Geoderma 150 (2009) 23–31

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

# Field use and calibration of a TDR-based probe for monitoring water content in a high-clay landslide soil in Austria

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ARTICLE INFO

*Article history:*
Received 4 July 2008
Received in revised form 27 December 2008
Accepted 6 January 2009
Available online 10 February 2009

*Keywords:*
Soil water sensors
Landslide soil
Clay soils
Field calibration
Measurement error
Regression analysis

ABSTRACT

Dielectric-based sensors are widely used for field monitoring of soil volumetric water content ($\theta_v$), including *in situ* applications in ecological monitoring programs. However, sensor response depends strongly on the location-specific soil properties, which in turn affects measurement accuracy and data processing. Published general or manufacturers' calibrations often misrepresent the $\theta_v$-sensor output relationship, requiring soil-specific calibration. We report on use of the CS615 Water Content Reflectometer (WCR) to monitor the soil water dynamics in a creeping flow at a landslide site (Bad Goisern, Austria), and on the soil-specific adjustment of measurement errors. Extraordinary soil conditions (high clay and water contents) caused anomalous overestimation of $\theta_v$ via the manufacturer's standard calibration. Further, a laboratory calibration had to be aborted due to the intractable soil material. However an *in situ* field calibration and an *ex situ* field-soil calibration successfully provided relations between $\theta_v$ and the probe output (multivibrator period, $\tau$). The calibration was performed as a two-stage procedure according to the inverse regression method. Linear (LR) and multiple (MR) regression models and polynomial (P2, P3) relations were generated via regression analyses. Bias, mean squared error (MSE) and mean deviation (MD) were used to evaluate the quality of $\theta_v$ estimation using the inverse prediction function. LR and MR models provided better data adjustment than polynomial functions. Best results were derived from MR models including as additional variables temperature ($T$) and porosity ($P$), and subset-specific ($S$) to sensor position in the field (model MR TP S). Measurement error was reduced from $0.068\pm0.122$ m$^3$ m$^{-3}$ (MSE$\pm\sigma$ for the standard calibration) to $0.001\pm0.002$ m$^3$ m$^{-3}$ (MSE$\pm\sigma$ for the MR TP S model). Restricted sample size and moisture range impaired the statistical analyses of both field soil calibrations. Deviations of sensor response specific to soil layer and sensor position were observed and statistically confirmed. However, reasonable location-specific calibration functions were obtained for both the entire water content range and the site-specific high moisture range. Our results indicate an especially anomalous, soil pH-dependent response of the WCR (which operates in the lower frequency range 15 to 45 MHz) in a smectite-dominated soil, partly consistent with the findings of Ishida and Makino (1999) for the dielectric behaviour of montmorillonite suspensions. Unfavourable soil conditions, especially high moisture levels combined with high clay contents, demonstrated the limits of WCR-application. Our findings strongly support media-specific sensor calibration over general calibrations, especially for soils with extraordinary and challenging properties.



## 1. Introduction

Afforestation of mountain slopes damaged by mass movements is an essential part of their technical stabilisation and drainage. Knowledge of the soil water dynamics of erosive and slide-prone sites is crucial for the management and performance of such forests. Many projects increasingly involve monitoring of the time development and spatial variability of the soil volumetric water content ($\theta_v$) of slide-prone sites, to assess critical values and further risks, and the impact of vegetation on the local water regime.

Recent sensor technology greatly improves efficiency of continuous monitoring for hydrological and earth science applications. Time domain reflectometry (TDR)-based devices are popular for multi-site monitoring (Jones et al., 2002; Robinson et al., 2003; Blonquist et al., 2005). Robustness, ease of use, and cost effectiveness are key factors for *in-situ* application.

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doi:10.1016/j.geoderma.2009.01.002

However, sensor responses can be strongly affected by ambient conditions and local soil properties, which impedes data interpretation and requires site-specific calibration. The prediction of $\theta_v$ from dielectric permittivity ($\varepsilon$) or other measured variables as estimators is also subject to a series of secondary factors. The influence of electrical conductivity and temperature on TDR accuracy is well reported (Campbell, 1990; Lin, 2003; Walker et al., 2004). Other factors include clay content, organic matter content, bulk density, and ion concentration, which can considerably affect the dielectric properties, creating potential errors in $\theta_v$ determination (Ishida and Makino, 1999; Gong et al., 2003; Blonquist et al., 2005). Site- and media-specific calibration, usually via empirical or dielectric mixing models, is required to adjust measurement errors and improve accuracy (Ponizovsky et al., 1999; Quinones and Ruelle, 2001; Woodhead et al., 2003). Such calibration reportedly performs better than generalised calibration equations (Jacobsen and SchjØnning, 1993; Quinones and Ruelle, 2001; Stenger et al., 2005).

Amongst a variety of electromagnetic sensor types, the CS615 Water Content Reflectometer (WCR, see Fig. 1), or its improved version CS616 WCR (Campbell Scientific, Ltd., Leicestershire, UK), are popular due to robustness, cost and accuracy (Sumner, 2000; Seyfried and Murdock, 2001; Chandler et al., 2004; Stenger et al., 2005). We used six CS615 WCRs for a monitoring program at a landslide site (Bad Goisern, Austria) to evaluate the impact of an alder forest on the local water regime. Extraordinary site and soil conditions in terms of precipitation input, saturation level, high clay content and its mineralogy, and soil physical properties revealed a strong overestimation of $\theta_v$ based on the manufacturer's standard calibration (Campbell Scientific, 1998). This overestimation was also specific to soil layer and sensor position. Temperature compensation alone was insufficient (Loiskandl et al., 2003), requiring location-specific sensor calibration.

Reports on restricting experiences with the CS615 WCR were published by some other authors: Quinones et al. (2003) reported that published calibrations were unsatisfactory for many soils, thus requiring specific calibration. Seyfried and Murdock (2001) reported the WCR to have varying output responses in different soils at identical water contents. Only in sand did measurements agree with the manufacturer's calibration. According to Chandler et al. (2004) and Kim and Benson (2002) high clay contents resulted in greater sensor output period ($\tau$), which could be corrected easily by using simple linear models or quadratic functions. Substrate-specific temperature effects on $\tau$ for all soils and water contents were reported by Stenger et al. (2005), Kim and Benson (2002) and Seyfried and Murdock (2001). Blonquist et al. (2005) confirmed that higher frequency sensor systems were impacted by bulk electrical conductivity and temperature to a greater extent than by dielectric relaxation. WCR-calibration data for moist soils ($\theta_v$>0.5 m$^3$ m$^{-3}$) with clay contents up to 70% were published by Stenger et al. (2005) and Veldkamp and O'Brien (2000), but were not applicable to our data for two reasons: a) our soils were more extreme in terms of saturation level and clay content, b) both over- and under-estimation of $\theta_v$ were described and differed from our observations.

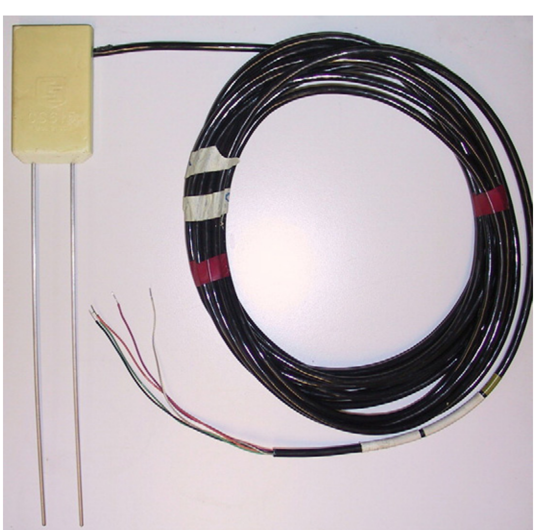

**Fig. 1.** CS615 water content reflectometer (WCR, Campbell Scientific, Inc.).

Our objective was to develop soil-specific calibration functions for the CS615 WCR. We report the difficulties encountered under adverse field conditions, and our approach to establish simple regression functions to compensate measurement errors. This paper focuses on calibration using data obtained from two approaches: a) an *in situ* field calibration (IFC); and b) an *ex situ* field-soil calibration (EFC). Particular attention is paid to the evaluation of linear calibration models, multiple regression and polynomial models for a) the total data set and b) data subsets partitioned according to the six sensor positions in the field.

## 2. Material and methods

### 2.1. Site and soil description

In 2001 and 2002, a 2-year field monitoring program was conducted at the site of a former landslide, 'Stambach' at Bad Goisern, Austria (47°39'N, 13°39' E, elevation 920 to 1,110 m). The site is in the northern Central Alps, with mean annual precipitation 1273 mm and mean annual temperature 8.5 °C.

The soil was classified as Clayic Stagnosol (Thaptomollic) (IUSS, 2007). The clay fraction ranged from 64.2% to 88.6%, with mineralogy dominated by vermiculite and smectite. Secondary components were illite and primary chlorite. In combination with high precipitation during both study years (1764 mm and 1862 mm), this caused nearly saturated soil conditions throughout both years. While the top soil (0–30 cm) responded to wet and dry periods with distinct day-to-day fluctuations, the sub soil (30–60 cm) was characterised by near constant $\theta_v$ up to 0.75 m$^3$ m$^{-3}$.

### 2.2. Instrumentation systems

Soil $\theta_v$ was measured at three different site positions (V1, V2, V3) using six CS615 water content reflectometers (WCR's, Campbell Scientific, Inc.) The CS615 (see Fig. 1.) uses a transmission-line oscillator principle (Campbell Scientific, 1998; Campbell Scientific, 2002; Blonquist et al., 2005; Campbell Scientific, 2006). A multivibrator in the probe head transmits voltage pulses along paired, parallel 30 cm long stainless steel rods. The return pulse reflected from the rod ends triggers the next pulse. The pulse period ($\tau$ in ms) is a measure of soil dielectric permittivity, which can be related to $\theta_v$ via calibration. The CS615 operates in the range of 15 to 45 MHz (Chandler et al., 2004).

At three positions two probes were inserted vertically in two layers (top soil 0–30 cm, sub soil 30–60 cm). Next to each probe position, temperature sensors (Pt100/HEL) were installed at depths 15 and 30 cm. Data were recorded hourly by data loggers (model Minicube VF, EMS Brno, CZ).

Before installation, to check on uniformity of the six CS615 sensors, readings were taken in air and in water. The readings were in close agreement as follows (mean ± $\sigma$, with the CS standard calibration): in air 0.0358 ± 0.006 m$^3$ m$^{-3}$; in water 1.0331 ± 0.0358 m$^3$ m$^{-3}$.

## 3. Calibration procedure

### 3.1. Laboratory calibration

CS615 calibration started with an attempted laboratory calibration based on the Gong et al. (2003) method, which uses upward saturation