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Spatial-TDR Moisture Measurement in a Large Scale Levee Model Made of Loamy Soil Material

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Abstract

The stability of levees with a more or less homogenous structure basically depends on the degree of saturation of the levee body. To analyse the stability of old levees with a quasi-homogeneous structure, which are not state-of-the-art from a technical point of view, a large scale levee model made only of loamy soil was constructed in the laboratory and exposed to various flood levels under differing initial hydraulic conditions.

To measure the water content distribution in the levee over time, a novel Time Domain Reflectometry (TDR) method is used. This method which is called Spatial-TDR allows a continuous monitoring of spatially resolved moisture profiles along elongated TDR sensors with a high spatial and temporal resolution. With an appropriate geometric arrangement using a large number of these profile sensors in a cross section, quasi 2-dimensional images of the infiltration process were obtained.

In total, 20 insulated flat-ribbon cables between 28 and 200 cm in length serving as TDR waveguide sensors were installed in the levee model during construction. Since the resolution of the moisture distribution improves significantly with two-sided measurements, the sensors were connected to the TDR device from both ends. To improve the signal quality along the sensor, remotely controllable relays optimized for switching high frequency signals were installed in the sensor ends. They are used to exactly identify the reflections in the TDR signal generated at the sensor's front and rear ends. This is especially helpful when measuring in lossy soil material under wet conditions. A linux based industrial PC controls the TDR device as well as the multiplexers and the relay switches. The measuring system is capable of round the clock measurement and automatic data transfer to a remote computer which carries out the reconstruction calculations.

In the paper the TDR measurement configuration for the levee experiment is presented and explained. Furthermore, the results of the spatial moisture measurements during a non-stationary retaining experiment are shown.

Key Words water content, Spatial-TDR, monitoring system, transient water flow, levee

Introduction

Along rivers and streams in Germany there are levees with a total length of more than 7 500 km. Most of these were constructed between the 18th and the early 20th centuries, when people moved closer to water courses during the oncoming industrialization. In those days the rivers were used for the supply of energy and as main transport routes for goods. Since there were no technical regulations and the building of the levees could only be done by hand at that time, most of these levees were built quasi-homogenously using the available river loam, with steep slopes and only weak compaction. Still today there is a remarkable share of levees in Germany in this inadequate condition.

These "old levees" are not suitable for withstanding long lasting hydraulic loads and tend to fail during lengthy floods especially when they have already been under hydraulic stress during a previous flood or heavy rainfall (Scheuermann & Brauns, 2002[1]). To examine the geohydraulic processes in such embankments and to observe the mechanisms of failure, a large scale levee model was constructed in the laboratory. The experimental facility makes it possible to generate transient hydraulic loads and to record the geohydraulic processes inside the levee. These experiments were to serve to improve the estimation of the risk of failure and to identify the requirements when rebuilding existing levees. The saturation process inside the dam was measured by a newly developed system called Spatial-TDR, which is suitable as a monitoring system in situ.

Large Scale Levee Model

The levees built in the Theodor-Rehbock-Laboratory (TRL) at the University of Karlsruhe have a height of 1.4 m. The slopes are inclined by 1 : 2.5, the crest is 1 m wide, so the base is in total 8 m wide. The length of the crest is approximately 2.2 m, whereas the exterior walls of the experimental rig are inclined by an angle of 2° to minimize the bypath of water along the boundary. In **Fig. 1** there is a photograph of the complete experimental rig, which consists of two symmetric levee models.

On the wet plane of each levee model there is a water basin with controllable water levels. The levee bodies are provided with pressure transducers, tensiometers and field vanes to measure water pressures, capillary forces and the shear strength of the soil. To monitor the water content, 20 insulated flat-ribbon cables between 28 and 200 cm in length serving as TDR waveguide sensors are installed in the levee model. These were assembled during the construction of the levee model. Twelve of the sensors are in vertical direction within one plane. The remaining 8 sensors lie in two horizontal lines, also within one plane close to the base. **Fig. 2** shows a view of the levee model with the above mentioned measurement equipment.

Fig. 1: Experimental rig with two large scale levee models

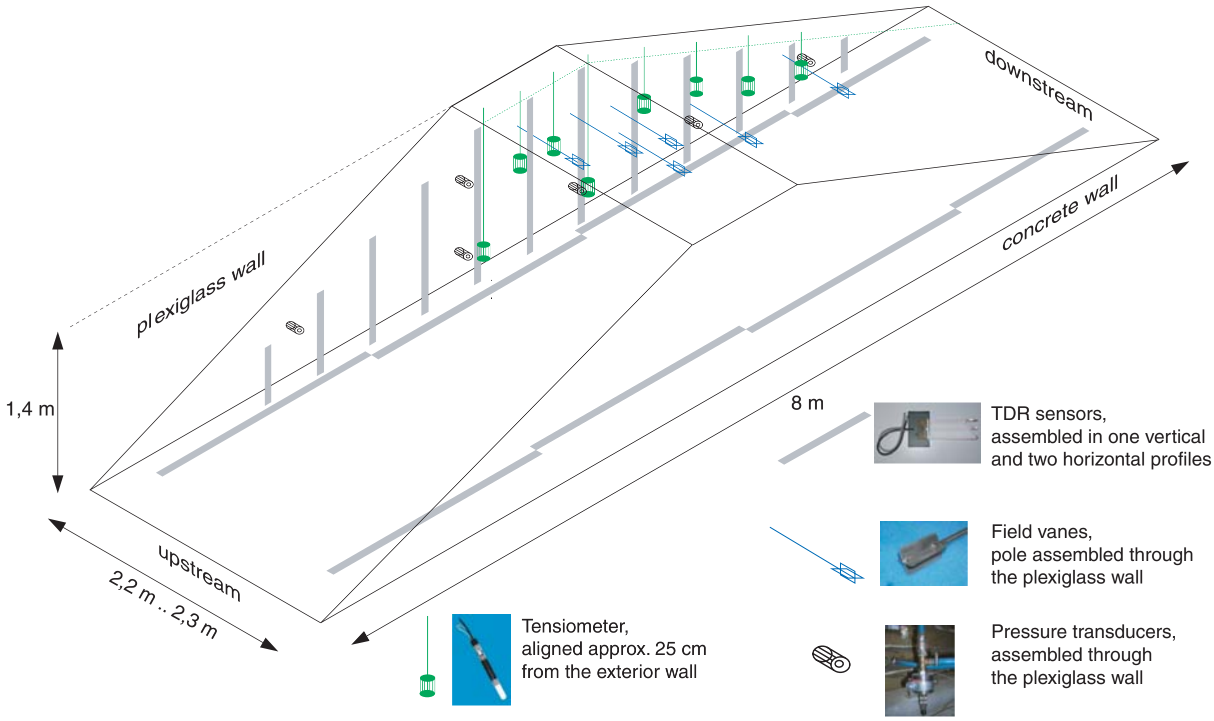

Fig 2: 3D-view of a levee body showing the measuring equipment

The basic principles of TDR

The determination of the water content using TDR (Time Domain Reflectometry) is based on the principle that the relative dielectric number of water ε_{water} is much larger than that of other soil constituents ($\varepsilon_{water} \approx 77$ to 88, $\varepsilon_{solid} \approx 3$ to 8, $\varepsilon_{air} = 1$). The dielectric number ε_m of soil as a multi-phase mixture depends on the dielectric number of the volume fractions of its components. The dielectric number can be measured by determining the propagation velocity c of an electromagnetic wave along uncoated metallic waveguides. The velocity is related to ε_m by

$$c = \frac{c_0}{\sqrt{\varepsilon_m \mu}} \tag{1}$$

where c_0 is the speed of light in vacuum and μ is the relative magnetic permeability, which can be estimated to be 1 for most soils.

To determine c in soil, a waveguide is installed in which very short electrical pulses are sent through. A commonly used waveguide for TDR measurements is an unshielded metallic 2 or 3-rod probe. Due to the impedance discontinuity at the end of the line the electrical pulse is reflected back and detected by a receiver. From the travel time t and the length l of the waveguide, which has been travelled along twice, the propagation velocity $c = 2l/t$ can be calculated. With equation (1) the relative dielectric number ε_m becomes

$$\varepsilon_m = \left(\frac{c_0 t}{2l} \right)^2 \tag{2}$$

The volumetric water content θ can now be correlated using a regression curve based on measured values for a given soil (e.g. Topp et al., 1980[2]). Alternatively the relation $\theta(\varepsilon)$ is determined with a model for a composite dielectric number of a soil (e.g. Roth et al., 1990[3]). Hence, if the soil water distribution varies along the TDR sensor with the method presented above, it is only possible to obtain an average value for the dielectric number of soil ε_m, which then leads to the mean water content of the soil sample.

Spatial-TDR

The reflected TDR pulse contains more information than just the travel time along the sensor. The water content profile information cannot be extracted directly from the TDR signal but has to be estimated by inverse modelling. Therefore, first a model is needed describing the TDR pulse propagation along the whole transmission line of signal (moisture probe). Second the distributed model parameters along the transmission line are to be modified until the simulated TDR signal matches the measurement. In this sense the resulting parameter distributions are the best estimate for the real conditions.

An equivalent electric circuit of an infinitesimal transmission line section is given in **Fig. 3**. In this model the transmission line is characterized by four electrical parameters: the inductance L, capacitance C, series resistance R and shunt conductance G. Regarding the conditions for this electronic circuit model, wave modes other than the transversal-electromagnetic mode and the frequency dependence of transmission line properties may be ignored. The first condition requires a well-behaved transmission line with little distortion on the signal propagation, the second is only met, if the losses in the system being tested are not too large.

Schlaeger (2002)[4] derived the following wave equation from the circuit model for describing the propagation of a voltage pulse *U(x,t)* along a transmission line:

$$\left(L(x)C(x)\frac{\partial^2}{\partial t^2} + L(x)G(x)\frac{\partial}{\partial t} + \frac{\partial L(x)/\partial x}{L(x)}\frac{\partial}{\partial x} - \frac{\partial^2}{\partial x^2} \right) U(x,t) = 0 \tag{3}$$

Capacitance *C(x)* and effective conductance *G(x)* are influenced by the soil water content distribution $\theta(x)$ along the sensor line. Inductance *L(x)* is a function of the transmission line only and piecewise a constant for coaxial cable and sensor line. The spatial derivative of *L(x)* in equation (3) describes the change of inductance between coaxial cable and sensor. Resistance *R* along the transmission line has been neglected. All parameters are given per unit length.

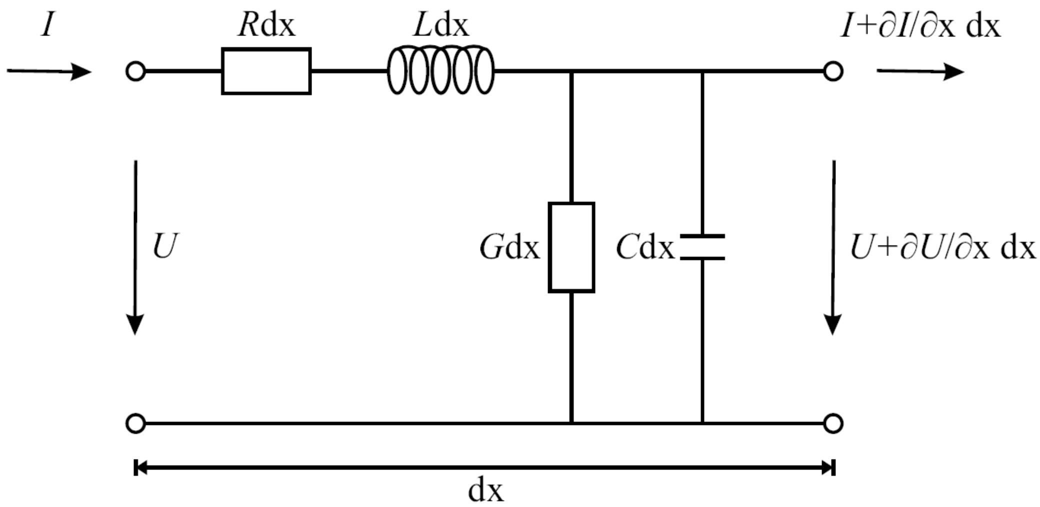

Fig. 3: Equivalent electric circuit of an infinitesimal section of a transverse electromagnetic transmission line

The basic principle of Spatial-TDR is to transform the output signal of a TDR measurement *U(x,t)* into the soil moisture profile $\theta(x)$ along the sensor line by means of inverse modelling. This reconstruction can be achieved by numerically solving equation (3) with the appropriate initial and boundary conditions and estimated *C(x)* and *G(x)* to obtain a simulated progression of *U(x,t)*. The result of the simulation is compared to the actual TDR measurement. An optimization algorithm described in (Schlaeger, 2002[4] and Schlaeger, 2005[5]) is used to modify the electrical parameters *C(x)* and *G(x)* along the simulated moisture probe until the simulated TDR reflectogram *U(x,t)* matches the measurement sufficiently well. The final parameter distributions resulting from the simulation are the best estimate of the electric properties along the real sensor line in soil.

The wave equation (3) needs two parameter distributions *C(x)* and *G(x)*. For inverse modelling of one-sided measurements there must be a functional relation between *C* and *G* such as *G(C(x))* in Håkansson, 1997[6]. By using two-sided, physically independent measurements it is possible to reconstruct both values along the sensor line.

The advantage of the two-sided measurements is not only the independent reconstruction of both electrical parameters *C(x)* and *G(x)*, but also the more exact spatial resolution, especially with long sensor lines. If it has a relatively high effective conductance *G(x)* in the surrounding soil along the sensor line (e.g. because of ions or high water content), the reflection of the TDR signal is absorbed with increasing distance. This effect can also be partially compensated with two-sided measurements. In addition, a coating of the waveguide reduces the effective conductance *G* and opposes the absorption of the signal thus making longer sensors lines feasible (e.g. Ferré et al., 1996[7]). However, if a coating is introduced to the transmission line, the relation between ε and c given in equation (2) is no longer valid. Therefore a probe-specific function $\varepsilon(C)$ has to be determined that calculates the influence of the coating and the sensor geometry.

TDR Measurement Equipment

For the measurements in the levee model in the TRL flexible 3-core flat-ribbon cables coated with PE are used. These were developed and patented at the Institute for Meteorology and Climate Research at the Forschungszentrum Karlsruhe (FZK). According to the equivalent circuit for the flat-ribbon cables given in **Fig. 4** the total capacitance C can be expressed by three capacitances C_1, C_2, and $\varepsilon_m C_3$ and can be transformed into a direct relation between the relative permittivity ε_m of the surrounding soil and the total capacitance:

$$C(\varepsilon_m) = C_1 + \frac{C_2 \cdot \varepsilon_m C_3}{C_2 + \varepsilon_m C_3} \tag{4}$$

The three unknown capacitances C_1, C_2, and C_3 were derived from calibration measurements of three different materials with well known dielectric properties, e.g. air, oil, and water (Hübner et al., 2005[8]).

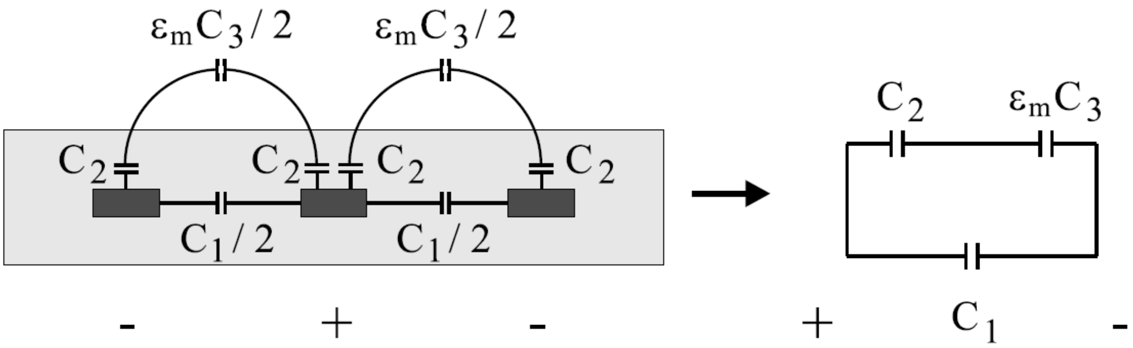

Fig. 4: Capacitance model of the insulated flat-ribbon cable

For the two-sided measurements both ends of the sensor line are provided with high frequency switches which are remote controlled by a bifilar cable. As input lead for the TDR signal a 50 Ω low-loss coaxial cable is used (**Fig 5**).

The switches allow the boundary conditions in the sensor ends between transmission and total reflection to be changed. The advantage of this procedure is that the automatic reconstruction algorithm can exactly distinguish between the sensor ends. Thus the quality of the water content determination is further improved, especially in wet conditions with lossy material (Scheuermann et al., 2005[9]).

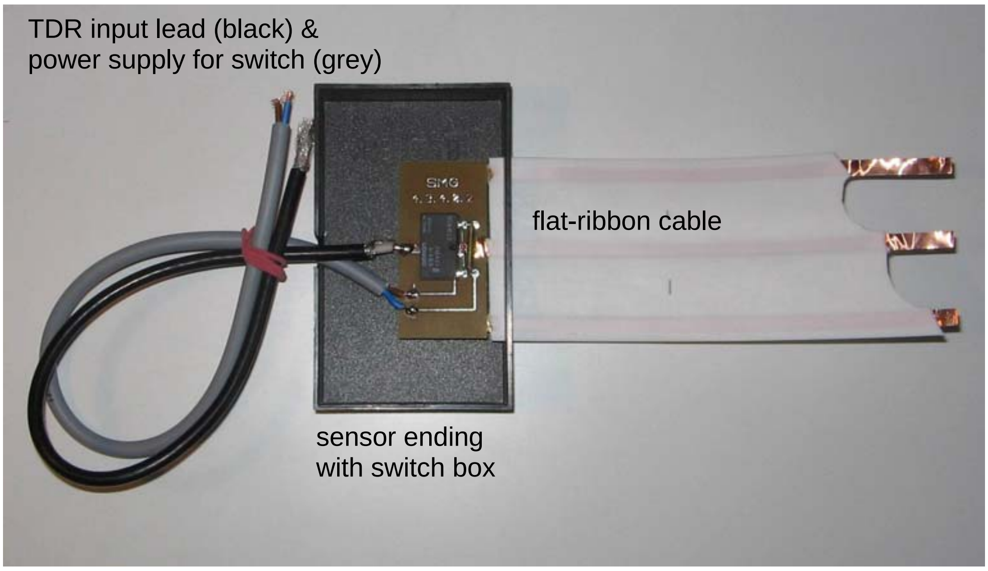

Fig. 5: TDR sensor composed of a PE-coated 3-core flat-ribbon cable with a relay switch on the sensor ending, which is effused with epoxy resin before use

In **Fig. 6** a principle sketch of the set-up for one sensor with two-sided measurements is shown. In the presented example the TDR pulse travels from the TDR device through a multiplexer and the input lead to the sensor. Switch A is closed and allows the transmission of the signal into the sensor. There it is totally reflected when reaching the opened switch B. By means of a relay device, which is BUS-controlled by a linux based control unit, the condition of both switches can be changed. By switching the multiplexer, the sensor can be measured from the other side. The multiplexer as well as the TDR device are controlled by the same control unit which also stores the measured data. In total there are six possible states for the sensor measurement as shown in **Table 1**. When taking all six measurement traces together, it is called a set.

It takes less than one minute to obtain one set. Thus it is feasible to measure cycles for all 20 sensors within 15 minutes. In order to monitor the saturation of the levees, each sensor was measured every 15 minutes. All data was sorted in a database for reconstruction.

Table 1: Denotation for the six possible states measured by one sensor taken together to a set

denotation	type	TDR signal	switch A	switch B
A_I	Input	from side A	open	any
A_O	Output		closed	open
A_C	Control		closed	closed
B_I	Input	from side B	any	open
B_O	Output		open	closed
B_C	Control		closed	closed

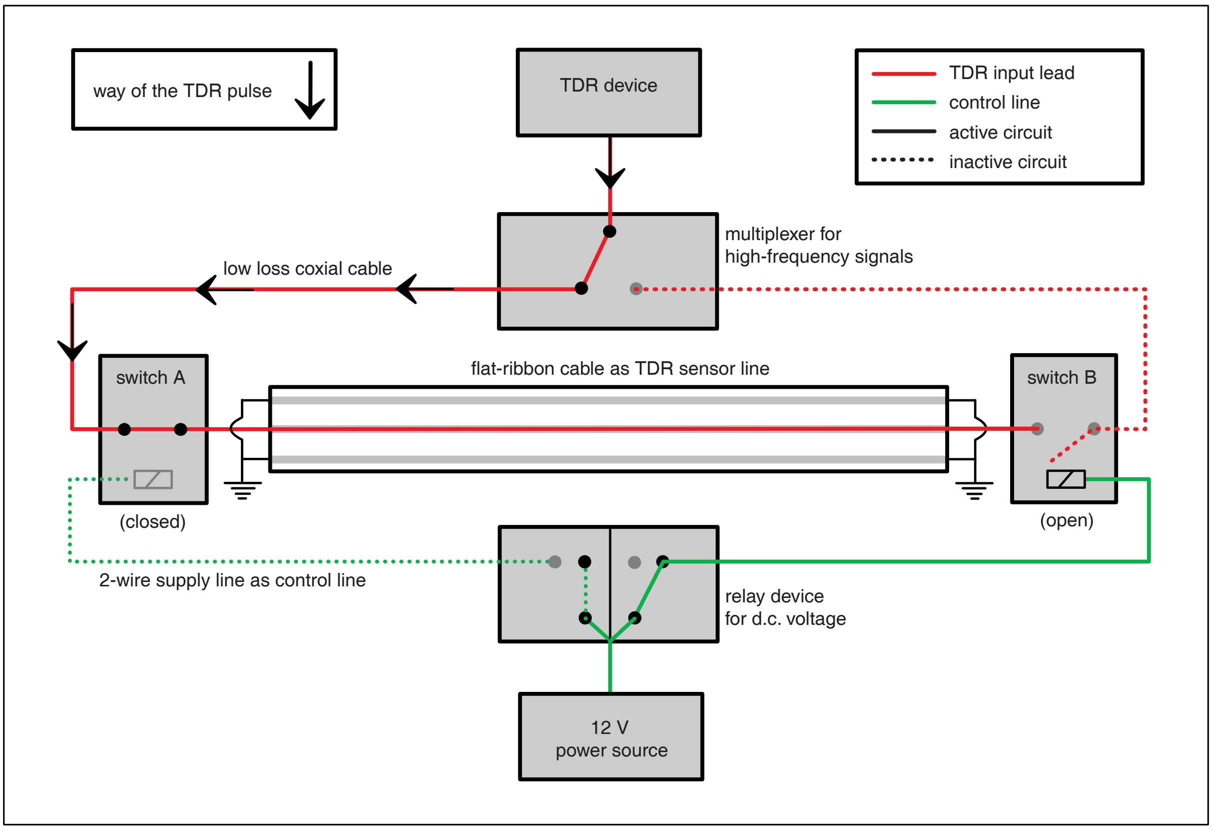

Fig. 6: Schedule of the set-up for the two-sided measurements under changing boundary conditions

Measurement results

A measurement set with TDR traces from both sensor sides under all possible (boundary) conditions at the sensor ends is shown in **Fig. 7**. After reconstruction, the distribution of *C*, *G* and ε at intervals of 1 cm along the sensor line is obtained. For the conversion from the dielectric number ε to the volumetric water content θ a regression curve is used, which was determined in laboratory experiments for the soils used (see e.g. Scheuermann et al., 2005[9]). For the loam of the levee body regarded in this paper the equation is as follows:

$$\theta(\varepsilon) = 23{,}309 \cdot \varepsilon_m^{\;0{,}3321} - 30{,}472 \qquad (5)$$

After the reconstruction of all measurement data at a defined time, the water content distribution inside the levee body can be shown in 2D-contour-plots. The space between the sensor lines is interpolated. When additional data are added, such as the water level in the basin and the recorded water pressures, the plots turn out as shown in **Fig. 9**.

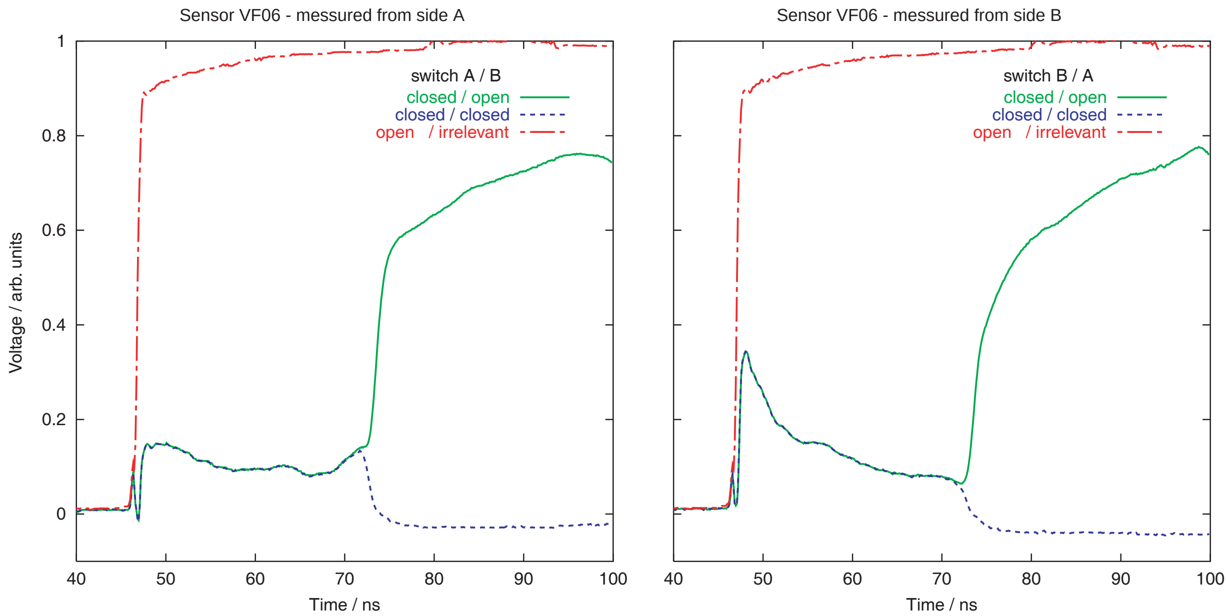

Fig. 7: TDR traces for a cycle consisting of six measurements from both sides of the sensor under changing boundary conditions. On the left: measurement from the base to the dike crest (wet / dry), on the right: opposite direction (dry /wet).

Experiment with the first filling

In an experiment a levee made of loamy silt was constructed. The hydraulic conductivity k_f of that soil was about $1 \cdot 10^{-6}$ m/s. The porosity was about 44 %. First the water level was raised to 0.5 m and kept at this level for approximately 9 days. In order to correct a technical problem it was lowered to zero for several hours and afterwards increased to 1 m. After a further 10 days it was constantly lowered to zero within a span of 3 days. In **Fig. 8** the temporal progression of the water level is shown.

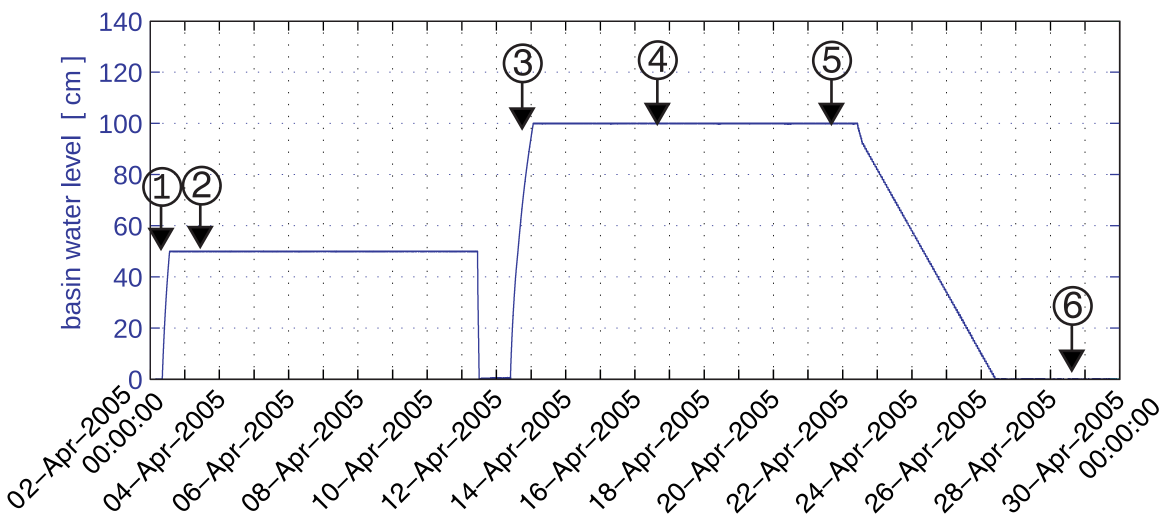

Fig. 8: Progression of the water level in the basin during the experiment

A sequence of the saturation process of the levee is displayed in **Fig. 9**. On the left the water level in the basin is shown. The white lines show the pore water pressures measured by the tensiometers, where the corresponding triangle symbols show the actual horizontal position of the transducers. The lines between the transducer-positions and the water level line are linearly interpolated. The water pressures recorded by the pressure transducers are marked in the same way in black. The numbers in the picture give the values of the volumetric water content θ at the marked positions measured by means of TDR. The positions of the vertical sensor lines can also be seen by these markings. The data between the sensor lines is interpolated to obtain 2-dimensonal images of the water content distribution.

1. The first picture shows the levee immediately before the hydraulic load. It has an average volumetric water content of about θ = 14 %. The crest has already dried up in the air.

2. In the second frame the water level had been raised to 0.5 m one day before. It can be seen that the first three sensors have already detected the oncoming saturation front.

3. The third frame shows the levee 10 days after the initial hydraulic load, when the water level was raised over 0.5 m for the first time. The unsaturated wetting front driven by capillary forces has already by far passed the middle of the levee body in the lower regions, whereas the water content at the crest is still unchanged.

4. Next a frame is shown, were the tensiometers and pressure transducer have already recorded positive pore water pressures. The saturation front has reached the middle of the levee. The capillary driven change of water content is about 1 m ahead.

5. The fifth frame shows the state only a few hours before water is drained out at the toe of the downstream slope for the first time. Except for a small space on the downstream slope the whole levee, right up to crest, has been reached by the initial water front. **Fig. 10** shows a photograph of the downstream slope taken about three hours later.

6. In the last frame the water level has been lowered to zero again. The pore water pressures have decreased again, whereas the water content is still near the saturation level in the lower regions.

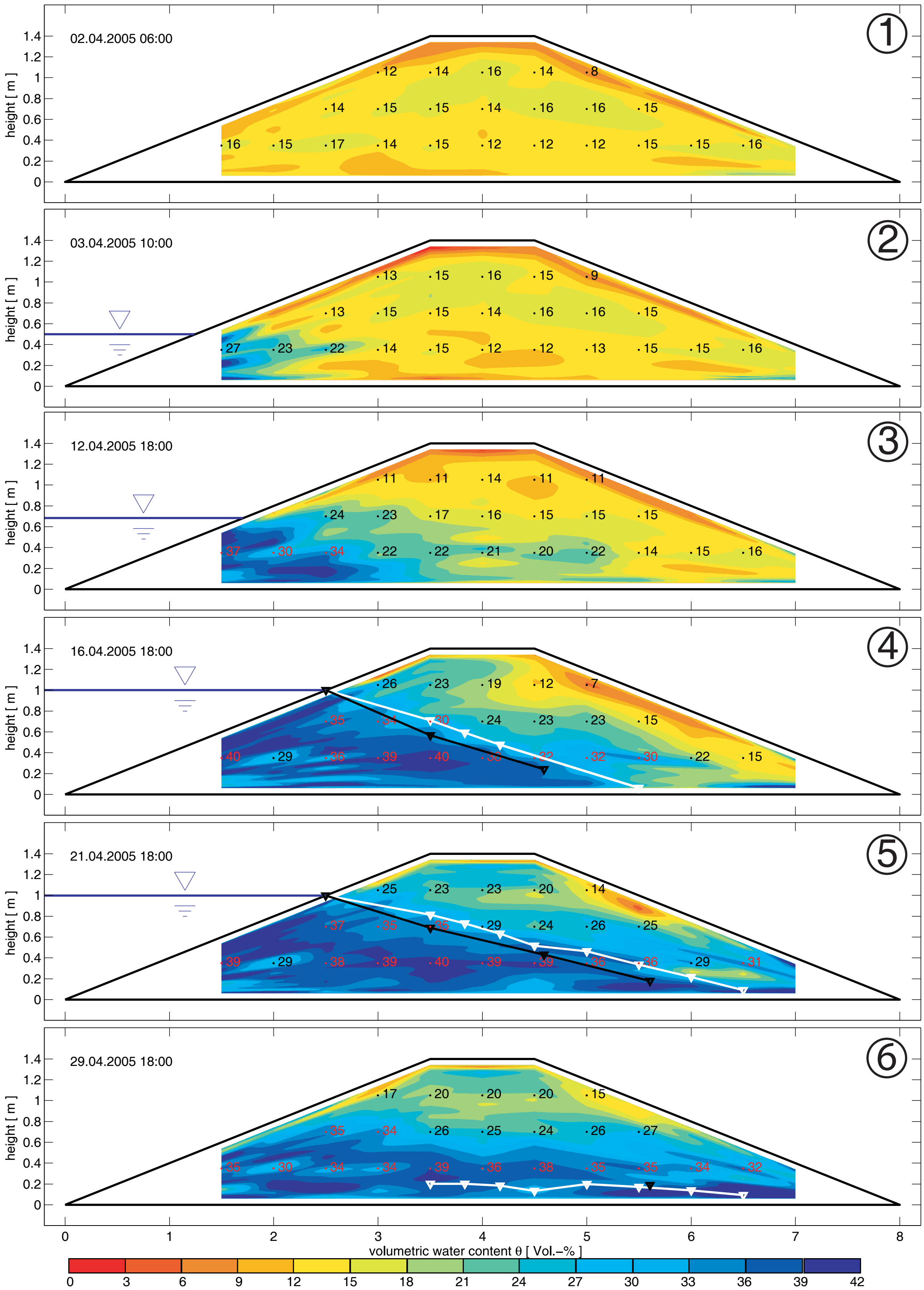

Fig. 9: Sequence of the saturation process of the levee according to the temporal progression of the water level given in **Fig. 8**

Fig. 10: Photograph of the downstream slope with water draining at the toe

Discussion and Conclusion

The Spatial-TDR method provides very good results in determining the water content matching optical observations and the measurements of the pressure transducers and tensiometers. Smaller difficulties only arose in the switches at the sensor ends, which sometimes produced a disturbing signal affecting the quality of the measurement close to the sensor ends. Better high frequency sensor switches have now been developed but have not yet been adopted.

Another important development in progress at the moment is the non-destructive installation of the TDR sensors in existing levees, dams or other soil constructions. Thus Spatial-TDR is a suitable monitoring system for geohydraulic processes (e.g. Scheuermann & Bieberstein, 2006[10]). It can help to assess the condition of constructions in critical situations and to appreciate their risk of failure.

In the next steps the levee will be stressed with varying hydraulic loads to examine the response of hydraulic and mechanic processes in the levee body. In a final scenario it is planned to investigate the mechanism of failure of the levee caused by the saturation process due to the softening of the loam.

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