Comparing Time Domain Reflectometry and Electrical Resistivity Tomography Measurements for Estimating Soil Water Distribution

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ABSTRACT. Two different methods to determine the spatial distribution of soil water were tested and compared on a full-scale dike model. TDR-measurements of the spatially distributed water content along transmission lines were compared with electrical resistivity tomography (ERT) measurements along the same cross-section. In contrast to the TDR method, ERT is a non-invasive method and does not require the perturbation of the dike’s interior for the measurements. However, determining the soil water content from the resulting electrical resistivity values is more difficult than in case of the dielectric coefficients using TDR. Field data were obtained during a controlled simulation of an extreme precipitation event in the context of water balance investigations. A comparison of both methods shows similar results, except for differences in spatial resolution.

Keywords: spatial TDR, geoelectric, dike model, comparison of methods

1 Introduction

Geophysical measurement methods are essential elements for monitoring systems. Especially storage buildings like earth dams have to be observed, because of their high exposure. For this purpose, pressure gauges are used normally. Increasingly fibre optical temperature measurements are implemented for example to localise temperature anomalies indicating leakages in sealing systems [1]. However, in many cases the geotechnical engineer is interested in quantitative water content distributions characterising the hydraulic situation within earthen structures. Based on this information it is possible to predict the hydraulic behaviour of an earth dam depending on hydraulic loads. Such continuous moisture measurements have been realised on a full-scaled dike model using Time Domain Reflectometry (TDR) for the first time [2]. In this experiment, the spatially distributed water content along expanded transmission lines was interpolated between the measurement profiles. However, the electrical field triggered by TDR-signals is limited to a small range around the transmission line, why local anomalies in some distance stay undetected.

One possibility to determine the fully two-dimensional spatial distribution of moisture in earthen structures is the electrical resistivity tomography (ERT) method, which is often used in combination with exploration drillings in order to determine the structural composition of dikes and subsoil [3]. Apart from many further applications in environmental, engineering and archaeological studies ERT has been successfully used to monitor the seepage in an earth embankment dam [4].

The following contribution shows a comparison of both systems (TDR and ERT) during a sprinkler irrigation test on a full scaled dike model. The aim of the combination of both systems is to improve the interpretation of 2-dimensional water content distribution.
2 Methods

2.1 Properties of Soils

Soil is a typical porous medium consisting of the three phases pore air, grain and pore water (cf. Fig. 1). The fractions of the soil phases vary both in space – due to composition and density of soil – and time – due to changing water content. For the determination of the water content of the soil, one utilise the fact that total permittivity and total resistivity are dependent on the fractions of the soil phases. A straightforward but laborious way to find the relation between water content and total permittivity or resistivity is to perform a specific laboratory calibration with gravimetric sampling. This is often impractical for operational use. Therefore, several empirical, semi-empirical and theoretical mixing rules with different degrees of experimental justification have been developed and applied. One of the commonly used empirical equations for the determination of the permittivity was given by [5]. A mixing rule depending on the bond form of water was developed by [6]. The most popular mixing rule for the determination of the resistivity was given by Archie [8].

Fig. 1 Electric (resistivity $\rho$ $[\Omega \text{m}]$) and dielectric (permittivity $\varepsilon_m$ [-]) properties of soil phases

2.2 Time Domain Reflectometry (TDR)

For TDR measurements a fast time voltage step is launched into a transmission line and the reflections are recorded (e.g. with an oscilloscope). The length of standard, non-insulated metallic forks as transmission lines are usually restricted to 30 cm because of high damping losses. For longer transmission lines, a new insulated flat band cable was developed [7, 9]. It shows much less pulse attenuation than non-insulated metallic forks in the same media. The flat band cable is shown in Fig. 2 together with its electrical field distribution in the cross-section for excitation in air. The cable consists of three copper wires covered with polyethylene insulation. The electrical field concentrates around the conductors and defines a sensitive area of 3
to 5 cm around the cable. For the calculation of the permittivity from the determined capacitance of the TDR measurement, a special capacitance model was developed [7].

![Flat band cable and electrical field distribution in the cross-section for symmetric excitation in air](image)

Fig. 2 Flat band cable and electrical field distribution in the cross-section for symmetric excitation in air

The standard TDR measurement procedure based on travel time analysis delivers only the mean water content along the transmission line. As the TDR response contains far more than the travel time of the reflected electromagnetic signal, a three-step algorithm has been developed to reconstruct the soil moisture profile from the full signal response along the transmission line [10]. This new TDR measurement system consisting of recorded step pulse with spatial analysis has already proved its effectiveness in different applications [2, 11, 12] and is introduced as spatial TDR.

### 2.3 Electrical Resistivity Tomography (ERT)

The ERT technique is based on electrical resistivity differences between different subsurface materials. With the development of fast, commercially available 2-dimensional inversion schemes for tomographic data sets, the DC resistivity method has been increasingly applied, especially for environmental and engineering problems [e.g. 4, 13, 14].

In DC resistivity surveys electrical current is injected into the ground via two current electrodes. The resistance of the ground is then determined by measuring the electric potential between two other electrodes and dividing by the current. By multiplying the resistance with a geometric factor depending on the distance between the electrodes and choosing different electrode spacings and locations, the so-called apparent electrical resistivity is determined on a 2-dimensional grid. By using a tomographic inversion scheme (RES2DINV) these apparent resistivities can be inverted to yield a 2-dimensional specific resistivity model of the ground [15]. For monitoring purposes, these measurements are repeated at certain time intervals using a permanently installed electrode array. The permanent electrode array effectively filters resistivity variations due to variable electrode contacts or geological background variations. By this, temporal resistivity changes can be related to changes in the subsurface water content on a 2-dimensional or even 3-dimensional grid.

An estimate of the water content of the ground through repeated resistivity measurements can be obtained by using a simple approach based on a well-known relation between the resistivity of a material and its pore fluid called Archie’s law:
\[ \rho = a \rho_w \Phi^{-m} S_w^{-n} \]  

where \( \rho \) is the resistivity of the material, \( \rho_w \) is the resistivity of the water in the pore spaces, \( \Phi \) is the porosity, \( S_w \) is the fraction of the pore space occupied by liquid water (i.e. the saturation) and \( a, m \) and \( n \) are empirically determined parameters [8]. By taking the ratio of the observed resistivities of subsequent measurements \( t_1 \) and \( t_0 \) the resistivity of the pore water \( \rho_w \) and the material parameter \( \Phi \), \( a \) and \( m \) can be eliminated, giving

\[ \frac{\rho(t_1)}{\rho(t_0)} = S_w^{-n}(t_1) / S_w^{-n}(t_0). \]  

The evolution of the saturation \( S_w \) at a later time \( t_1 \) can now be calculated using the initial saturation \( S_w(t_0) \) and the ratio of the observed resistivities

\[ S_w(t_1) = S_w(t_0) \cdot \left( \frac{\rho(t_1)}{\rho(t_0)} \right)^{1/n}. \]  

King et al. estimated the so-called saturation exponent \( n \) between 2-3 (for sands) and 5-8 (for clays) [16]. The water content as determined by the TDR cables can then be calculated by multiplying the saturation \( S_w \) with the porosity \( \Phi \) of the material.

3 Dike Model and Instrumentation

3.1 Dike Model

The transient progression of the seepage within a dike body during a temporary flood event depends among others on the initial soil water content of the earth material. In this connexion, the initial soil water content is the result of meteorological and hydrological water balance processes affecting the dike body. For the investigation of the hydraulic behaviour of dikes as earthen structures, a full-scale dike model is available (cf. Fig. 3).

Fig. 3 Full-scale dike model at the Federal Waterways and Research Institute in Karlsruhe during a flood simulation test in December 2000
3.2 Instrumentation

The dike model is permanently equipped with 12 vertically installed flat band cables from 1 to 3 m in length, connected from both sides with coaxial cables to a multiplexer and TDR device in a box on the crest of the dike. The data collection and controlling equipment (PC) of the system is located in a measuring container at the toe of the landside slope (cf. Fig. 4). ERT measurements were conducted manually from the crest of the dike using a conventional resistivity meter (ABEM Terrameter). For this, 23 resistivity electrodes were distributed along the top ground surface (cf. Fig. 4).

![Diagram of the TDR measuring system](image)

Fig. 4 Location of the flat band cables and the resistivity electrodes in the cross-section of the dike and schematic description of the TDR measuring system.

4 Results

Fig. 5 shows the results of TDR measurements as distribution of saturation (ratio of volumetric water content and porosity) from two time instances before and after the end of an irrigation experiment. The results after the irrigation show saturation values of around 30% at the surface, which is decreasing with depth to values below 20% in the dike interior. Maximal values are found at the surface about halfway down the dike’s flank, where the water input during the irrigation experiment was maximal.

In contrast to the TDR results, the ERT results of Fig. 6 depict not directly the water content or saturation but the electrical resistivity (in $\Omega$m). In homogeneous material low resistivities (dark shading) can be associated with high saturation and high resistivities (light shading) with low saturation. As the ERT method is surface-based, measurements had to be conducted across a small stone path on top of the dike crest (cf. Fig. 3), which is clearly seen by the anomalously high resistivity in this region.

In dry state resistivities are lowest along the surface and increasing to greater depths. Maximal resistivities are found at the bottom in the central part of the dike, which is in good agreement with the corresponding low water contents ($< 20\%$) in the TDR results. After the irrigation resistivities are markedly lower throughout the whole dike’s interior and lowest (corresponding to maximal water contents) around halfway down the flank, where the water input during the experiment was maximal. Again, this is in good agreement with the corresponding high water contents visible in the TDR results.
Fig. 5 Result of TDR measurements presented as saturation (top) in dry state and (bottom) after an irrigation experiment.

Fig. 6 Result of ERT measurement represented as resistivity in $\Omega$m (top) in dry state and (bottom) after an irrigation experiment.
For a quantitative comparison between the two methods, the distribution of saturation at a later time instance (5 hours after the irrigation) is calculated from the resistivity results using Equation (3).

Fig. 7 shows a comparison between the calculated ERT results (left) and TDR (right). Apart from the crest of the dike, where the presence of the stone path leads to differences between the in-situ method (TDR) and the surface-based method (ERT), both measurements are in good quantitative agreement.

5 Summary and Conclusion

We presented a comparative study using spatial TDR and electrical resistivity tomography (ERT) to determine the spatial and temporal variability of water content distribution in a full-scale dike model. Whereas spatial TDR determines the in-situ water content distribution along up to 3 m long flat band cables by analysing the full signal response and relating it to the dielectric properties, the ERT system determines the 2-dimensional electric resistivity distribution from surface-based geoelectric measurements and subsequent data inversion. TDR and ERT results from experiments before and after a sprinkler-irrigation test were shown.

Both methods show good agreement, both, concerning the spatial variability before, as well as concerning the temporal evolution during and after the irrigation experiment. The advantages of the spatial TDR system are the high spatial resolution near the sensor cable and the well-established relation between dielectric parameters and water content. The advantages of the ERT approach are the full 2-dimensional representation of the parameters in the dike's interior and the non-invasive character of the measurements. A combination of both methods, e.g. a
calibration of the ERT approach using spatial TDR and large-scale measurements using the surface-based ERT, seems promising for future earth dam monitoring systems.

References