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Monitoring of Dams and Dikes – Water Content Determination using Time Domain Reflectometry (TDR)

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ABSTRACT

In many cases geotechnical engineers are interested in qualitative or even quantitative water content distributions characterising the hydraulic situations within earth structures in order to assess the efficiency of structural elements (e.g. the sealing element) or the stability of the system. One possible method to measure water contents is Time Domain Reflectometry (TDR), which is widely-used especially in hydrology or soil-physics. For this method moisture sensitive transmission lines (flat band cables) are used, which are buried in the soil. Electromagnetic pulses are applied to the sensor and the reflections are recorded with a time domain reflectometer. With a new inversion algorithm, which uses the full information content of the TDR reflection data, the spatial variability of the dielectric properties of the soil, respectively the water content around the transmission line, can be determined (spatial TDR). This new measurement system was used in a full-scale dike model for the first time. Transient water transport processes could be monitored for the first time with this new method. Also conventional TDR methods can be used for monitoring purposes in dikes or dams in order to estimate the effectiveness of structural elements like the upstream sealing. Both possibilities of application are presented in this paper.

Keywords: Time Domain Reflectometry, water content measurements, monitoring, dike

1 INTRODUCTION

Earth constructions along waterways – like dams and dikes for technical flood protection purposes – are subjected to constant or at least temporarily limited hydraulic loads. Here the task of the construction is to reduce the piezometric head and to discharge the seepage water safely. In the case of an unexpected hydraulic situation (e.g. a double flood wave or a flood after ample precipitation) or when a constructive element is damaged (for example the upstream sealing), it is possible that the construction cannot continue to fulfill its task. Under such circumstances the stability of the construction could be even endangered.

The task of the geotechnical engineer is to take into account this kind of extreme hydraulogic events or possibly occurring failures of the construction for example by observing the hydraulic situation inside the construction. For this purpose, pressure gauges are used normally. Increasingly fibre optical temperature measurements are implemented for example to localize temperature anomalies indicating leakages in upstream sealing systems (Aufleger et al. 1998). But this kind of system based on temperature measurements is normally unable to receive information on absolute values of the water content. However in many cases the geotechnical engineer is interested in quantitative water content distributions in order to get a better insight in the hydraulic situation. One possible method to measure the distribution of water content along extended transmission lines is spatial Time Domain Reflectometry (spatial TDR).

2 MOISTURE MEASUREMENT USING SPATIAL TDR

2.1 *Properties of soils*

Soil is a typical porous medium consisting of the three phases pore air, grain and pore water in different forms of bonding (cf. figure 1). The proportions of the soil phases vary both in space – due to the composition and density of soil – and time – due to the changing water content. For the determination of the water content of the soil, the fact is utilised that the total permittivity is dependent on the proportions of the soil phases. A straightforward but laborious way to find the relation between water content and total permittivity 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 (Topp et al. 1980).

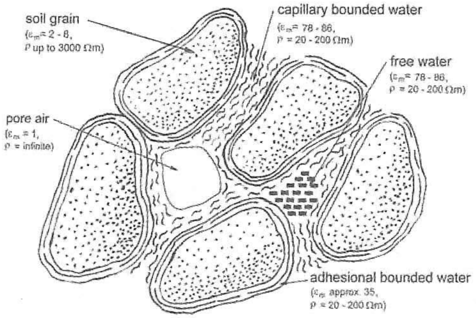

Figure 1. Dielectric (permittivity ε_m) and electric (resistivity ρ) properties of the soil phases

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 is usually restricted to 30 cm because of high damping losses. For longer transmission lines, a new insulated flat band cable was developed (Huebner et al. 2005). It shows much less pulse attenuation than non-insulated metallic forks in the same media. 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 capacity model was developed (Huebner et al. 2005). The flat band cable with laid open copper wires (for demonstration) is shown in figure 2.

The standard TDR measurement procedure based on travel time analysis provides 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 (Schlaeger 2005). This new TDR measurement system consisting of recorded step pulse with spatial analysis has already proven its effectiveness in different applications (Huebner et al. 2005, Becker et al. 2003) and is introduced as spatial TDR.

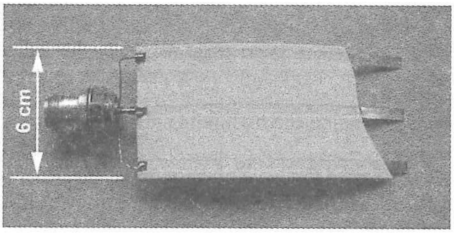

Figure 2. Flat band cable

Against the background of the safety and monitoring of dams and dikes respectively, in the following two different applications of TDR are presented. On the one hand measurements of the spatial distribution of water content in a full-scale dike model are shown. On the other hand a monitoring system for upstream sealing elements of river dikes shows the use of conventional TDR measurements with long transmission lines.

3 MEASUREMENT OF SPATIAL WATER CONTENT DISTRIBUTIONS IN A FULL-SCALE DIKE MODEL

3.1 *Dike model and instrumentation*

In a recently finished research project the seepage through dikes due to a hydraulic load depending on the initial water content was investigated (Scheuermann and Bieberstein 2005). For this investigation a full-scale dike model was available at the Federal Waterways and Research Institute in Karlsruhe (see figure 3). The dike is built up homogeneously with uniform sand (grain size 0.2 – 2 mm) and is based on a waterproof sealing of plastic, so that the water within the dike body will flow to a drain at the toe of the landside slope. In order to simulate flood events a basin is included in the construction.

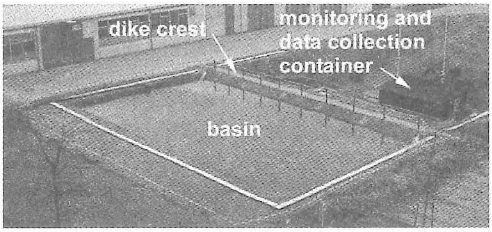

Figure 3. Full-scale dike model at the Federal Waterways and Research Institute in Karlsruhe during a flood simulation test in December 2000 (steady state of seepage condition)

The aim of the research is the quantitative description of the influence of an initial distribution of the water content within the dike body on the progression of the seepage during a flood event. Therefore the dike is equipped with pore water gauges at the base to measure the hydraulic head inside the dike and with the new TDR monitoring system using flat band cables (cf. figure 4). The advantage of this system is its high resolution both in space and time, which is required for monitoring the process of unsaturated transient water transport within the dike. The system consists of 12 flat band cables from 1 to 3 m length, which are installed vertically inside the dike. They are connected on both ends with coaxial cables (cf. figure 2) to a multiplexer and TDR device in a box on the crest of the dike. The data collection and controlling equipment (PC) of the multiplexer and the TDR device are placed in a measuring container at the toe of the landside slope (figures 3 and 4).

With this system the data acquisition time for the whole cross section is only 5 minutes. Subsequent processing of the time-dependent data into a spatial distribution of the water content requires several hours on a desktop PC. The changes in water content are reconstructed with a spatial accuracy of about 3 cm and an average deviation of ± 2 % compared to independent water content measurements.

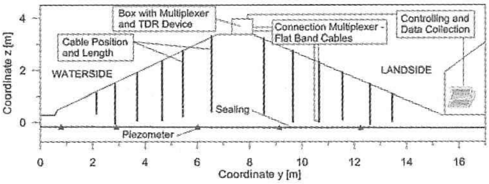

Figure 4. Setup of measuring devices with positions and length of the flat band cables and positions of piezometer gauges in the base of the dike model

3.2 *Results*

Within the framework of the investigations mentioned above different physical simulations were carried out on the dike model. Figure 5 shows water content measurements as distributions of saturation indicating different hydraulic situations. The vertically oriented dots represent the positions and lengths of the installed flat band cables (cf. figure 4) and the values at the side show the measured water content at these locations (see also the colour bar in figure 5). For better visualisation the single measurements were interpolated over the observed area in the cross section. The dark colours show wet zones whereas the light grey colours represent the more dry zones. In addition, levels of the hydraulic head are given in the figures representing the approximate position of the phreatic line inside the dike body. The independently measured water level in the basin is also marked.

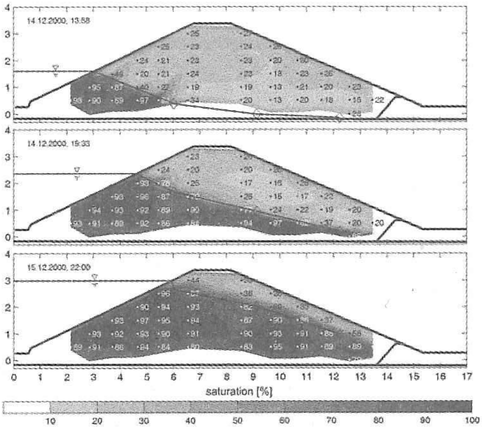

Figure 5. Distributions of saturation during a flood simulation test on the full-scale dike model

The measured phreatic line and the location of the transient of the wet to the dry zone correspond well. One can also recognise a gradual transient from the wet to the dry zone on a small area above the dark zone representing the capillary border. Underneath the phreatic line in the wet zone of the dike different values of saturation below 100 % can be recognised indicating a fairly high residual rate of air remaining in the pores. This observation was verified by independent measurements during the steady state condition.

An extreme precipitation event for Karlsruhe which occurs about once in every 100 years (148 mm in 72 h) was simulated using artificial sprinkler irrigations on the dike model. Despite the high quantity of irrigated water no homogeneously distributed saturation was reached. In fact a larger part of the water was stored near the surface in the slopes of the dike. In these more saturated areas the sand has a higher hydraulic conductivity, so that water can flow laterally to the waterproof base of the dike due to capillary barrier effects. As a consequence a nearly unchanged area in the middle of the cross-section remained (cf. figure 6).

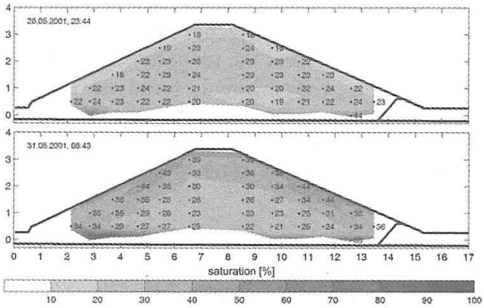

Figure 6. Measurements of saturation at the beginning (above) and end (below) of an artificial sprinkler irrigation test (148 mm in 72 h) on the full-scale dike model

In order to investigate the influence of the hydraulic initial condition on the transient seepage through dikes, several physical flood simulation tests were carried out on the full-scale dike model. In this way different natural meteorological and hydrological situations were physically simulated in advance of the actual flood simulation test. In December 2000 a flood simulation test was carried out starting from an unaffected natural situation (cf. figure 7 a)). In May/June 2001 the initial condition was modified using artificial sprinkler irrigation as mentioned before (see figure 7 b) and figure 6). Finally a small precursory flood wave was simulated in July 2001, which resulted in a water content distribution shown as saturation in figure 7 c). Using this new measurement method for monitoring water content distributions it was possible for the first time to prove the influence of the transient seepage through dikes on the hydraulic initial condition inside the dike body (Scheuermann and Bieberstein 2005).

The presented results from the dike model show clearly the high advantage of spatial TDR measurements along extended sensors for the estimation of transient water movement processes inside of earth structures. However the reconstruction of spatial water content distributions from TDR traces takes too much time to use this technique as an online monitoring system at present. Due to this circumstance the next application of TDR will present an ongoing monitoring system used on a real dike on the Rhine River.

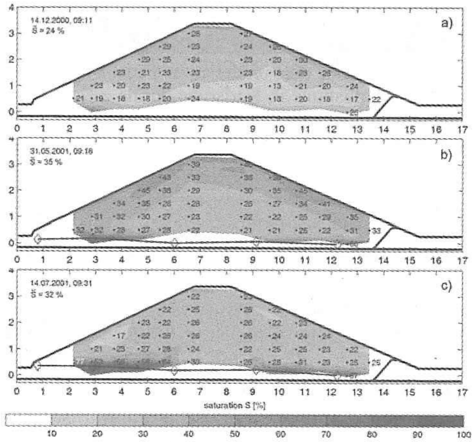

Figure 7. Distributions of saturation as initial conditions in advance of flood simulation tests
a) unaffected natural situation,
b) after artificial sprinkler irrigation and
c) after a small precursory flood wave

4 MONITORING OF ZONED DAMS

4.1 *Measuring field and instrumentation*

Depending on the situation, in some cases it is not necessary to have information about the spatial distribution of the water content along an extended sensor e.g. along a flat band cable. Mostly it is sufficient to use time-dependent changes of the water content over an interesting range in order to interpret the effectiveness of construction elements like the sealing of a dike for example. This is the task of the monitoring system introduced here. In figure 8 the cross-section of the dike with the positions of the flat band cables is presented. The dike has a standard cross-section with an upstream sealing and a drain on the landside toe of the slope designed as a berm. Infiltrating water through the sealing (e.g. due to a hydraulic load caused by a flood) will be dammed at the base of the dike from where it flows to the drain. In any case the sensors underneath the sealing will be affected by moving water which can be detected using TDR measurements. Other reasons for the positioning of the sensors underneath the sealing are the electric and hydraulic properties of the sealing material. Because of the capillary behaviour water changes could be quite small under certain circumstances and the high electrical lossy behaviour due to the conductivity allows only short lengths of the flat band cable to be used. Because of the chosen instrumentation it was possible to use 20 m long sensors. Figure 9 shows the measuring field with the setup of the measuring devices. With 20 sensors at two levels the monitoring field spans an area of 200 m.

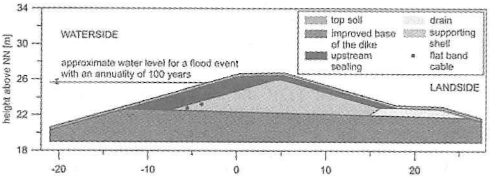

Figure 8. Cross-section of the dike on the Rhine River with positions of the flat band cables

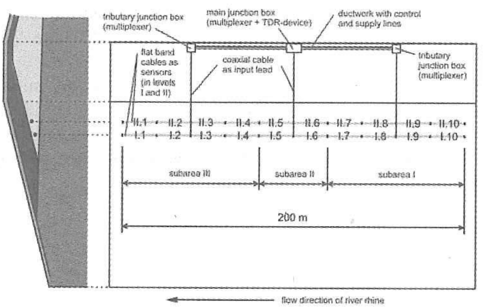

Figure 9. Top view of the waterside slope with setup of the measurement system

4.2 *Results*

Since summer 2003 almost continuous measurements of the water content have been carried out at the monitoring field. For the analysis the travel time of the TDR measurements was determined and the mean water content along the sensor was calculated. In this way it is possible to draw a time-dependent hydrograph for the individual sensors. With this information and the knowledge about the hydraulic meteorologic influences on the dike (flood or precipitation) the effectiveness of the observed sealing element can be evaluated.

Figure 10 shows measurements at the turn of the year 2003/2004. The symbols correspond to individual measurements with a temporal resolution of 6 h and the lines show a moving average over 48 h. The levels of daily precipitation events are shown in the bar graph on top. The upper hydrograph shows water content measurements as effective values relating to the maximal measured water content at three different areas on level II at the beginning of the monitoring field (downstream, II.2), in the middle (II.5) and at the end of the monitoring field (upstream, II.10). The lower hydrograph shows measurements on level I in the same areas (I.2, I.5 and I.10, cf. figure 9).

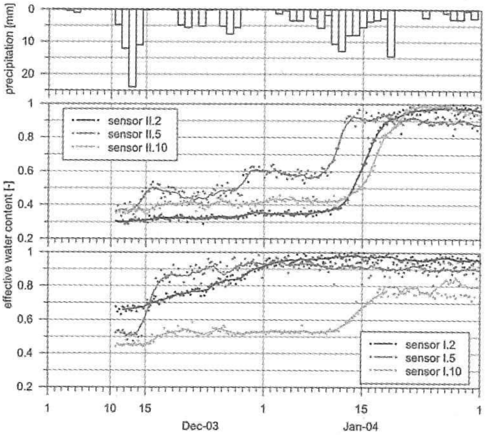

Figure 10. Time-dependent progression of the effective water content at some sensors of the measuring field; the symbols represent individual measurements with a temporal resolution of 6 h and the lines show a moving average over 48 h

The changes in the effective water content correspond only to the precipitation series in this time period without any change due to a flood. As can be seen, there are completely different reactions in the time-dependent progression of the water content. For example the black line of sensor I.2 in the lower level I shows a gradual rise in the effective water content, whereas in the level above (II.2, black line) the rise takes place in a much shorter time. A totally different progression of the curves can be recognised in the middle area of the monitoring field. In the lower level I the curve shows a fast increase in the effective water content (I.5, dark grey line). But in level II the progression of the curve shows a gradual stepwise increase in the water content (II.5, dark grey line) due to the series of precipitation events. The downstream sensors in area 10 (I.10 and II.10, light grey lines) both show a quite similar fast rise in the effective water content within a short period. The presented measurements permit a rough estimation of the effectiveness of the upstream sealing, but for a long-term assessment of the conditions of the hydraulic conductivity it is necessary to carry out continuous measurements at the monitoring field. This includes a flood event, which has not occurred up to now.

5 SUMMARY AND CONCLUSION

The newly developed TDR method using flat band cables as sensors offers new possibilities regarding monitoring of dams and dikes. Especially the measurement of the spatially distributed water content along extended sensors (flat band cables) provides important information about unsaturated transient hydraulic processes. With a high spatial and temporal resolution the measuring system on the full-scale dike model has proved the operational readiness of the system for the special task of water content measurements with a high accuracy. In a future research project, monitoring fields at different dikes in Germany will be equipped with this system in order to develop a real time monitoring system for the forecast of the transient seepage through dikes in the case of a flood event and the following prediction of the dike stability.

The real-time monitoring system at the dike of the River Rhine has shown the advantage of a more or less direct method to measure water content via physical properties of the soil like the electrical permittivity. The presented application has clearly shown that for the estimation of the effectiveness of a structural element – like the upstream sealing of a dike – it is sufficient to observe the hydraulic reaction of the system depending on meteorological or hydraulogical influences. These hydraulic reactions inside the dike body in the form of water content changes can be analysed using numerical methods or possibly even analytical methods leading to an adequate assessment of the sealing. Thus the basis of an online monitoring system has already been founded with the system presented here.

The TDR measurement method presented is applied in multifarious fields of application and scientific disciplines. A group of scientists from different branches of research are working together in the recently developed scientific working group Soil Moisture Group (SMG) at the University of Karlsruhe in order to advance the technical development of spatial TDR and its physical basics but also to obtain cooperation in different application areas.

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