Journal of Hydrology 501 (2013) 205–212

Contents lists available at ScienceDirect

Journal of Hydrology

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

Field comparison of selected methods for vertical soil water content profiling

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ARTICLE INFO

Article history:
Received 2 March 2013
Received in revised form 29 July 2013
Accepted 5 August 2013
Available online 12 August 2013
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Niklas Linde, Associate Editor

Keywords:
Vertical soil water content profiling
Direct push
Gravimetric analysis
Neutron probe
Water Content Profiler

SUMMARY

High-resolution information about vertical variations in soil water content is important for applications ranging from agricultural water management to flow and transport modeling. Commonly applied tools for the investigation of vertical soil water content distribution in hydrogeological field investigations are: gravimetric laboratory analyses of soil samples, logging a cased borehole using a tool with a radioactive source (neutron probe), or yet less well established, direct push-based moisture sensor probes. Due to differences in their underlying measurement principles as well as different operation modes, each of the aforementioned methods is associated with certain advantages and limitations. A common field evaluation of these methods has not been performed until now – raising the question of how well these individual methods perform when applied under different depositional and hydrogeological conditions. For field evaluation direct push-profiling was performed at three different test sites under different hydrogeological settings and varying degree of sediment heterogeneity and compared with results obtained from gravimetric analysis of soil cores and neutron probe measurements. In direct comparison the applied direct push-based Water Content Profiler proved to be a suitable alternative to neutron probe technology for measuring the vertical water content distribution. Moreover, the Water Content Profiler proved to be advantageous over gravimetric analysis in terms vertical resolution and time efficiency. Results of this study identify application-specific limitations of the methods and thereby highlight the need for careful data evaluation, even though some of the methods described in this paper are well established.

1. Introduction

The importance of determining volumetric soil water content (θ) has been long recognized in hydrology (see amongst others Robinson et al., 2008; Vereecken et al., 2008). Application examples include agricultural water management (Michot et al., 2003; Iqbal et al., 2005; Cassiani et al., 2012), water resources management (Sciuto and Diekkruger, 2010; Bales et al., 2011; Swarowsky et al., 2011), and ecology (Kieft et al., 1993; Sandvig and Phillips, 2006). Thereby, knowledge of the spatial distribution of soil water content is a prerequisite for the parameterization and calibration of flow related models. In addition, soil moisture content determination is an efficient way to estimate total porosity of sedimentary aquifers in the phreatic zone. A variety of experimental techniques to determine volumetric soil water content is available; see Dobriyal et al. (2012) for a review. For vertical (semi)-continuous profiling of soil water content distributions (in depths of up to tenths of meters), approaches such as gravimetric analyses of soil samples, borehole logging methods, and direct push (DP)-based sensor probes are applicable. Borehole logging methods include neutron probe (NP), gamma, and nuclear magnetic resonance (NMR) logging technology; see amongst others for a detailed overview and further references: Keys (1990), Serra and Serra (2004), and Kobr et al. (2005). A recent development is the application of NMR in small diameter wells (Walsh et al., (2013). Another commonly-used technique is Time Domain Reflectometry (TDR), however, it is often limited to shallow depths or excavations. A rather novel exploration strategy is the application of non-invasive surface geophysics to map the vertical distribution of soil water content, such as ground penetrating radar (GPR) and surface NMR data, see

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http://dx.doi.org/10.1016/j.jhydrol.2013.08.004

among others: Walsh (2008), Minet et al. (2011), Schmelzbach et al. (2011), Schmelzbach et al. (2012), Steelman et al. (2012). Nevertheless, direct measurements of soil water content using invasive techniques are often required for the calibration of such approaches. Among the aforementioned methods, gravimetric analysis and neutron probe measurements have been commonly applied for hydrogeological site investigations for decades.

Against this background, it is essential to consider that these methods have certain advantages and disadvantages (as listed in Table 1). For gravimetric analysis of soil samples, disadvantages include soil disturbance during sampling, removal of the soil from its natural stress field, sample transport, and labor costs. In situ measurements of soil water content are therefore preferable and are usually obtained using an active source neutron probe in a cased borehole, or access tube, to determine a vertical profile of soil water content. However, the handling, transport, and storage of radioactive sources requires special training and is subject to regulatory approval in most countries. In addition, both methods only yield discontinuous measurements, where decreased resolution and data interpretation often requires previous knowledge of sediment type distributions. Over the last couple of decades, minimally invasive direct push-based sensor probes have been developed that measure in situ vertical soil water content profiles based on the dielectric properties of the soil. These sensor probes can be operated independently or in combination with other direct push probes, such as cone penetrometers for cone penetration testing (CPT). For an overview of direct push technology, see McCall et al. (2006), Dietrich and Leven (2006), Leven et al. (2011), Liu et al. (2012).

Until now, a joint field evaluation of these methods under varying conditions has not been conducted – raising the question of how well these individual methods perform when applied under different depositional and hydrogeological conditions. For field evaluation of these tools, direct push profiling was performed at three different test sites with different depositional and hydrogeological regimes and varying degrees of sediment heterogeneity and compared with results obtained from gravimetric analysis of soil cores and neutron probe measurements. We provide a brief overview of the applied methods in the following section. Since gravimetric water content determination and neutron probe technology are well described and established methods, our focus is therefore placed upon direct push-based sensor probe technology. A brief introduction of the three test sites is given and the work program is outlined, followed by a description of measurement results and, finally, discussion of these results.

2. Applied methods

In our study, gravimetric analysis of soil cores, neutron probe technology, and a direct push-based capacitance probe were applied. The individual techniques are explained in the following section.

2.1. Gravimetric analysis of soil cores

Core samples were taken using the direct push-based Geoprobe® Dual tube sampling system. For soil sampling, a solid barrel sampler inside a drive casing was pushed and hammered into the subsurface. The sampler was equipped with a 122 cm long and 4.96 cm inner diameter PVC liner for sample recovery. This setup allows continuous soil sampling. For further information on the Dual tube system, see McCall et al. (2006) and Zschornack and Leven (2012). The PVC liners were pre-cut into 10 cm sections for sampling. The retrieved core samples were weighed both before and after 12 continuous hours of 110 °C oven drying to determine volumetric water content. The volumetric water content of the soil sample is calculated according to (see Delleur, 1999; Todd and Mays, 2005):

$$\theta = \frac{V_w}{V_T} \quad (1)$$

where V_w is the volume of the water and V_T is the volume of the sample. To translate weight into volume, a location-specific soil and groundwater temperature of 10 °C was assumed.

2.2. Neutron probe measurements

Hignett and Evett (2002) give a comprehensive overview of the neutron probe principles, equipment and measurement procedures. The working principle of neutron probe measurements is based on a radioactive source that emits fast neutrons and a detector for slow (thermalized) neutrons. When emitted in the subsurface, fast neutrons are slowed to thermal energy levels by the collision with hydrogen nuclei. In our study, the change in hydrogen content is primarily driven by changes in soil water content. Therefore, the concentration of the slowed thermal neutrons can be related to the volumetric soil water content (see Hignett and Evett, 2002). However, soil density and chemical composition of the subsurface can affect the neutron measurements. In heterogeneous media with changing textures, calibration routines must be adapted to the geological conditions. Using a common regression line between volumetric water content and neutron count ratio can introduce considerable error and complicate data interpretation under these conditions; especially in the presence of clay (Hignett and Evett, 2002). At sites with a broad sedimentary spectrum, previous knowledge of sediment distribution is essential for data interpretation. Vertical profiling was conducted in the subsurface through access tubes. The intrinsic area of influence, i.e. the volume over which the probe measures an integral parameter value at one measurement point, is estimated for neutron probe measurements according to Cameron (1970) as a sphere with radius:

Table 1
Major advantages and drawbacks of gravimetric, neutron probe, and direct push-based Water Content Profiler measurements to determine soil water content.

	Gravimetric analysis	Neutron probe	Water Content Profiler
Type	Ex situ	In situ	In situ
Frequency	Depth oriented	Discontinuous	Continuous
Time effort	High	Medium (low for repetitive measurements)	Medium
Resolution	Sample size dependent	Decimeter scale	Centimeter scale
Effects on measurements	Sample disturbance; removal from natural stress field	High clay content; chemical composition; water within access tube	Loss of electrode contact; hydrocarbons
Restrictions	High effort for reliable retrieval of saturated cores (e.g. core freezing)	Subjected to regulatory requirements	Complex underlying dielectric theory; deployment only with DP equipment
Application	Soil investigation, if additional information such as grain size distribution is needed	Soil water content monitoring	Soil water content mapping