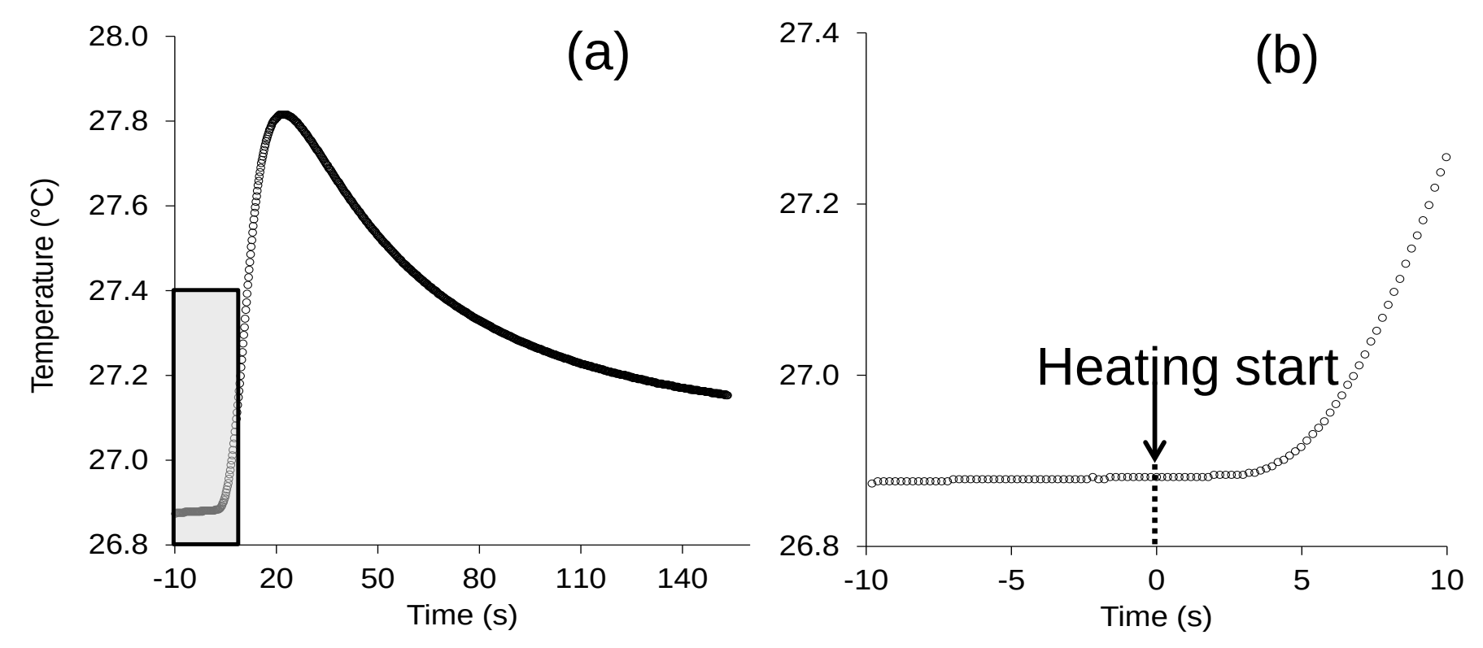
11-0108

INTRODUCTION

Soil thermal properties are of great interest in many scientific and engineering applications. In recent years considerable effort has gone into developing techniques to determine soil thermal properties. One technique that has received attention employs heat-pulse technology. The Dual-Probe Heat-Pulse (DPHP) sensor consists of a pair of stainless steel needles. One needle acts as an heater and the other is used to monitor temperature changes. After the sensor needles are inserted into the sample, a current is applied to the heater for a given time duration. The specific heat of the material is inversely proportional to the height of the sensed temperature rise, and the thermal diffusivity of the material is related to the time taken for the pulse peak to pass the temperature sensor. The thermal conductivity can then be computed as the product of the thermal diffusivity and the specific heat. This solution is a particularly attractive instrument as, apart from providing the thermal properties, it can also assess the water content . Although numerous methods for determining water content are available, such as the time domain reflectometry (TDR), the DPHP sensors are preferred when small volume of soils are investigated like, for instance, when near surface water content is assessed.

The objective of this work is the design of a low cost - open hardware portable device for the measurement of soil thermal properties and water content.

THEORETICAL BACKGROUND



$$\Delta T(r,t)=\begin{cases}-\dfrac{Q'}{4\pi\kappa}Ei\left(\dfrac{-r^2}{4\kappa t}\right) & 0<t\le t_0\\[2ex] \dfrac{Q'}{4\pi\kappa}\left\{Ei\left[\dfrac{-r^2}{4\kappa(t-t_0)}\right]-Ei\left(\dfrac{-r^2}{4\kappa t}\right)\right\} & t>t_0\end{cases}$$

where t is time from beginning of heating, Q' is the source strength per unit time (m^2 K s^{-1}), κ is the thermal diffusivity (m^2 s^{-1}) of the medium surrounding the heater, and $-Ei(-x)$ is the exponential integral function with argument x. Q' is defined as $Q'=q'/\rho c$, where q' is the energy input per unit length of heater per unit time (W m^{-1}) and ρc is the volumetric heat capacity (J m^{-3} K^{-1}).

$$\kappa=\frac{r_n^2}{4}\left\{\frac{1/(t_m-t_0)-1/t_m}{\ln[t_m/(t_m-t_0)]}\right\}$$

$$\rho c=\frac{q'}{4\pi\kappa\Delta T_m}\left\{Ei\left[\frac{-r_n^2}{4\kappa(t_m-t_0)}\right]-Ei\left(\frac{-r_n^2}{4\kappa t_m}\right)\right\}$$

The thermal diffusivity, κ, and volumetric heat capacity, ρc, can be determined using the single-point method. Soil thermal properties can be expressed as:

where r_n is the needle spacing of the DPHP (m), t_m is the time of the maximum temperature change (s), and ΔT_m is the maximum temperature increase (K) as recorded from the DPHP thermistor.

$$\lambda=\kappa\cdot\rho c$$

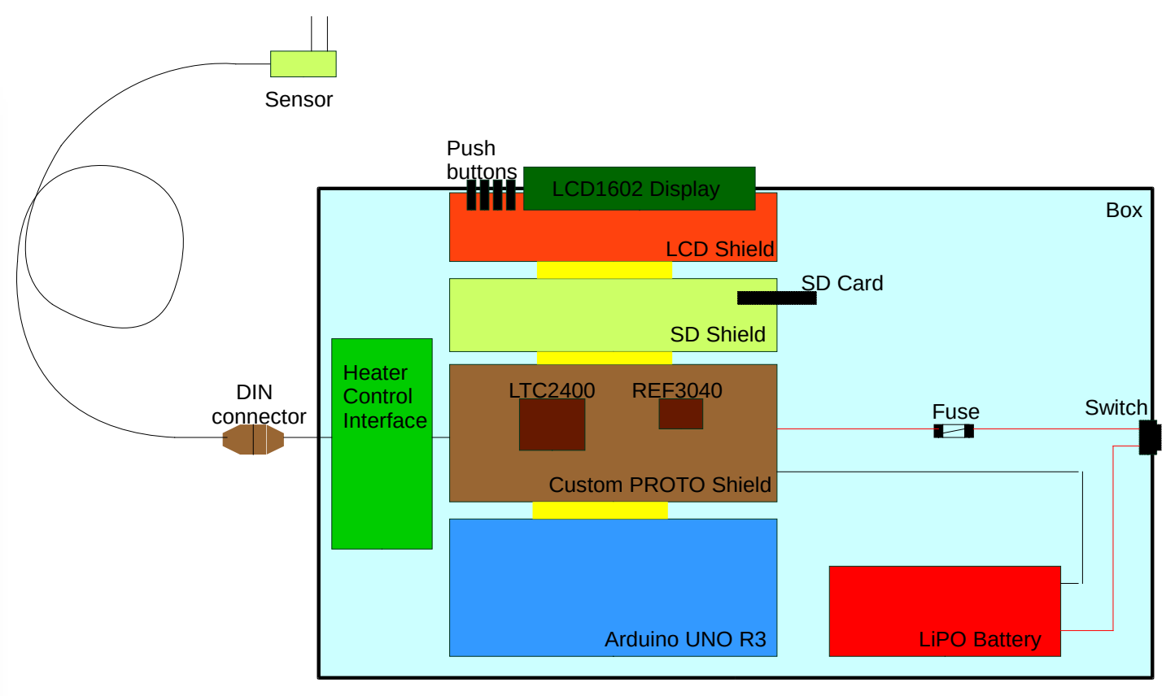
$$\rho c=(\rho c)_s\phi_s+(\rho c)_w\vartheta_v$$

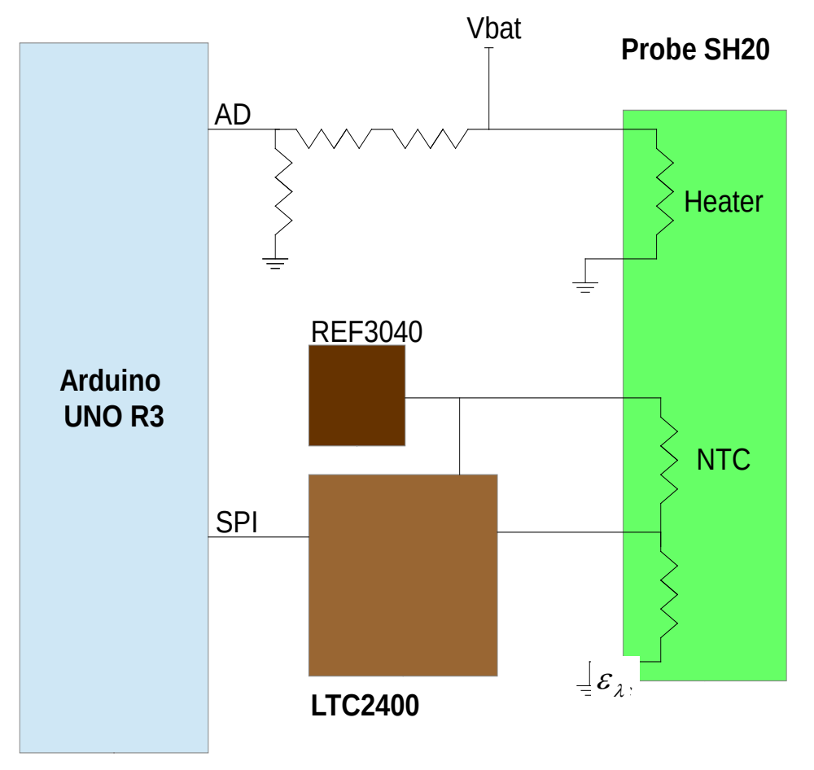
After κ and ρc have been determined, thermal conductivity, λ (W m^{-1} K^{-1}), can be obtained.

Volumetric heat capacity of soil can be determined as the sum of the heat capacity of water and solid, ignoring contribution given by air and defining solid to include the mineral and organic matter fractions, where ϕ_s is the volume fraction of soil (= (1-P) with soil porosity), $(\rho c)_s$ is the volumetric heat of soil solid, $(\rho c)_w$ is the volumetric heat of water, and ϑ_v is the volumetric water content. Because $(\rho c)_w$ is known, measurement of ρc obtained with the multi-needle probe can be used together with estimates or measurements of volumetric heat of soil to obtain ϑ_v.

DPHP SENSOR

Needle probe from http://www.east30sensors.com/





SENSOR SPACING CALIBRATION

Apparent probe spacing is calibrated against measurement on medium with known thermal properties, such as water.

agar-stabilized water (5 g L^{-1}) (21° C)

λ = 0.60106 $Wm^{-1}K^{-1}$

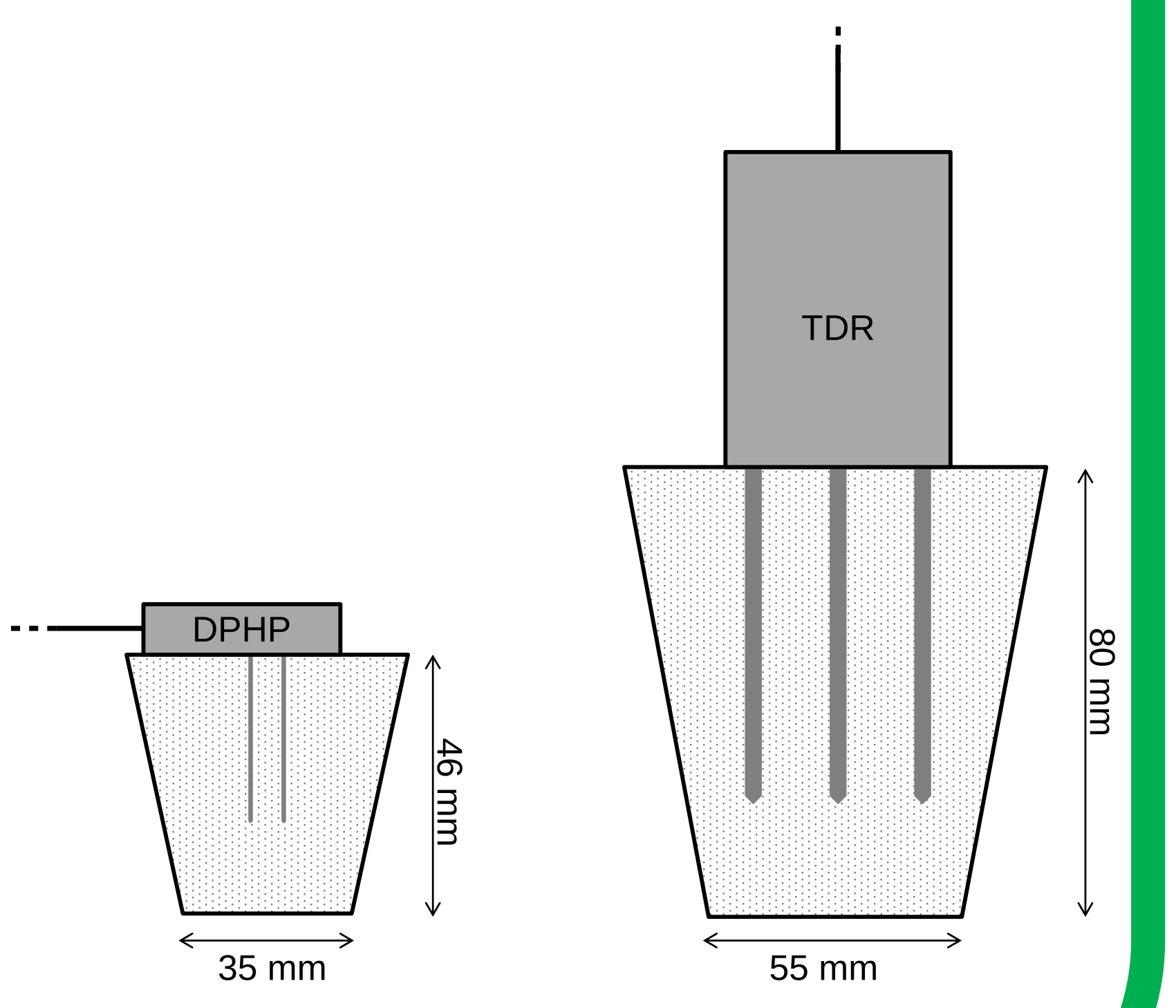
ρc = 4174000 $Jm^{-3}s^{-1}$

Maximum temperature increase, ΔT_m, (°C), time of the maximum temperature change, t_m, (s), energy input per unit length of heater per unit time, q', (W m^{-1}), effective needle separation, r, (m), volumetric heat capacity, ρc, (kJ m^{-3} s^{-1}), thermal conductivity, λ, (W m^{-1} K^{-1}), absolute percentage error of the volumetric heat capacity, $\varepsilon_{\rho c}$, (%), and absolute percentage error of the thermal conductivity, ε_{λ}, (%), acquired after measurements undertaken on agar solution for the calibration of sensor spacing.

ΔT_m	t_m	q'	r	ρc	λ	$\varepsilon_{\rho c}$	ε_{λ}
0.595	63.1	82.8	0.005705	4003	0.55272	4.10	8.04
0.601	62.28	81.87	0.005654	3988	0.54871	4.45	8.71
0.604	63.28	81.87	0.005672	3944	0.53673	5.50	10.70
0.572	63.08	81.64	0.005741	4054	0.56709	2.87	5.65
0.573	64.58	81.42	0.005770	3995	0.55053	4.30	8.41
0.598	63.98	81.19	0.005691	3924	0.53131	5.98	11.60
0.585	63.48	80.5	0.005698	3967	0.54305	4.95	9.65

EXPERIMENTAL SETUP

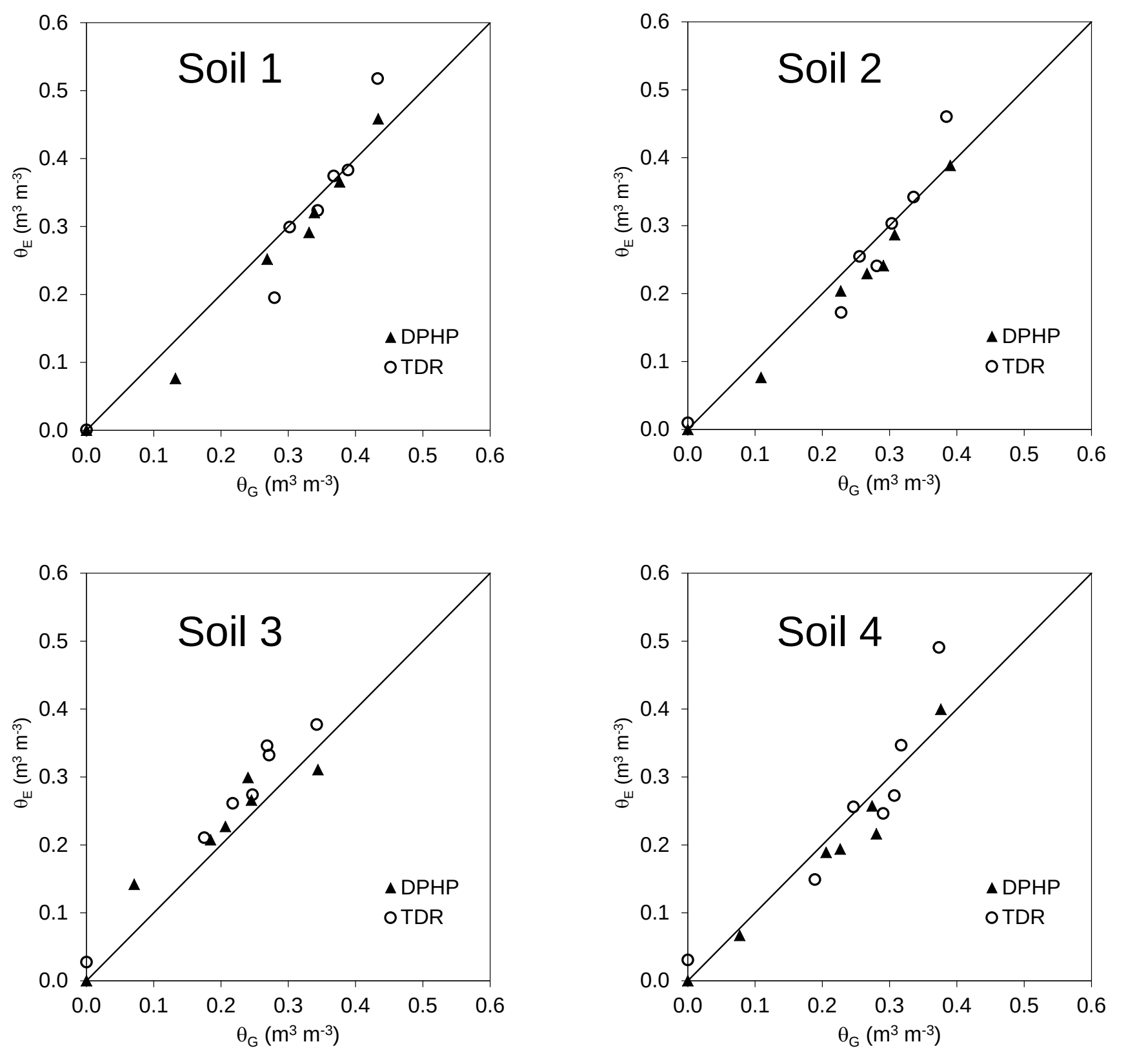
Volume and dimensions of the two types of containers were chosen in such a way that they are compatible to probe size and that measurements are representative of the entire soil sample



Description, origin, median grain size, D_{50} (mm), coefficient of uniformity, CU, computed as the ratio between the grain diameter at 60% passing, and the grain diameter at 10% passing, porosity (m^3/m^3), and bulk density (Mg m^{-3})

Soil ID	Description	Origin	D_{50} (mm)	CU	Porosity (m^3/m^3)	Bulk density (Mg m^{-3})
1	Medium sand	River Toce, Vogogna-Prata	0.30	3.25	0.434	1380
2	Coarse sand	River Toce, Masone	0.45	4.83	0.390	1460
3	Sandy loam	Cultivated field, Bibione	0.20	5.00	0.344	1464
4	Fine sand	Beach, Bibione	0.22	3.79	0.376	1606

EXPERIMENTAL SETUP



Soil ID	Heat capacity (MJ m^{-3} K^{-1})	CV
1	2.392 ± 0.093	3.9
2	2.459 ± 0.085	3.5
3	2.494 ± 0.065	2.6
4	2.723 ± 0.044	1.6

Soil ID	DPHP			TDR		
	MPE	MAPE	NMSE	MPE	MAPE	NMSE
1	-0.0953	0.1141	0.014	-0.0267	0.0984	0.027
2	-0.1134	0.1134	0.019	-0.0286	0.1008	0.027
3	0.2212	0.2536	0.045	0.1543	0.1543	0.040
4	-0.0849	0.1056	0.026	-0.0113	0.1469	0.054

CONCLUSIONS AND ACKNOWLEDGEMENTS

In this work, a portable probe for the assessment of soil thermal properties and water content using the DPHP method is presented. The DPHP probe is based on open hardware architecture that ensures a cost effective realization of the probe based on free sharing design. The DPHP probe has been tested for soil thermal properties assessment and compared to TDR probe for the water content estimation in four different soils. The DPHP probe showed an accuracy comparable to TDR in estimating water content, but the DPHP can be used to investigate smaller volume of soil. The counterpart is that TDR is much faster than DPHP in measure acquisition. TDR applied without a soil specific calibration overestimated water content under saturated condition.

Acknowledgements

I thank one of my best friends, who prefers to be anonymous, for his help in assembling and programming the portable device, and my son Angelo Huhao Ravazzani for his help in collecting beach sand.