THE URBANFLOOD EARLY WARNING SYSTEM: SENSORS AND COASTAL FLOOD SAFETY

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ABSTRACT

The *UrbanFlood* early warning system (EWS) is an Internet-based system designed to monitor data from extremely large sensor networks in flood defences such as embankments, dikes, levees, and dams. The EWS uses real-time sensor information and Artificial Intelligence (AI) to quickly calculate the probability of dike failure and possible scenarios of dike breaching and predicted flood spreading. It presents results on interactive decision support systems that assist dike managers and public authorities during flood events. It can also be used for flood management policy development and for routine dike condition assessment. The Virtual Dike module can be used for advanced research into dike stability and failure mechanisms. To ensure that the EWS is aligned with user requirements the results of an international stakeholder consultation were used in the design of the system.

Keywords: *flood, early warning system, ICT, climate change, sensor networks, dike failure, flood management*

1 INTRODUCTION

More than two thirds of European cities have to deal with flood risk management issues on a regular basis; this will worsen as climate change effects result in more extreme conditions. Early Warning Systems (EWS) can play a crucial role in mitigating flood risk by detecting abnormalities and predicting the onset of flood defence (dike) failure before the event occurs, and by providing real time information during an event. EWSs thus fulfil multiple roles as general information systems, decision support systems and alarm systems for multiple stakeholders including government, companies and the general public.

Currently EWS's are often localised, using on local computer resources and custom-designed, duplicating efforts and hampering exchange of experiences, data and results. Standardisation in data and systems is slowly taking place at national scale in many countries, but the full potential of the Internet for setting up the actual EWS's is hardly used. Likewise the use of electronic sensors to monitor infrastructure is only now starting to take off.

The *UrbanFlood* project creates a EWS framework that links sensors to predictive models and emergency warning systems; the general framework is validated for dikes. The data from sensors are interpreted to assess the condition and likelihood of failure of dikes. Several trusted and widely used models are used to predict the failure mode and subsequent potential inundation. The models have been adjusted to run on 'virtual machines' on the Internet and use additional 'Cloud' computer resources available on demand. *UrbanFlood* combines known and tested technologies in a novel way, combining ICT and flood management, building the dike monitoring and EWS system of the future [1].

2 THE *URBANFLOOD* EARLY WARNING SYSTEM

The *UrbanFlood* flood early warning system (EWS) is an Internet-based system designed to monitor data from extremely large sensor networks in flood defences such as embankments, dikes, levees and dams, using Internet resources, Artificial Intelligence and special computational models.

The EWS uses real-time sensor information to quickly calculate the probability of dike failure and the possible scenarios of dike breaching, hydrographs and flood spreading. Computed information is presented via the internet on interactive decision support systems, like the *UrbanFlood* multi-touch table (Figure 1), which is optimized to assist the decision making process of collaborating, multidisciplinary, medium-sized emergency teams and decision makers. This interactive user interface also allows intuitive map-based access to libraries of pre-calculated detailed flood scenarios, as well as initiating multiple computer simulations as part of "what-if" scenario analysis. Web-based interactions and smart phone apps using intuitive map-based user interfaces are also supported.

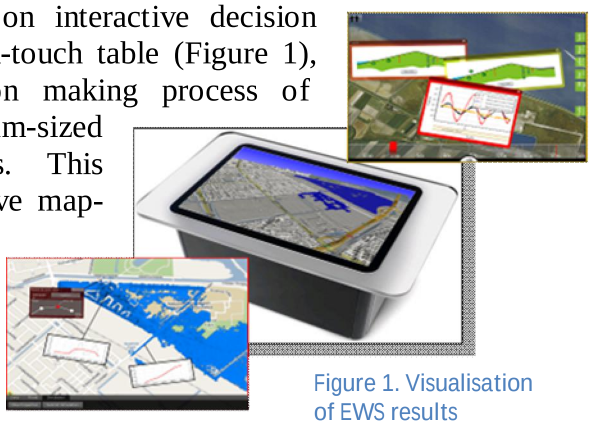

Figure 1. Visualisation of EWS results

2.1 STAKEHOLDER REQUIREMENTS

To match the initial concept and design with the requirements of the stakeholders, one of the first activities of the *UrbanFlood* project was to conduct a stakeholder survey. The first step of the stakeholder analysis was to write down the known issues in an outline. Based on this a series of interviews was held in the Netherlands, verifying the outline and adding detail. The second part of the survey used questionnaires, sent in a targeted manner to international key resource persons; responses from 8 countries were received. The resulting report [2] provides background on relevant policies, programmes and projects; it gives a number of example "smart dike" implementations and a list of stakeholder requirements for EWS and smart dikes in three classes:

1) Technical requirements for the system. These must be met to ensure that the system actually works and a working prototype could be build: robust sensors, reliable communication during emergencies, standardized formats and protocols, reliable computing, trusted models, easy, intuitive and interactive visualisation and compatibility.
2) Non-technical requirements. These have mostly to do with the security, reliability and economics of the system: Security and access, legal standards, financial aspects.
3) Institutional issues – a system that is proven as a working prototype which is secure, reliable and economical still has to be accepted by the organisation that is going to implement it, and by the people who have to work with it.

Based on the stakeholder requirements adjustments have been made in the original design, and are still being made. One clear example: the *UrbanFlood* EWS can now also be used for flood management policy development in non-emergency situations, and is able to support dike managers in routine dike condition assessment. This way it becomes an integral part of the professional toolkit providing information on the actual conditions of the embankments and fact-based computations of their strength, which ensures that staff members will have the necessary routine and practice to use the EWS effectively and with confidence when a flood emergency occurs.

2.2 DESIGN AND FUNCTIONALITY

The *UrbanFlood* EWS is built on a generic Internet-based EWS framework. It can use virtually all types of digital (sensor) information. It is able to run computationally demanding applications such as almost instantaneous flood modelling in Internet-connected Cloud-based data centres that allocate computational resources according to priority and requirements. For dependable use during flood emergencies, several EWS can run in parallel in different geographic locations, possibly operating different computational models. This enhances the reliability of the system and offers a second opinion for assessment of the current emergency situation. In addition, local mirroring, alternative communication means and even the ability to use a minimum set of functionality locally should be considered.

3 WORKFLOW AND COMPUTATIONAL MODULES

The *UrbanFlood* EWS is built in a modular way [1]. The EWS workflow is presented in Figure 2. The *Sensor Monitoring* component receives sensor data from the sensors installed in the dike. Raw sensor data is filtered by the *AI 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 breach, calculates the water discharge through the breach and estimates the total time of the flood. After that, the *Flood Simulator* models the inundation dynamics (Figure 3) and the *Evacuation Simulator* calculates the escape routes from the affected areas.

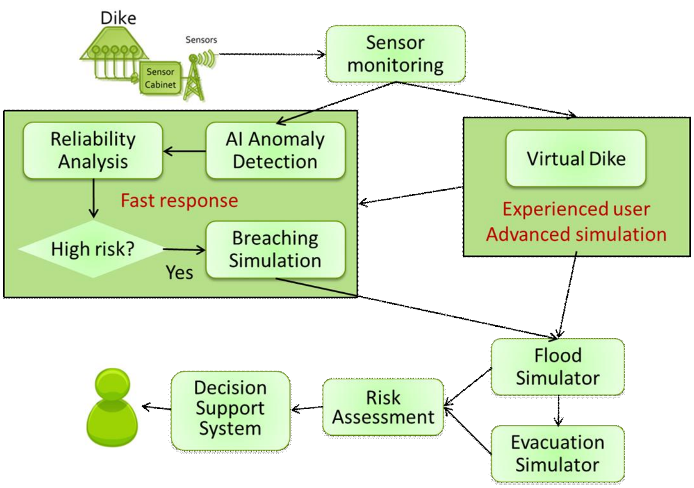

Figure 2. Early warning system (EWS) workflow.

Information from all the modules is visualized in the *Decision Support System*, which works as an intelligent interactive interface from the raw data to the users. For the advanced research into dike stability and failure mechanisms, the *Virtual Dike* component is available for experienced users and experts. All these modules are automatically invoked by the EWS on distributed Cloud computing resources [5]. Flood Simulator and Virtual Dike modules have been ported and successfully tested on the SARA BiG Grid HPC Cloud [6].

A detailed description of the workflow and computational models has been published in [1,5,7,10]. In subsections 3.1 and 3.2 we briefly describe the two updated modules: Artificial Intelligence and Virtual Dike.

Figure 3. Flood simulation results, St. Petersburg Vasilievsky island.

3.1 ARTIFICIAL INTELLIGENCE

The Artificial Intelligence (AI) component of the EWS aims to detect abnormalities in the behaviour of monitored objects by analyzing the sensor data with machine learning methods. The core of the component is a *Committee* of one-side classifiers [8] (Figure 4). It is trained on historical data of "normal" (reference) conditions and on extracted "features" of dike behaviour. The *Committee* is created and configured taking into account the domain knowledge and specific data. For instance in Figure 4, separate classifiers are created for every cross section of the dike.

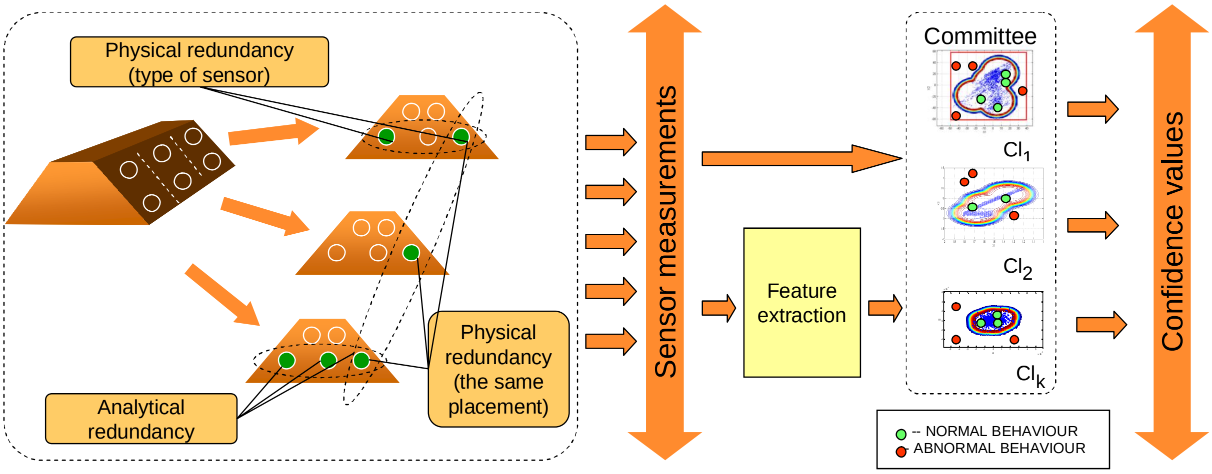

Figure 4. Abnormality detection scheme

After the training stage, the *Committee* of classifiers calculates the *Confidence values* indicating the current state of the system in order to detect possible deviations from the reference state. If previously unknown combinations of particular parameters are detected, it flags exceptions and alerts flood experts. A more detailed description of the AI module can be found in [9].

Based on all available information, the experts or the EWS makes a decision if the exception indicates a potentially dangerous situation or if further analysis should be carried out, e.g. by using the Virtual Dike for identification of potential failure mechanisms.

3.2 VIRTUAL DIKE

The Virtual Dike computational module employs the finite element method to analyse dike stability and investigate failure mechanisms. The module solves a coupled problem of flow through porous media and structural stability analysis, using elastic-perfectly plastic material model with Mohr-Coulomb slip criterion [7]. The Virtual Dike can compute the same observables that sensors are registering (including pore pressure, strain and stress fields). Therefore the model can explain the physical mechanism that may cause the observed behaviour. The module is also used to train the AI component to detect anomalous combinations of sensor measurements.

The first test case performed to validate the Virtual Dike module is slope stability analysis of the *LiveDike Eemshaven* (a sea dike in Groningen, the Netherlands, see Section 4), under tidal load. The dike is equipped with a water level sensor and pore pressure sensors installed inside the dike in four cross-sections shown in Figure 5A. The water level sensor signal is streamed in real-time to the Virtual Dike application. The pore pressure sensor data was used to calibrate soil parameters, so that sensor data and simulation results agree (see Figure 5B, C). The dynamics of stability parameter distribution under tidal load have been published in [7]. The results prove that the *LiveDike Eemshaven* is stable under tidal load.

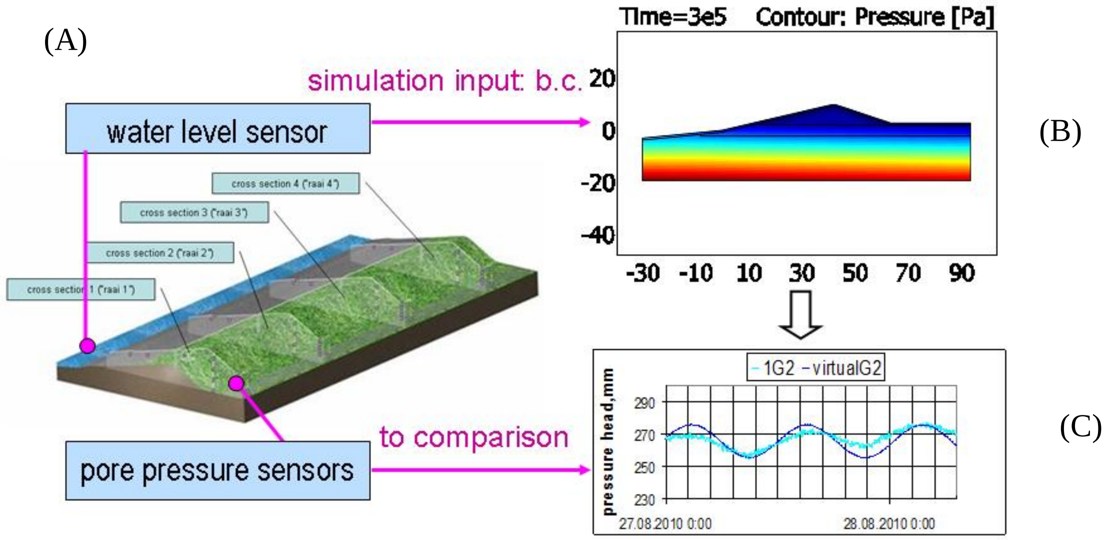

Figure 5. Virtual Dike module: workflow of the dike stability analysis under tidal load. (A) – a dike and its cross-sections with sensors installed; (B) – pore pressure field at one moment of time (simulation results); (C) – comparison of pore pressure dynamics obtained from sensor and from simulation, in the point of sensor location.

3.3 INTEGRATION AND VISUALISATION

In order to organize individual components into a working Early Warning System, *UrbanFlood* provides the *Common Information Space* (CIS) [3,4], a generic framework for creating and hosting any EWS which works according to a four-step cycle: Monitoring, Analysis, Value Judgment, Advice/Act. The CIS takes care of the organisation of the resource management processes ‘under the hood’, like virtual machine control, provenance, data management etc.

Visualization can be used by one or more client applications. The applications allow users to create new simulations by first defining simulation parameters and then submitting the simulation to the CIS for execution. Several client applications have been created: a prototype of a Decision Support System (DSS) for a multi-touch device, a web-based interface that visualizes pre-executed simulation results and an application for visualization of sensor data. Despite the complexity of the system architecture, simulations are computed and visualized within a timeframe of less than one minute. This allows the system to be used for interactive testing of different flooding scenarios.

4 PILOT SENSOR NETWORKS

For the *UrbanFlood* project, several sensor networks have been installed in various types of dikes and levees in the Netherlands and the United Kingdom, demonstrating the usefulness of a EWS based on sensor networks. In addition, data of other pilot sensor networks can also be used within the *UrbanFlood* project. Although the currently available networks are rather limited in size, a significant variety of useful parameters is measured. The current short dike lengths which are instrumented can easily be extended to hundreds or thousands of kilometres, the system is completely scalable.

Existing pilot sensor networks of which the data is available to the *UrbanFlood* project are:

- LiveDike Eemshaven, in the North of the Netherlands: a large sea dike, mainly composed of sand with a clay cover and an asphalt revetment, equipped with over 50 sensors measuring water levels, pore pressures, temperature and local tilt, supplemented with an 800 metre long fibre optic cable measuring temperature changes in the ground and thereby groundwater flow. Probable failure mechanisms are slope failure and failure of the revetment (Figure 5A);
- Stammerdijk, near Amsterdam, the Netherlands: a small river dike with a nearly constant river water level, composed of clay on top of soft layers with a deep sand base, with two instrumented cross-sections, each of eight instruments measuring pore pressures, temperature and local tilt. Probable failure mechanisms are landward slope stability and piping;
- Ringdijk, in an Amsterdam city polder area: a secondary dike with a nearly constant outside water level, with a deep construction pit and trees causing damage on the landside, composed of clay and peat layers, with three instrumented cross-sections, each of six instruments measuring pore pressures, temperature and local tilt. Probable failure mechanisms are landward slope stability, possibly influenced by dry conditions;
- Grand Sluice embankment in the centre of Boston, United Kingdom (Figure 6): an embankment under significant tidal influence composed of clay, sand and till, with three instrumented cross-sections where inclination over depth, pore pressures, temperature and local tilt are measured, and two lines of fibre optics at two levels over a length of 300 metres measuring deformation and temperature (Figure 7). Probable failure mechanisms are outward slope stability after rapid drawdown, followed by erosion and breaching.

Figure 6. View of Boston, UK; the instrumented bank is on the left side.

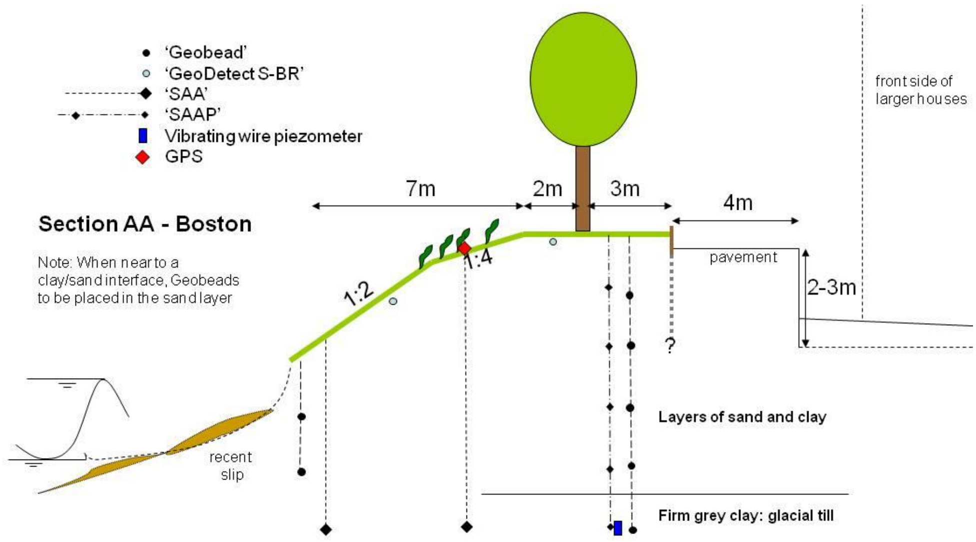

Figure 7. Cross-section indicating instrumentation at Grand Sluice embankment, Boston, UK.

Most of the installed instruments are 'Geobeads'. These compact instruments measure pore pressure, temperature (to detect flow) and local tilt. In Boston, UK, additional instruments were installed: 'GeoDetect S-BR', a fibre optic cable that measures deformation and groundwater flow; and in close collaboration with USA partners also 'SAA' (ShapeAccelArray) which measures global tilt and temperature, and 'SAAP', like SAA but also measuring pore pressure. A vibrating wire piezometer and a GPS were installed too.

Before the CoastGIS conference other locations may be instrumented: the Rhine dike near Emmerich, Germany, prone to piping (backward seepage erosion) and landward slope stability, and the St. Petersburg Flood Protection Barrier, where sensors control the sluices and dam gates, to ensure that they do not fail to close in flood emergency.

5 CONCLUSION

In this paper a technology for building early warning systems based on real-time signals from sensors and its application for monitoring dikes is described. Sensors are becoming ubiquitous in our modern society, and have evolved into smaller, cheaper and easier to read instruments. The *UrbanFlood* project and its partners have shown that combining such sensor networks, modern communication technology and evolving Cloud computer technology can be used to build the monitoring and early warning systems of tomorrow.

For operational implementation the methodology will need to be tested and proven in mission-critical circumstances. As technology improves even further and the need for better and cost-efficient real-time monitoring of large infrastructure works becomes increasingly clear, we are confident that this is only a matter of time, not least because the system is built using proven technologies, combined in an innovative way. The *UrbanFlood* project is looking forward to work with all water managers who install sensor networks to monitor dikes or other large infrastructure.

ACKNOWLEDGMENTS

Special thanks are due to the organisations that made the installation of sensors in 'their' dikes possible. The first clearly is the IJkdijk Foundation (www.ijkdijk.eu), for creating a testing facility for sensors in dikes; this has given the field a huge boost. Then the organisations and individuals who made the brave step to install sensors in their flood defences: Waternet of Amsterdam, the Netherlands, and the Environmental Agency in the UK. Without these organisations and individuals we would not have any data to show how useful this technique is. And finally we wish to thank all stakeholders who shared their insights with us, and continue to share them, to make the *UrbanFlood* EWS a system that is made *for* the users and *by* the users.

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