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Modeling earthen dikes using real-time sensor data

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SUMMARY

The paper describes the concept and implementation details of integrating a finite element module for dike stability analysis "*Virtual Dike*" into an early warning system for flood protection. The module operates in real-time mode and includes fluid and structural sub-models for simulation of porous flow through the dike and for dike stability analysis. Real-time measurements obtained from pore pressure sensors are fed into the simulation module, to be compared with simulated pore pressure dynamics. Implementation of the module has been performed for a real-world test case, an earthen levee protecting a sea-port in Groningen, The Netherlands. Sensitivity analysis and calibration of diffusivities have been performed based on pore pressure sensor data during tidal fluctuations. An algorithm for automatic diffusivities calibration for a heterogeneous dike is proposed and studied. Analytical solutions describing tidal propagation in a one-dimensional saturated aquifer are employed in the algorithm to generate initial estimates of diffusivities.

1. Introduction

Regular floods pose a serious threat to human life, valuable property and city infrastructure. Many international projects are aimed at the development of flood protection systems (Krzhizhanovskaya et al., 2011; Pengel et al., 2013). The European Union Framework Programme 7 (FP7) project *SSG4Env* is focused on development of semantic sensor grids for environmental protection. The *Flood Probe* FP7 project coordinates related work on combining sensor measurement techniques. A big national Dutch project *Flood Control 2015* aims to share sensor measurements datasets and to provide a user interface to explore sensor data for researchers, technical maintainers and civil population. The *IJkDijk* (http://www.ijkdijk.nl) is a project on experimental physical study of dike failure mechanisms. The tests are carried out on full-scale experimental dikes equipped with large sets of sensors. The project has produced extremely detailed datasets of sensor data, including pore pressures, inclinations, stresses and strains. Our research was conducted under the *UrbanFlood* FP7 project (http://www.urbanflood.eu), which unites the work on monitoring dikes with sensor techniques (Pyayt et al., 2011a), physical study of dike failure mechanisms (Krzhizhanovskaya et al., 2011), and software development for dike stability analysis (Melnikova et al., 2011a; Pyayt et al., 2011b), simulation of dike breaching, flood, and city evacuation (Melnikova et al., 2011b; Gouldby et al., 2010; Mordvintsev et al., 2012).

The early warning system is a multi-component system that runs in real-time mode, gathering and analyzing measurements form sensors installed in dikes, predicting dike stability, possibility of flooding and optimal evacuation routes. A general workflow and interaction of software components in the *UrbanFlood* early warning system are presented in Fig. 1.

The *Sensor Monitoring* module receives data streams from the sensors installed in the dike. Raw sensor data are filtered by the *AI* (*Artificial Intelligence*) *Anomaly Detector* that identifies abnormalities in dike behavior or sensor malfunctions. The *Reliability Analysis* module calculates the probability of dike failure in case of abnormally high water levels or an upcoming storm and extreme rainfalls. If the failure probability is high then the *Breach Simulator* predicts the dynamics of a possible dike failure, calculates water discharge through the breach and estimates the total time of the flood. After that, the *Flood Simulator* models the inundation process and *Evacuation Simulator* optimizes evacuation routes. Then *Risk Assessment* module calculates flood damage. Finally, *Decision Support System* provides access to different information levels, for experts and citizens. The simulation modules and visualization components are integrated into the Common Information Space

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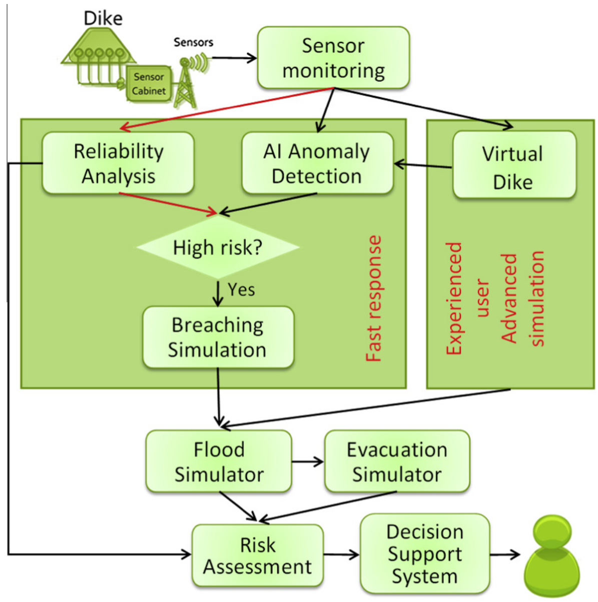

Fig. 1. Early warning system workflow.

(Balis et al., 2011). They are accessed from the interactive graphical environment of a multi-touch table or through a web-based application.

The *Virtual Dike* component runs in parallel with the *Reliability Analysis* module, offering direct numerical simulation to analyze dike stability under specified loadings (Melnikova et al., 2011a). The module can be run with a real-time input from water level sensors or with predicted high water levels due to upcoming storm surge or river flood. In the first case, comparison of simulated pore pressures with real data can indicate a change in soil properties or in dike operational conditions (e.g. failure of a drainage facility). In the second case, simulation can predict the structural stability of the dike and indicate the "weak" spots in the dikes that require attention of dike managers and city authorities. Simulated dynamics of dike parameters (including local and overall stability, pore pressure, local stresses and displacements) describes the non-stationary behavior of the dike (changing over time) We define a concept of a "virtual sensor" for the data obtained from finite element solution in the point where a real sensor is located. Data from the virtual sensors are compared to the real-life sensor measurements. The result of the *Virtual Dike* simulations are used to train the Artificial Intelligence system on "normal" and "abnormal" virtual sensor dynamics (Pyayt et al., 2011b).

The EWS is described in detail in (Balis et al., 2011). In the current paper we only focus on the *Virtual Dike* module design.

Dike stability analyses under hydraulic and structural loads are usually carried either by probabilistic breach analyses based on empirical engineering criteria (Vorogushyn et al., 2012) or by direct simulation techniques including conventional limit equilibrium methods (Verruijt, 2001) and finite element modeling of dike deformations (for example, Spencer and Hicks, 2007). While the first approach is more robust and is widely used for dike stability analysis, the second approach, especially finite element analysis, allows more profound study of physical processes occurring in the dike before the actual failure. Under the frame of the *UrbanFlood* project we create a number of pre-defined and calibrated structural stability analysis models for the dikes connected to the early warning system. Realistic modeling of water flow through the dikes is necessary for correct estimation of effective stresses in the dikes and hence for predicting their stability. Calibration of diffusivities for the tidal groundwater flow is often performed by tidal methods (Smith and Hick, 2001; Slooten et al., 2010; Williams et al., 1970) based on one-dimensional analytical models of semi-infinite or finite aquifers. This method is suitable for aquifers with nearly horizontal phreatic surfaces. A more accurate way that works well for high amplitude of water level variation is direct numerical simulation. In the present work, both analytical and numerical approaches have been tested and compared. Calibration of diffusivities of soil strata has been performed by matching tidal pore pressure fluctuations obtained from numerical simulation and from piezometers installed in several cross-sections of the dike. For heterogeneous soil structures, some averaged and simplified yet heterogeneous soil build-ups have been obtained, so that the response of the dike to the tidal load corresponds well to sensor measurements.

Tidal oscillations of sea level influence the position of a phreatic surface in the dike. A moving water table creates zones with partially saturated soil. Resistance of porous media to the flow is modeled by Darcy's law suitable for low flow velocities (Bear, 1979). A problem of unconfined porous flow can be solved either by solving Darcy's equation on a moving mesh with adjusting mesh boundary to coincide with surface of zero pore pressure (Fenton and Griffiths, 1997), or by using a stationary mesh and solving Richards' equation with non-linear rheological properties for the media, dependent on the effective water content. These non-linear properties can be modeled by classical models of Van Genuchten (1980) or Brookes and Corey model (Brooks and Corey, 1966), as well as by other approximations of water retention curves (Bathe and Khoshgoftaar, 1979) simplified for faster numerical convergence. We have used Richards' equation with the Van Genuchten model, performing simulations on a fixed mesh.

In this paper we present numerical and analytical results of sensitivity analysis of the porous flow parameters to the variation of soil diffusivity and calibration results performed for the LiveDike, an earthen sea dike in Groningen, The Netherlands. Some preliminary results have been published in (Krzhizhanovskaya and Melnikova, 2012). Now we present a more extensive study of the problem, complementing numerical simulations by analytical analysis, and suggesting an algorithm for *automatic* calibration of diffusivities for a heterogeneous dike.

2. LiveDike: geometry, soil build-up, loadings and sensor data

LiveDike is one of the research sites of the UrbanFlood project. It is an earthen sea dike protecting a seaport in Groningen, The Netherlands (Fig. 2a and b). The height of the dike is 9 m, the width is about 60 m and the length is about 800 m. The dike has a highly permeable sand core covered by a 60 cm thick clay layer.

The LiveDike has been equipped with sensors with GPS locations shown in Fig. 3a. Sensors are placed in four cross-sections (slices), see Fig. 3a and b. These slices have been simulated in 2D models under tidal water loading, in order to calibrate diffusivities, simulate flow through the dike and finally analyze the structural stability of the dike.

A geometric model of a dike slice with sensor locations is presented in Fig. 3c. Sensors E1–E4 and G1 and G2 measure absolute pore pressure and temperature and produce data stream which is available in real-time via a LiveDike Dashboard (http://livedijk-www.ict.tno.nl/). For calibration of the model, we used signals from the E3, E4 and G2 pore pressure sensors located below the phreatic surface. An input signal for simulation was the water level registered by the sensor installed outside of the dike (see Fig. 3c). The sea-side toe of the dike is located at $x = 0$ m, $y = -0.7$ m, while the mean sea level is at $y = 0$ m.