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Experience of using FEM for real-time flood early warning systems: Monitoring and modeling Boston levee instability

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A B S T R A C T

Boston levee has a documented history of slope slippages under tidal fluctuations reaching 6-m range on spring tides. A finite element model of the Boston levee has been developed in the off-line mode; after that, it was integrated into the common information space of the UrbanFlood early warning system and connected to live sensor data stream registering tidal fluctuations of river level and corresponding response of pore pressures and media temperatures. Stability analysis was carried in a real-time mode.

Besides finite element method, limit equilibrium analysis of levee stability was used in parallel. Real-time assessment of stability was performed by interpolating between safety factors pre-computed for a number of different tidal phases. FEM results indicate instability and agree with real-life observations, while LEM predicted safe condition of the dike. The mismatching is caused by a simplified procedure of pore pressures calculation which is typically used in LEM. For clayey levees, this simplification can lead to over-estimation of slope stability.

The Boston levee case has become one of the pilot sites for validation of the UrbanFlood early warning system (EWS) for flood protection. This validation case has shown that the FEM module for levee stability analysis successfully operates in the real-time workflow of the EWS and correctly predicts levee instability.

1. Introduction

Recent catastrophic floods around the world have spawned a large number of projects aimed at the development of stronger and “smarter” flood protection systems. 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 defense systems.
- 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, modeling software and advanced scientific visualization.
- Providing internet-based interactive access to CIS for researchers and maintenance personnel.

- 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.
- Development of a decision support system for public authorities and citizens that will help making informed decisions in case of emergency and in routine levee quality assessment, thus reducing flood risk and providing advanced tools for flood management.

Many projects, among which are FLOODsite http://www.floodsite.net, Flood Control 2015 http://www.floodcontrol2015.com and development of the International Levee Handbook http://www.leveehandbook.net, attempt to solve some of the EWS aspects listed above. Our research was conducted under the UrbanFlood European 7th Framework Program project (http://www.urbanflood.eu), which unites the research on a physical study of levee failure

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mechanisms [25–27], general design and implementation of an EWS [19,29], development of EWS components for simulation of dike breaching and flood spreading [15,21,22], city evacuation [28], and development of an artificial intelligence (AI) system employing data-driven methods [31,32] and its application in conjunction with the finite element analysis module [30,10,11].

Early warning systems may use the following methods for levee stability assessment: (a) data-driven methods for anomaly detection – machine learning, statistical methods (e.g., [36,33]; (b) reliability analysis based on empirical failure criteria which have been worked out in geotechnical practice during the past two hundred years [41]; (c) limit equilibrium analysis dated to the beginning of 20th century [12,4], et cetera), which is limited to slope slippage prediction only, and therefore is not generic enough to rely on in a general EWS design. A physical-model approach based on the numerical solution of differential equations describing soil deformations is the most generic and comprehensive method for levee stability analysis. This approach has not yet become an established part of typical early warning systems, due to rather high complexity (an expert user support is required for the functioning of such part of an EWS) and high computational costs. 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 real-time monitoring systems. One of our novel contributions is integration of an advanced physics-based finite element model "Virtual Dike[1]" in the UrbanFlood EWS.

In this paper, we present validation of the FEM Virtual Dike module on the Boston levee pilot site, with sensor data analysis and comparison of two stability analysis methods: FEM and LEM. Both methods are standard approaches in soil mechanics, but the question of their applicability and accuracy is still open. Here we investigate this issue and suggest some recommendations on increasing LEM reliability, especially for dynamically changing saturation of clayey soils.

The rest of the paper is organized as follows: integration of the Virtual Dike module into the UrbanFlood early warning system is presented in Section 2. Section 3 contains a description of the Boston pilot site, ground conditions and the levee construction. Sensors and their measurements are discussed in Section 4; Section 5 describes mathematical models involved in the finite element and limit equilibrium modeling and numerical implementation details. Simulation results and cross-validation of the two methods are presented in Section 6, followed by conclusions (Section 7).

2. Integration of the Virtual Dike module into the UrbanFlood early warning system

The UrbanFlood early warning system workflow is presented in Fig. 1 [25].

The sensor monitoring module (Fig. 1) 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; the module combines empirical methods described in [41] and limit equilibrium analysis by Bishop's method [4]. 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. They are accessed from the interactive graphical environment of a multi-touch table or through a web-based application.

The Virtual Dike (Fig. 8) component runs in parallel with the reliability analysis module, offering direct numerical simulation to analyze dike stability under specified loadings [24]. 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, a real-time comparison of simulated data and measured signals is performed and visualized to expert users in real-time mode. We define the concept of a "virtual sensor" as a simulated transient solution obtained for a measured levee parameter (pore pressure, inclination, strain, etc.) by the Virtual Dike in the corresponding location. A registered real-time discrepancy between real and virtual sensors data is treated as an alarm for expert EWS users; it may indicate a change in soil properties in the dike (due to erosion) or in the dike operational conditions (e.g., failure of a drainage facility). In the second case of off-line simulations with pre-computed flood profiles, simulation can analyze structural stability of the dike and indicate "weak" spots that require constant observation by maintainers and possibly strengthening the dike. Functionality of the Virtual Dike module includes a procedure for automatic calibration of soil strata diffusivities based on history of pore pressure readings [25].

Another beneficial and novel idea concerning FEM in EWS is training data-driven models (artificial intelligence anomaly detector) on simulated sensor data sets, for the cases where real sensor data are not available, like failure patterns for "healthy" levees. This hybrid approach combining data-driven and physics-based modeling has been tested on one of the pilot sites – Livedike, a sea dike in Groningen, the Netherlands. FEM simulations have been used for training artificial intelligence system on "normal" and "abnormal" virtual sensor dynamics; the results have been published in [30].

Integration of the modules within the EWS framework is performed via common information space (CIS), as schematically shown in Fig. 1. CIS is an architectural framework providing services to address problems common to all early earning systems as complex software systems: integration of legacy scientific applications, workflow orchestration, allocation of computational resources and robust operation. The key components of CIS are [1]: (a) integration platform (PlatIn), providing core technologies for component integration, data exchange and workflow orchestration; (b) metadata registry (UFoReg): a generic service for hosting and querying metadata; (c) dynamic resource allocation service (DyReAlla): a service for dynamic allocation of resources to running early warning systems. Multiply instances of EWS can be dynamically invoked by the system, for monitoring entire dikes or separate specified cross-sections. The FEM module was deployed on a cloud computing resources of the SURFsara BiG Grid High Performance Computing and e-Science Support Center in Amsterdam, the Netherlands https://www.surfsara.nl/. The cloud is hosted on a 128-core cluster and uses OpenNebula open source cloud computing management toolkit with KVM Virtual machine software. Simulations were run under Linux Ubuntu, in a shared memory parallel mode, in Comsol package. To start a new simulation, CIS launched a new instance of Linux Ubuntu virtual machine with the Virtual Dike model and wrote sensor input (sea/river level value) to the specified directory in real-time (the directory was updated every 5 min). The output from the Virtual Dike was stored in a specified directory on a hard drive, from where it was accessed by the CIS, compared to sensor measurements and visualized at the user front-end. Monitoring input and output directories for new files and deleting the old files

[1] A levee is called "dike" in the Netherlands.