Monitoring and prediction of the transient seepage through levees during a flood event

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ABSTRACT

Spatial Time Domain Reflectometry (Spatial TDR) was used in combination with modified flat ribbon cables as sensors installed in boreholes to measure moisture distributions in a levee system in Germany at the river Elbe. During flood events, these moisture measurements not only characterize the moisture condition including the existence of a phreatic surface within the dam body, but can also be used to define the initial condition with a suitable numerical model for predicting the further evolution of the phreatic surface for the duration of the flood. Based on this prediction, an assessment of the stability of the levee can be made.

Keywords: monitoring; electromagnetic method; moisture measurement; prediction model; seepage

1 INTRODUCTION

Levees as technical flood protection system along rivers are frequently quasi-homogeneous with no structural elements in form of sealing and drainage layers that are required to control the seepage within the levee. In the case of a flood event, transient seepage through the levee occurs influenced by the initial water content distribution within the levee that can be raised due to former small flood events or ample precipitation occurring before the flood. In order to be able to predict the transient seepage through the levee during a flood, a monitoring system based on Spatial Time Domain Reflectometry (Spatial TDR) was developed. This system allows the observation of water content profiles at selected locations within the levee. The measurement results can then be imported into a numerical model for quantifying the hydraulic initial condition. For the duration of a forecasted flood, the transient seepage can be predicted and analyzed to identify a critical situation for the stability of the levee. In the following, the monitoring system is introduced and a measurement example given. Subsequently, the approach for the prediction model is presented together with the used numerical tool. The paper closes with the presentation of measurement examples and a conclusion.

2 MONITORING SYSTEM

2.1 Overall concept

The monitoring system consists of a TDR device, multiplexers for running several sensors, a computer for controlling the system and a GSM modem for transferring the data into a database. Fig. 1 shows the system as it was installed at the Elbe.

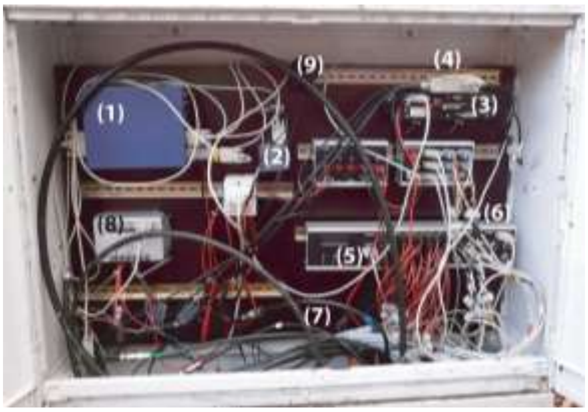

Fig. 1. Monitoring system for Spatial TDR. (1) Linux PC, (2) modem, (3) TDR100, (4) 8-channel multiplexer, (5) DC switch for controlling connection between sensor and input lead, (6) controlling of temperature sensors, (7) HF coaxial cables as input leads, (8) control of battery charge status, (9) GPRS antenna.

The monitoring system at the Elbe also involved temperature measurements since the dielectric permittivity of water strongly depends on the ambient temperature. Low-loss coaxial cables have been used to connect the multiplexer in the main enclosure to connect a second multiplexer located at the monitoring section. The second multiplexer was then connected with the sensors installed in the levee.

2.2 Flat ribbon cables used as sensors

An optimal application of Spatial TDR in combination with flat ribbon cables requires measurements from both ends of the sensor to be able to back analyze the two parameters associated with the material under test, namely the capacitance and the conductance (Scheuermann et al. 2009). If only one measurement is possible, e.g. when rod sensors are used, suitable assumptions need to be made with respect to the value of the conductance, or a function needs to be calibrated that allows the computation of the conductance from the capacitance (Becker et al. 2008).

In the presented case, measurements from both ends of the sensor have been made. Because of the long distance between TDR device and sensor (up to 200m), high-frequency (HF) low-loss coaxial cables have been used to connect the TDR device with the sensors via the multiplexer. In order to improve the detection of the end of the sensor in the TDR signal, a DC switch was installed at the connection between coaxial cable and sensor (Scheuermann et al. 2009). These switches allow to connect or disconnect the coaxial cable. By changing this electrical boundary condition, the beginning and end of the sensor can be identified using simple signal analysis. The time difference between the beginning and end of the sensor defines the mean capacitance that is an important input parameter for the inversion algorithm. For analyzing the TDR measurements, the algorithm of Schlaeger was used that has been successfully applied previously in other studies.

The flat ribbon cable used at the Elbe has been modified with a thinner polyethylene insulation and a broader trim at the sides of the cable to be able to glue it on a hose formed by PVC (Scheuermann et al. 2009b, Fig. 2A). The flat ribbon cable together with the PVC hose was placed in a borehole. The hose was then filled with a special polyurethane (PU) foam that creates a high foaming pressure to press the hose with sensor against the wall (Fig. 2B). Even smallest gaps can falsify measurement results whether the gaps filled with either air or water. The initial measurements taken with the system showed satisfactory agreement with water contents taken from samples (Fig. 4).

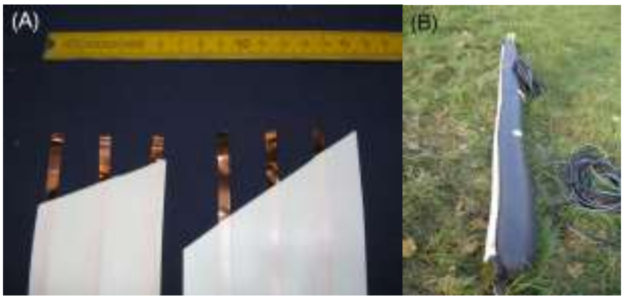

Fig. 2. (A) Left: Original flat ribbon cable with three copper wires. Right: Thinner version of the flat ribbon cable with trims. (B) PVC hose with a sensor glued on it and filled with PU foam.

2.3 Monitoring site

Fig. 3 shows the example of an instrumented cross section of the levee at the river Elbe. In total six cross sections have been instrumented with sensors. The levee body is quasi homogeneous comprised of a loam with lenses of gravel and sand. The aquifer is composed of sand (Scheuermann et al. 2009b). Samples of the cross sections have been used to quantify shear strength parameters and the soil hydraulic parameters, hydraulic conductivity and soil water retention curve (SWRC).

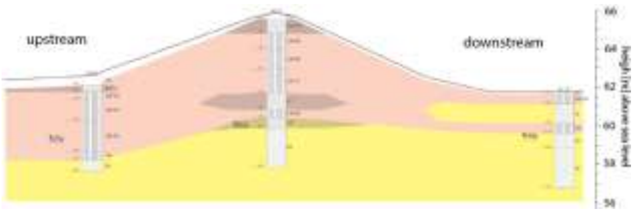

Fig. 3. Example of an instrumented levee at the river Elbe. The yellow aquifer is composed of sand. Top soil and dam body comprises of loam (red) with lenses of sand and gravel (shaded).

3 PREDICTION MODEL

3.1 Overall concept

The basic idea of the prediction model is to use moisture measurements taken with the monitoring system for defining the hydraulic initial condition (including the history) to be used in a suitable numerical method. The basic steps for the prediction model are:

1. Measurement of TDR Signals
2. Reconstruction of moisture profiles
3. Derivation of the hydraulic situation
4. Quantification of the stability
5. Forecast of the hydraulic condition for the period of the predicted flood
6. Quantification of the evolution of the stability

While steps 1 and 2 are covered by the monitoring method and are well established, step 3 is critical as it not only defines the water content existing within the levee, but also includes the pore water pressure conditions influencing both, the further evolution of the hydraulic condition and the stability of the levee. Ideally, the numerical model should be able to predict the seepage within the levee and the resulting stability in parallel and in real-time. As this can be computationally expensive, a two-step approach is followed. As the first step, the hydraulic condition is predicted using a fast and reliable model. The second step is the calculation of the stability with a simple analytical model.

3.2 Definition of the initial conditions based on moisture measurements & numerical model

In the case of a flood event with existing phreatic surface, a water content distribution measured with Spatial TDR would show a smooth transition from partly saturated conditions above the phreatic surface to nearly saturated conditions below (Fig. 4). From a numerical point of view, all water contents below the phreatic surface are considered fully saturated. As a consequence, the volumetric water content matches the porosity of the soil. Above the phreatic surface, the water content is used to calculate the negative pore water pressure or suction based on the material information in form of the SWRC. The water contents in the space between the sensors are simply linearly interpolated and the values outside are extrapolated.

For every material point below the phreatic surface, full saturated conditions are assumed. In this way, the hydraulic conditions for the complete domain can be

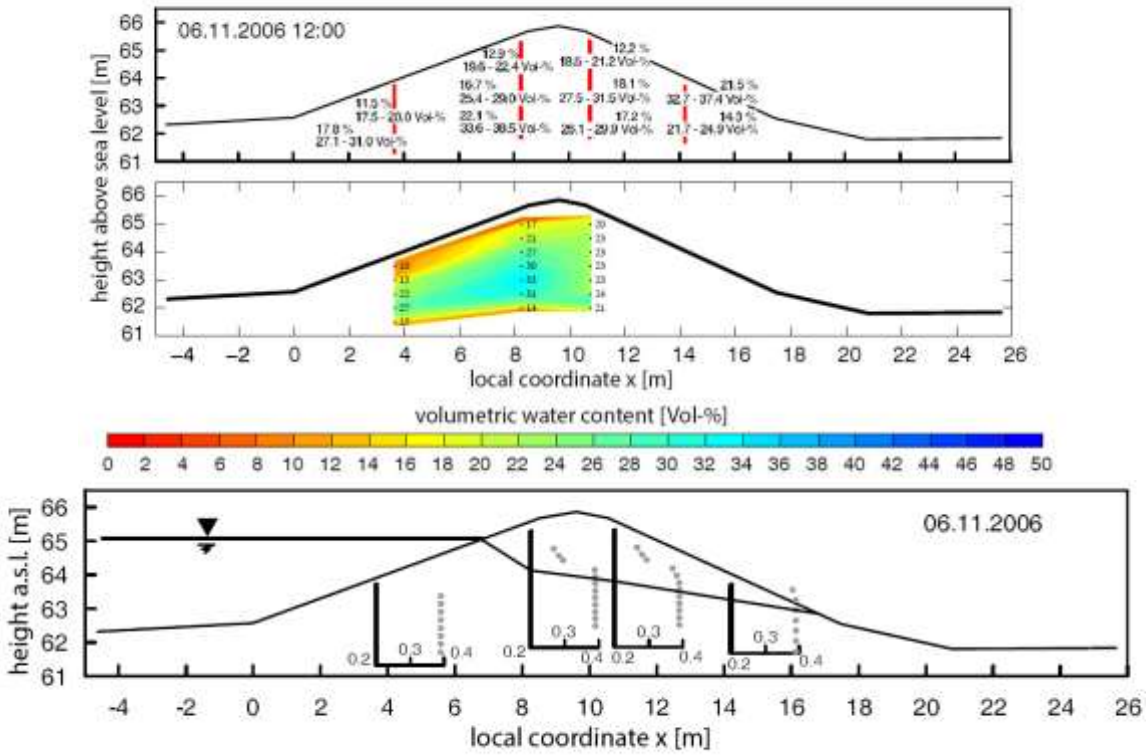

Fig. 4. Top: Results of gravimetric moisture content measurements taken during drilling. Middle: Measurement example taken with sensors shortly after installation. Bottom: Artificially created moisture measurements from numerical simulations at same locations with similar spatial resolution. The phreatic surface is determined based on the shown moisture profiles.

determined based on only four water content profiles.

The numerical model used for simulating saturated /unsaturated seepage due to flood and precipitation was Hydrus2D. The program simulates flow of water based on the Richards' equation. Hysteresis of the SWRC was neglected in the presented study. The initial condition was defined based on the moisture measurements, and the program automatically determines the pore water pressures based on the SWRC. Below the points, where full saturated conditions have been reached, hydrostatically increased pore water pressure is assumed.

Table 1. Mechanical parameters of the levee materials

Soil	γ_d [kN/m^3]	ϕ' [-]	c' [kN/m^2]
Loam	16.3	22	2
Sandy loam	17.2	27.5	2
Sand	18.5	30	0
Gravel	18.5	30	0

Based on this initial condition and other hydraulic conditions simulated with Hydrus2D, the slope stability can be assessed. For this study, the simplified Bishop method was implemented in Matlab with the mechanical parameters of Table 1 that have been measured in the laboratory. Fig. 5 shows the example of an initial condition defined with artificial moisture measurements and the result of a slope stability analysis.

3.3 Development of the prediction model

The development of the prediction model was made based on time series of floods and precipitation events that have been artificially generated based on statistical characteristics of measured events. Measured evaporation data were used to introduce realistic atmospheric conditions. Figure 6 shows the example of a simulation over 85 years of flood and precipitation events.

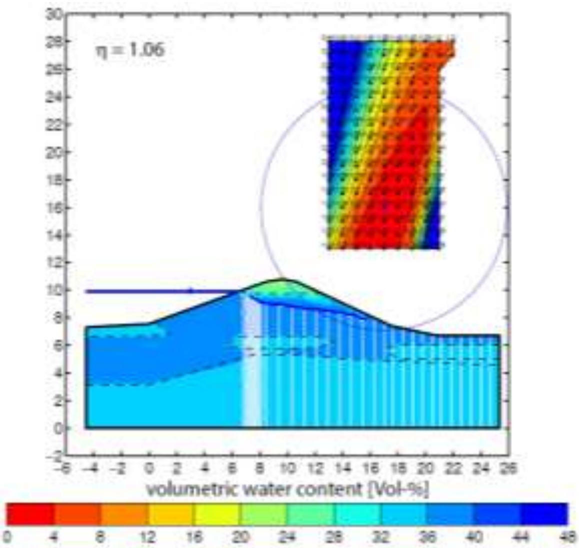

Fig. 5. Initial hydraulic condition determined based on artificial – meaning from simulations derived – water content profiles as shown in Fig. 4 (bottom) with result of slope stability analysis based on a simplified Bishop approach.

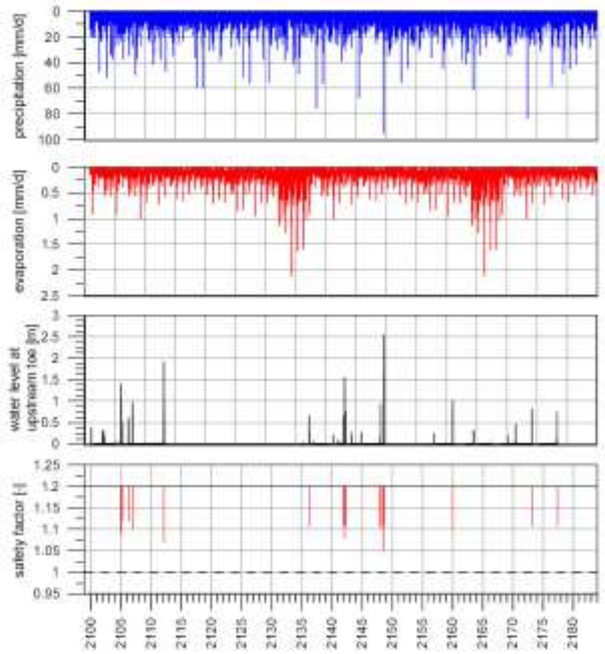

Fig. 6. Result of simulations based on time series of precipitation and flood events that have been developed using on a coupled statistical characterization of flood and precipitation events.

The hydraulic conditions have been simulated first for the complete time series (including flood, precipitation and evaporation). The safety factor of the downstream side slope was calculated subsequently based on the results of the hydraulic simulation as shown in Fig. 5. For testing the presented prediction method based on TDR measurements, moisture content profiles have been extracted from the numerical solutions and used to define a new hydraulic initial condition (Fig. 4 and 5) for a new numerical simulation.

This new simulation was carried out for a duration of 48 hours assuming that both, precipitation and flood, have been predicted over this time period. Fig. 7 shows the result of the predicted evolution of the transient seepage and the resulting changes in the safety factor for the stability of the downstream side slope. The predicted evolution of the hydraulic condition (mean water content in unsaturated area and water table at the sensor) matches well with what would be measured using TDR sensors, and the resulting factors of safety are also not very different of the original simulation.

4 CONCLUSION

Overall, there is a very satisfactory match between original simulation and prediction (Fig. 7). This result proves, that the initial condition can be accurately quantified using moisture measurements taken at selected locations within a levee. The simulations are quick and can be conducted in quasi real-time. However, the coupling with the mechanical response is very simplified, but can be further improved with more realistic analytical methods.

Spatial TDR as a monitoring method requires the use of sophisticated devices and analysis tools. The development of new measurement systems and miniaturized sensors that can be used in wireless sensor networks offers more flexible and cost efficient solutions than the one presented here. Such a solution can also be adapted to other geotechnical problems and structures, such as natural slopes and tailings.

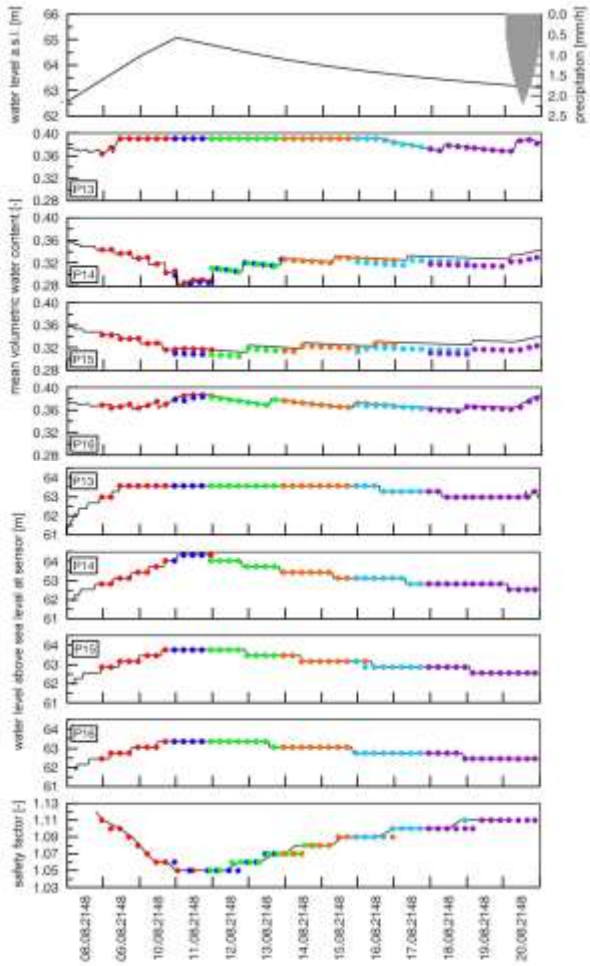

Fig. 7. Comparison between original simulation (black solid line) and predictions over 48 h (dots) using artificial initial conditions. Every new color shows a new prediction simulation.

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