Finite element analysis of levee stability for flood early warning systems
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Chapter 1 Introduction\(^1\)

1.1 Motivation and scientific challenges

Floods are common natural disasters frequently taking their dramatic toll in global warming conditions and causing high economic and humanitarian losses. Hundreds and thousands kilometres of sensor-monitored flood protection barriers are built at the coastlines all over the world. Rapid development of communication technologies and innovative sensor systems has inspired scientific and engineering community for the development of smart decision support systems (DSS) for early flood protection. The power of computational science and sensor technologies helps levee maintainers in tracing early signs of failure and taking efficient steps to minimize possible losses. In case of emergency, access to a DSS lets public authorities and citizens make informed decisions on optimal ways of evacuation based on inundation forecast and on traffic jam minimisation. Alarms generated by DSS are transferred to mobile phones and to information displays in public places.

The design of Early Warning Systems (EWS) for flood protection and disaster management poses a grand challenge to scientific and engineering communities and involves the following fields of research:

- Sensor equipment design, installation and technical maintenance in flood defence barriers;
- Information and Communication Technologies in application to:
  - gathering, processing and visualizing sensor data;
  - developing Common Information Space (CIS) middleware for connecting sensor data, relevant documents, analysis tools, modelling software and advanced scientific visualization;
  - providing Internet-based interactive access to CIS for researchers, maintenance personnel and public;
- Development of computational models and simulation components for stability analysis of flood protection barriers, failure probability evaluation, prediction of flood dynamics and ways for evacuation.

The present research relates to the third group of tasks and it is focused on the development of computational models of earthen dikes for the on-line dike stability analysis. The work was carried under the frame of the UrbanFlood FP7 project (http://www.urbanflood.eu), which united the research on all three EWS design aspects mentioned above, including monitoring dikes with sensor techniques (Pyayt et al., 2014), physical study of dike failure mechanisms (Krzhizhanovskaya et al., 2011), software

development for dike stability analysis (Melnikova et al., 2013; Pyayt et al., 2011b) and simulation of dike failure, inundation dynamics and city evacuation (Melnikova et al., 2014a; Gouldby et al., 2010; Mordvintsev et al., 2012).

A typical, established approach for dike failure prediction in flood monitoring systems implies data-driven methods (e.g., machine learning, statistical methods) and reliability analysis based on simple limit equilibrium methods and on empirical engineering failure criteria which have been worked out in geotechnical practice during past two hundreds of years and which may have been intuitively used in civil engineering for thousands of years. A detailed physical-model based approach has not been used in early warning systems before, because it’s traditionally considered as computationally heavy. However, growing computational power and rapid development of soil mechanics applications make it interesting and reasonable to integrate complex physics-based computational models into automatic and rather autonomic monitoring systems.

Below we will outline the potential benefits coming from such integration. In mathematical analysis, earthen levees are considered as deformable porous structures subjected to hydraulic and structural loads. Finite element method (FEM) in application to soil mechanics theory offers the most generic and powerful computational tool to take a deep insight in simulation of complex physical processes occurring in levees, both in normal mode and at failure. For an operating levee monitored by a EWS, such FEM levee simulator produces “virtual sensors” data to be compared with sensor recordings under real-life loads in real-time mode. Discrepancy of the signals is then treated as an alarm for the expert users of the EWS. Another beneficial and innovative idea about using a model-based approach in EWS is training data-driven models on simulated sensor data sets, when real sensor data are not available (for example, failure recordings for an absolutely healthy levee).

The complexity of failure mechanisms in dikes has brought us to a problem of finding an optimal balance between realism and adequacy of mathematical models employed in dike stability analysis, on the one hand, and fast and reliable convergence of numerical solution procedure in real-time mode, on the other hand.

Scientific questions raised in this thesis were:

- Can a computational model of an earthen dike adequately predict real-life failure under prescribed loads (obtained from sensors or pre-defined by the user)?

-Though the question is as old as soil mechanics (which started in 1773 with Charles Coulomb’s systematic application of frictional mechanics to civil engineering problems), it has not become less actual nowadays: soils are complicated non-linear structures which continue spawning a large number of mathematical models describing their constitutive behaviour. In this connection, the UrbanFlood project gave a unique opportunity for the researchers: it collected a big amount of well-organized sensor data sufficient for the profound study of physical processes in dikes and for extensive verification of computational models involved at all stages of analysis, including physics simulation modules for dike stability assessment as well as data-driven analysis in the artificial intelligence system. The sensor data were
recorded for real-life dikes, including the IJkDijk full scale failure experiments carried under well documented loading regimes (http://www.ijkdijk.nl). The sensor data have been accomplished with detailed information on soil build-up and geometrical shape of the dikes. Running ahead, we can say that our simulation model provided the best prediction of the IJkDijk slope instability experiment and won a contest for the best prediction (http://ijkdijk.rpi.edu) organized before the test by its designers (see Chapter 6).

- Can a computational model produce realistic dike failure patterns for the artificial intelligence (AI) system training, so that AI trained on such sets could afterwards make a correct and early enough detection of a real-life failure?

-This was an innovative idea proposed and tested by us in cooperation with the AI development team of the UrbanFlood Project (Pyayt et al., 2011a). The AI analysis for structural health monitoring is nowadays a standard technique used in software for sensor monitoring systems. For real-life “healthy” levees, AI typically lacks data on failure patterns. So, for “healthy” levees it was proposed to generate failure patterns in our FEM module Virtual Dike and to train AI on these sets. In order to produce realistic failure patterns for the AI, a comprehensive simulation of complex physical processes happening in the levee at failure was absolutely necessary. After validation of the Virtual Dike module on the real-life dike failures, we have applied this innovative hybrid approach for real-time assessment of dike stability by a monitoring system: for a full-scale dike prototype, the AI system was trained on failure patterns simulated by the Virtual Dike (Chapter 7).

- Uncertainties handling: how critical are uncertainties in soil properties for the quality of dike stability assessment?

- In this area, there have been a number of investigations on sensitivity of the stability margin to variation in soil strength parameters (such as cohesion and friction angle), we have accomplished them with analytical and numerical studies of sensitivity of hydraulic condition of a dike to variation of diffusivities (Chapter 4). On the base of sensitivity analysis, we have proposed and developed a new automatic procedure for calibration of soil diffusivities in an arbitrary heterogeneous dike equipped with pore pressure sensors (Chapter 4).

For the first time in the history of dike monitoring systems, we have integrated our finite element stability analysis module Virtual Dike into an early warning system, so that it works with live sensor data, produces real-time alarms and interacts with other components of the EWS.

Speaking about up-to-date finite element tools for dike stability analysis, it’s worth mentioning that at the industrial level, a number of well-established commercial FE packages for soil mechanics analysis have been developed during past two decades. With a wide variety and complexity of soil models available for users, commercial packages lack
flexibility for programming add-ons and they are not light-weighted enough for real-time work in a total workflow of an early warning system. Our Virtual Dike module has successfully stood a validation against commercial software (Chapter 5). The module has been easily integrated into the UrbanFlood EWS, it was efficient in real-time work with live sensor input and output, and contained a software add-on for automatic calibration of soil diffusivities procedure developed by the authors.

1.2 Early Warning Systems for Flood Protection

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 the 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.

As it was mentioned above, the UrbanFlood project united the work on all the aspects of the EWS design, including sensors, communications and numerical modelling related to dike monitoring. The project has developed an internet based EWS service platform that can be used to link sensors via the Internet to predictive models and emergency warning systems. The data collected from the sensors are interpreted to assess the condition and likelihood of failure; different numerical models are employed to predict the failure mode and subsequent potential inundation in near real time. Through the Internet, additional computer resources required by the framework are made available on demand.

UrbanFlood validated the EWS framework and its implementation in the context of dike performance (failure) in an urban environment. For that purpose, a number of live pilot sites have been worked out to prove the methodology. The pilot sites included the following earthen levees: Livedike (Groningen, Netherlands), Boston levee (Boston, UK), “Stammerdijk” and “Ringdijk” (Amsterdam, Netherlands), Rhine dike (Germany) and three full scale levees which were built and brought to failure during the IJkDijk experiments in 2012. The test dikes have been equipped with sensor systems and the EWS service was built up from a series of dike failure and flooding specific modules which included dike breach evolution and flood-spreading models. UrbanFlood has investigated and shown the feasibility to remotely monitor dikes and floods, whether from nearby offices or from other countries and continents through secure use of web based technologies (Simm et al., 2012a; Pyayt et al., 2014). For the development of flood mitigation scenarios and the training of personnel, the framework has been connected to a simulator that computes flood responses associated with failing dikes.

A general workflow and interaction of software components in the UrbanFlood early warning system are presented in Figure 1-1.
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 behaviour 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 (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, 2013, 2014). 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 pore pressure, local stresses and displacements) describes the non-stationary behaviour of the dike (changing over time). We define a concept of a “virtual sensor” for the data obtained from finite

Figure 1-1. Early warning system workflow
element solution in the point where a real sensor is located. Data from the virtual sensors are compared to the real-life sensor measurements.

Software architecture and tools used for the EWS implementation are described in details in (Balis et al., 2011); a general philosophy of the UrbanFlood EWS design is discussed in (Meijer et al., 2012).

1.3 Overview of the thesis

The thesis is organized as follows:

Chapter 1 contains introduction and description of the UrbanFlood early warning system workflow. Chapter 2 analyzes the collection of existing mathematical models for dikes analysis and selects the most suitable, providing the optimal balance between simulations realism and fast work in real-time mode.

Chapter 3 describes numerical solution issues: implementation of the Virtual Dike module in Comsol package, integration of the module into the UrbanFlood decision support system and parallel efficiency assessment.

The next three chapters, Chapter 4, Chapter 5 and Chapter 6, describe three validation test-sites which were studied in the present research. The test-sites are analyzed in the order of increasing complexity, starting with the Livedike (a sea dike in Groningen, the Netherlands), for which a purely hydraulic (uncoupled) model was developed and tested (Chapter 4). Besides the Livedike modelling, Chapter 4 contains analytical and numerical analyses of sensitivity of porous flow in soils to the variation of soil diffusivity and a description of an automatic procedure proposed by us for calibration of hydraulic diffusivities in an arbitrary heterogeneous dike equipped with pore pressure sensors.

In Chapter 5, a more complicated test case is considered: the Boston levee (United Kingdom) which is a real-life levee operating close to safety margin, with occasional slope failures at high tidal range, typically at springtime. The third case study (the IJkDijk slope failure in Bad Nieuweschans, the Netherlands) has become an ultimate validation of the Virtual Dike module and a winner of a special contest for the best failure prediction (Chapter 6).

Chapter 7 describes experience with training artificial intelligence system on a prototype of the Livedike. Chapter 8 and Chapter 9 bring summary and conclusions in English and Dutch, respectively; Chapter 10 gives acknowledgements; Chapter 11 lists references and the last chapter lists publications by the author.