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Finite element analysis of levee stability for flood early warning systems

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Chapter 8 Conclusions and directions for further research

8.1 Conclusions

In this thesis, a problem of employing finite element analysis of earthen dikes stability in a functional workflow of an early warning system for flood protection was studied. As it was mentioned in Chapter 1, a detailed physical-model based approach has not been used in early warning systems before, because it has been traditionally considered as computationally heavy. For the first time in dike monitoring practice, we have integrated a finite element module called *Virtual Dike* into the *UrbanFlood* EWS and studied the benefits of such integration, including outcome from *Virtual Dike* solo work and from its interaction with the artificial intelligence (AI) module. *Virtual Dike* has become the first finite element module for dike modelling that works with live sensor data, produces real-time alarms and interacts with other components of the EWS, according to the workflow described in Chapter 1.

All scientific objectives posed in the research (Chapter 1) have been accomplished. Below we discuss separately the progress on each objective.

At the early stage of this research, we have collected, tested and compared existing mathematical models for earthen dikes analysis, including mathematical models of filtration through porous media and soil mechanics (Chapter 2). After a series of numerical tests, we selected the two-dimensional model with linear elastic perfectly plastic associated flow rule defined by the Drucker-Prager yield function. This choice provided the optimal balance between realism and adequacy of the computational model, on the one hand, and high speed of numerical convergence in real-time, on the other hand.

Finite element method in application to soil mechanics theory has been chosen for the *Virtual Dike* implementation, as the most powerful computational technique suitable for simulation of arbitrary failure mechanisms in dikes on a macroscopic level. The module has been implemented in Comsol finite element package and ported on a computational core of supercomputing cloud SARA of the University of Amsterdam. Efficiency benchmarks performed on SARA let us choose optimal settings for the package in order to minimize computational times (Chapter 3).

The first scientific question raised in this thesis was check of a principal ability of an earthen dike computational model to adequately simulate complex physical processes occurring at failure and to predict failure under prescribed loads. Given a huge amount of sensor data recorded for the experimental dikes under documented loading regimes, we had a unique opportunity for validation of our computational model. Validation analyses of the module included one absolutely “healthy” dike in Groningen (the Livedike), the Boston levee prone to occasional slope failures at high tidal range at spring, and one full-scale experimental dike intentionally brought to slope failure during the IJkDIjk-2012 experimental series (Chapter 4-Chapter 6).

The Boston levee analysis (Chapter 5) included cross-validation of the *Virtual Dike* against two other models: a FEM model built in finite element software package Plaxis (commercial software for soil mechanics modelling) and a LEM model based on the established Bishop's method. Two FEM models (Plaxis and *Virtual Dike*) have produced very close results, particularly, close values of strength reduction factors. LEM analysis was a bit less precise: a typical LEM assumption on the hydrostatic distribution of pore pressures in the dike became critical for the correct assessment of the clayey Boston levee stability: a capillary fringe in the dike is very high and water storing effects must be taken into consideration (and they were accounted in FEM models).

The IJkDijk slope failure experiment in Bad Nieuweschans, the Netherlands, (Chapter 6) has become the ultimate validation of the *Virtual Dike* module and a winner of a special contest for the best failure prediction organized before the test (<http://ijkdijk.rpi.edu>). Several commercial corporations and scientific research organizations modelling levee systems participated in the competition; our computational model provided the best class-A prediction for the South levee macro-instability experiment, according to the decision of the jury. The *Virtual Dike* model precisely predicted the simulation mode (slope sliding) and the collapse stage in the loading sequence. A posterior comparison of tilts measured by Geobeads sensors with simulated displacements has shown that the computational model realistically reproduces sensor dynamics, including response of sensors to excavation, container loading and core water pumping.

Successful validation of our module on all three test sites, and especially on the IJkDijk South levee failure experiment, has shown that our computational model is capable of generating virtual sensor patterns of the abnormal and normal behaviour for the artificial intelligence system training. This innovative hybrid method of combining artificial intelligence analysis with FEM-based modelling was proposed and implemented by us in co-operation with our colleague from the UrbanFlood project (Pyayt et al., 2011). The objective for using the hybrid approach lies in a rather typical situation — lack of failure sensor data for “healthy” levees.

The hybrid method was successfully tested on a numerical model of a Livedike prototype with weakened soil strength, under strong storm condition with very high water level (Chapter 7). The FEM module generated time series for the first principal strain and horizontal displacement, which were fed into the AI module as training sets. After training, the artificial intelligence module successfully detected the onset of dike instability. The AI module showed a very sharp drop of the dike safety confidence value from normal behaviour to anomaly. After the anomaly detection, it took about 10 hours to develop real dike instability as evaluated by the stability criterion calculated in the *Virtual Dike* model.

Hybrid approach testing (Chapter 7) allowed us to accomplish the second scientific objective and gave a positive answer to the question of feasibility of the hybrid approach.

The third scientific question posed in the research was estimation of uncertainties influence on the dike stability assessment; it was important to find out how variations in soil properties alter dike safety margin.

We have focused on the influence of variation in soil diffusivity on the pore pressure distribution. As we have shown in Chapter 5, correct calculation of pore pressures in the

dike is critical for the appropriate assessment of dike safety margin. Sensitivity analysis has shown that for coarse media (gravel, coarse sand), distribution of pore pressure amplitudes within a model dike is close to linear and it is defined by water levels at the boundaries (water levels are obtained directly from sensor readings), while diffusivity value does not affect this distribution. For dense soils (fine sands, clays), pressure amplitudes distribution is highly non-linear and to a large extent depends on the diffusivity value. Time lag between local oscillations and tide is entirely determined by diffusivity, both for coarse and fine media. On the base of these conclusions, we have constructed and implemented a new automatic procedure for calibration of soil diffusivities in an arbitrary heterogeneous dike based on historical pore pressure sensors recordings (Chapter 4). The procedure has been successfully tested for the LiveDike diffusivities calibration: simulation results with calibrated soil parameters match experimental data, not only on the "training set" but also for a much longer period of time. The calibration procedure employs the analytical solution obtained by us for the problem of tidal propagation in a one-dimensional bounded aquifer.

8.2 Directions for further research

Our future plans include an extensive study of our hybrid approach to dike health monitoring: training AI on a FE simulation of a real experimental dike collapse (for example, the IJkDijk 2012 South Levee failure), with subsequent validation of the AI failure prediction against the actual observations.

An extremely interesting direction for the future research is combining macro- and micro-scale models. In connection to dike stability analysis, this approach offers a deep insight into mathematical modelling of erosion processes and related failure mechanisms (e.g., piping, wave erosion). For piping modelling, it looks reasonable to couple our porous flow - soil deformations model with the pore-scale erosion model; the latter would assess variation of macroscopic soil parameters (strength, stiffness, density) with the particles transfer. For wave erosion simulation, a CFD (computational fluid dynamics) model would represent the macro-level, with water-soil erosion at the pore-scale level.

The problem of designing a dike stability analysis module for early warning systems is worth developing an own program code. We have programmed the module using MATLAB scripts and Comsol FE package; however, implementing entirely original program code would allow us to:

- (a) Reduce memory demand and increase computational speed – and hence, consider fully-coupled and three-dimensional dike models in real-time mode;
- (b) Use tracing and profiling tools for *Virtual Dike* efficiency enhancement;
- (c) Increase parallel efficiency of the module (in the present implementation, it was reasonable to use not more than 2-4 cores; for more than 4 cores, synchronisation costs were too high (Chapter 3))

Another interesting issue relates to the aspects of long exploitation of the *Virtual Dike* module within the EWS. In the UrbanFlood project, we have fed the *Virtual Dike* module with sensor data recorded during weeks or months. If the module functions for

years or even decades, perhaps there will be a need in special treatment of simulation errors accumulation, as well as in organizing file handling procedures to clean disk storage from multiply input and output data files generated in the working process.