The use of smart infrastructure in dams to protect communities from flooding

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Abstract

The RTIM system outlined in this paper arose out of the EU funded UrbanFlood research project (2009-2012), which looked at combining sensors, embedded in urban flood embankments, with predictive breach and flood consequence models. The system was piloted on 3 sites in Europe. This successful demonstration of a new approach to asset monitoring, using cloud computing, sensor technology and predictive models, was assessed as an ‘excellent’ project by the EU evaluators. The technology has since evolved into the RTIM system, as a joint initiative between HR Wallingford and Siemens, and is currently being trialled for a UK dam owner. The RTIM system contains a cascade of physical process models for levee reliability, breaching, flood spreading and life safety. This enables scenarios of levee or dam failure to be run based on real time information and the resulting flood consequence assessed for emergency management. The paper will describe the background of the various elements of the RTIM system, with examples from the Boston pilot site in England. The system makes use of the Life Safety Model (LSM) for evacuation planning. HR Wallingford, in partnership with BC Hydro, is now responsible for the development and maintenance of the model, which is being used for emergency planning of flood evacuations internationally, which are briefly described.

1. Introduction

Although it is normal to monitor dams manually by visual inspections, it is becoming common practice to install instruments in new dams to monitor performance during construction and impounding. Many older dams, particularly those showing signs of deterioration, have had instruments installed subsequent to construction as part of an investigation. It is quite common to install instruments in dams where no problems have been identified previously, since regular monitoring of a dam's behaviour is a useful element of routine surveillance. Developments in ICT hardware and software technologies are enabling vast amounts of data to be generated, stored and analysed from new monitoring techniques. The Real Time Infrastructure Monitoring (RTIM) system described in this paper is a tool that can be used to handle these large volumes of data with the use of Artificial Intelligence (AI). It builds on a prototype system developed under an EU-funded research project.

Risk assessment methods form a key part of the planning, design and operation of dams around the world. As with all risk methods and assessments, where the probability of failure is high or the consequences are significant, then greater analysis is required to better understand the risk and to put in place a range of measures to control or reduce the risk. So dams sited above major centres of population will require detailed assessments of the potential flood wave in the event of planned or unexpected water release, which in turn will be used in the preparation of emergency and evacuation plans. This is where a model such as the Life Safety Model (Lumbroso et al. 2011) can be used to inform a detailed emergency plan, including location of safe havens and warning centres, evacuation routes and time needed for safe evacuation. However, all of these different assessment methods are usually run in a planning mode and in isolation from each other. The RTIM technology outlined here allows for integrated modelling of the hazard and risk, in both a planning and operational setting.

2. The UrbanFlood Project

2.1. Overview

UrbanFlood (www.urbanflood.eu) was an ICT project funded by the European Union under the Framework 7 Programme for research, and ran from 2009 to 2012. Its main aim was to demonstrate the use of sensor technology to improve monitoring of flood defence assets in the 21st century, making use of developments in cloud computing, sensors and predictive models of asset failure, flood spreading and evacuation. Flood defence assets, in common with dams, require routine or periodic monitoring to assess their condition and hence continuing performance. However this is a non-trivial task, given that many countries have thousands of kilometres of raised defences and associated flood structures. Such monitoring will become more pressing with the impacts of climate change which is predicted to put more pressure on the defences from rising sea levels, higher peak river flows and storm rainfall. For example, some 5.2 million properties are at risk of flooding in England, and annual flood damage costs are in the region of £1.1 billion. These costs could rise to as much as £27 billion by 2080. It has been estimated that maintaining existing levels of flood defence would require flood defence spending to increase to over £1 billion per year by 2035 (Bennett and Hartwell-Naguib 2014). The UrbanFlood project was therefore looking at the options for remote, continuous monitoring of critical flood defences, looking at the feasibility of the initial investment in sensors and other hardware versus the savings in staff time to visit each defence. Such technology also raises the opportunity for reduced costs from asset failure by providing early warning of ‘hidden’ problems.

2.2. System components

The UrbanFlood system components are shown in Figure 1. The aim was to develop an Early Warning System framework that can be used to link sensors via the Internet to predictive models and emergency warning systems. By hosting data in the Cloud, it was possible to have several EWSs accessible from any internet connection. The data collected from the sensors was interpreted to assess the condition and likelihood of failure; different models will be used to predict the failure mode and subsequent potential inundation in near real time.

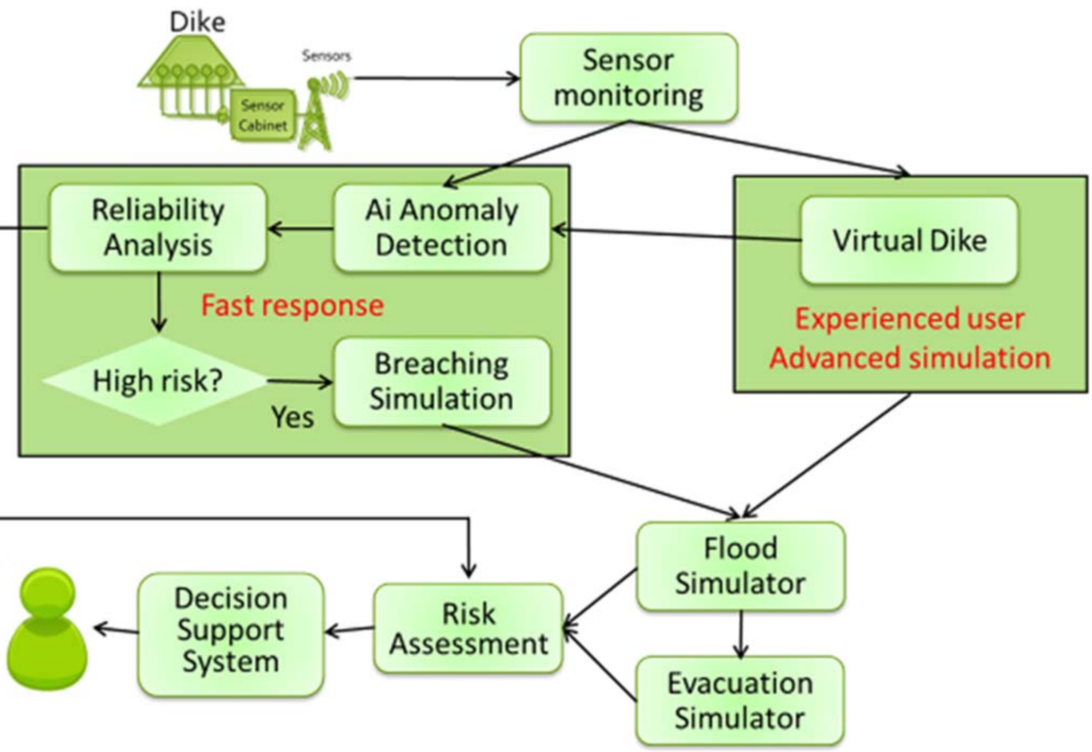

Figure 1 UrbanFlood system components

Two methods were demonstrated for translating the sensor data into a prediction of likelihood of failure. The first was a sophisticated AI algorithm that was trained onto the data through both temporal and spatial dimensions, so that likely regions of anomalous behaviour could be determined. Pilot site data along the toe of the flood defence were assessed together, as was data along a specific cross-section parallel to the river. In this way, the 4D behaviour could be captured. Anomalous conditions are flagged up to the user, who can then confirm whether the 'acceptable' range can be expanded into the new measurement zone. The other assessment method used a 'virtual dike' to reproduce the actual behaviour, based on advanced engineering simulation and professional judgement.

Some of the components in Figure 1 represent the modelling chain developed by HR Wallingford independently, and which were integrated into the UrbanFlood system. Firstly the RELIABLE tool is used to derive fragility curves for any structure, using limit state equations, and these were derived for each of the pilot sites. The fragility curves are used with the sensor data to determine if a failure is likely, supported by engineering judgement. If a failure is predicted, the breach model (HR BREACH / EMBREA) (Morris et al. 2011) would be started, which provides a dynamic evolution of a potential breach, and the subsequent outflow hydrograph. This would either be routed down the river valley or spread over a wider floodplain, say for a coastal site, using the Rapid Flood Spreading Model (RFSM) (Gouldby et al. 2008; Lhomme et al. 2008). Finally the 2D flow outputs of depths and velocities are used in the DSS and risk assessment, which includes using LSM for potential loss of life and emergency management options. The above has provided a very simplified explanation of the system tested by UrbanFlood; readers are advised to visit the web site, which includes a wide range of outputs, including a video, if they wish to learn more of the system.

2.3. The Boston pilot site

The UrbanFlood system was developed to predict a failure of an urban flood embankment. Three pilot sites were selected in Amsterdam (Netherlands), Boston (UK) and the River Rhine (Germany). The particular dike in Boston, a town on the east coast of England at high risk of flooding, was selected partly because it was subject to significant tidal forcing (up to six metres) and partly because of a history of slope instability.

The instrumentation at the various sites was selected on the basis of previous experimentation and comparison of instruments installed in full scale dike failure tests in the Netherlands (IjkDijk). Sensors installed included

- MEMS modules able to detect local tilt, pore pressure and (via temperature) seepage
- Sensor enabled-geotextile strips based on fibre optic sensing technology, able to detect soil strain by distributed light back-scattering along longer stretches of embankment.

At Boston, three cross-sections along the embankment were selected to understand the variation in properties, with boreholes drilled into the bank at the top, middle and toe. Into these a series of Geobeads and Shape Acceleration Arrays (SARs) were inserted and backfilled. In addition, a geotextile strip with fibre-optic sensors was laid parallel to the river in trenches at the top and middle (see Figure 2).

All of the sensors performed very well, with the daily variation in river level being clearly seen in the pore pressures, and seasonal variation temperature also apparent, with a damped response further away from the river. Results appear to be dominated by the direct (‘elastic’) response of the structure and pore pressures. However, the results also suggest that the instrumentation is able to pick up slow ongoing plastic movement of the embankment including ‘hot spots’ of deformation. This was detected by both the fibre-optic strip (Figure 3) and by the SARs (Figures 4). The increased movement shown on the right of Figure 4 agrees well with the historical areas of slippage. Emerging empirical and AI analysis of the pore pressure response is suggesting that the changes in the phase lag in pore pressure response between borehole locations may provide a useful indicator of deterioration.

Figure 2 Installation of the fibre optic sensor at the levee crest in Boston

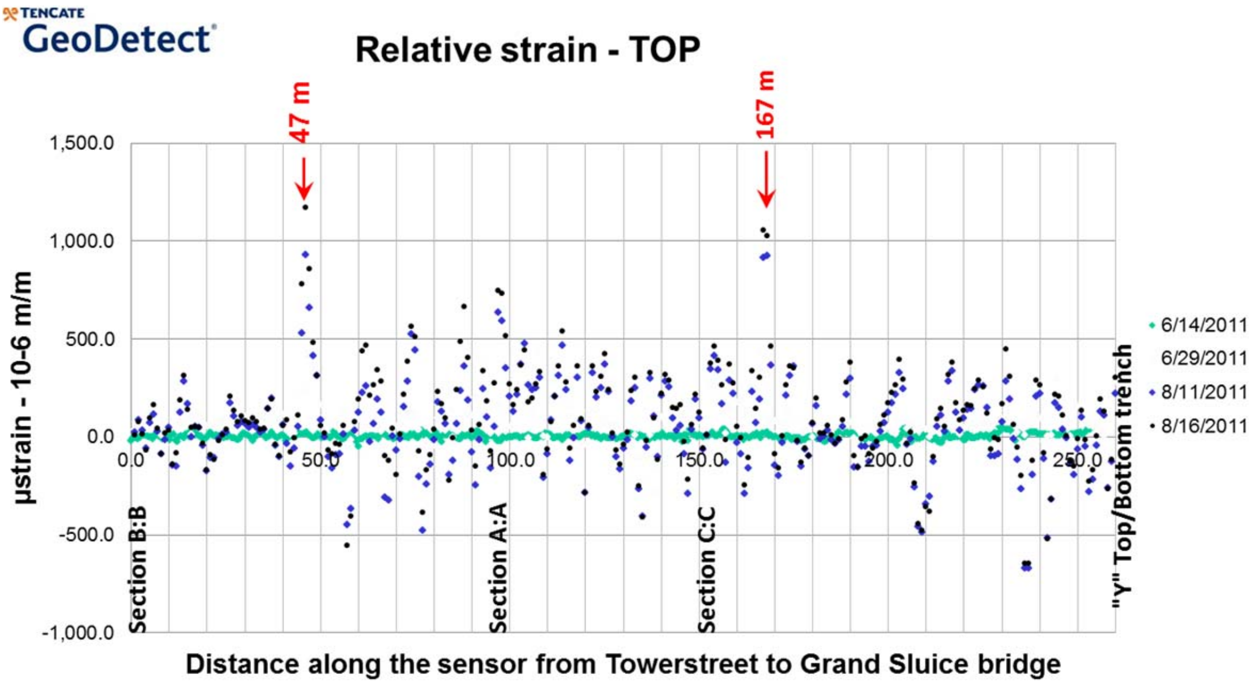

Figure 3 Example of fibre optic readings, with two 'spikes' associated with bank movement

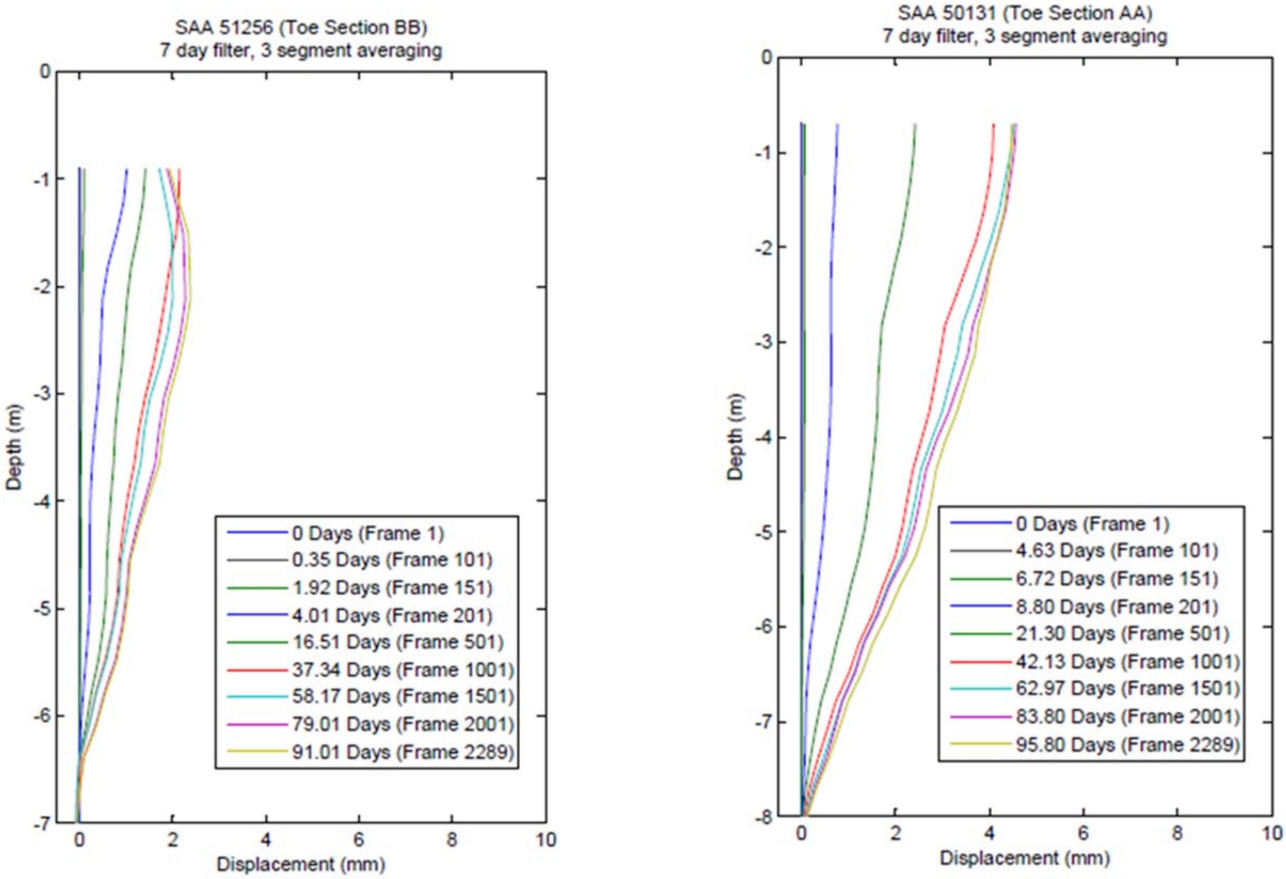

Figure 4 Shape Acceleration Array outputs (with increased deformation in area of known slippage (right figure)

3. The 'smart' RTIM concept

3.1. Overview

The Real Time Infrastructure Monitoring system (RTIM), developed jointly by Siemens and HR Wallingford, involves a detailed assessment of the key issues affecting any dam and a resulting specification of 3rd part sensors to monitor and characterise the main properties. The data feeds from the system of sensors are all directed to a single RTIM secure server where Artificial Intelligence (AI) software constantly monitors the data streams, compares different sources of information and looks for anomalies that it cannot explain. Anomalies are then flagged up in the MS Windows based user interface software for the attention of the dam owner and for anomaly investigation. Anomalies may for example necessitate IT hardware investigation, geotechnical engineering like slope stability analyses, or reservoir engineer involvement (see Figure 5).

The system has total flexibility in terms of the sensors that can be used, so these can be sourced from any manufacturer. In the same way, the system can be seamlessly embedded in a client's existing data storage and security systems with no compromise of existing protocols or performance. A modular approach has been adopted so that the most relevant ones can be installed in each location, with the option for extending the system to add functionality, such as emergency planning. This approach also facilitates the development of new modules to meet future client requirements.

The flexible nature of the system means that after the initial set up, it becomes relatively cost-effective to add additional dams (or even different asset types) on to the RTIM system. This means that you can monitor simultaneously, continuously, and easily from the same user interface.

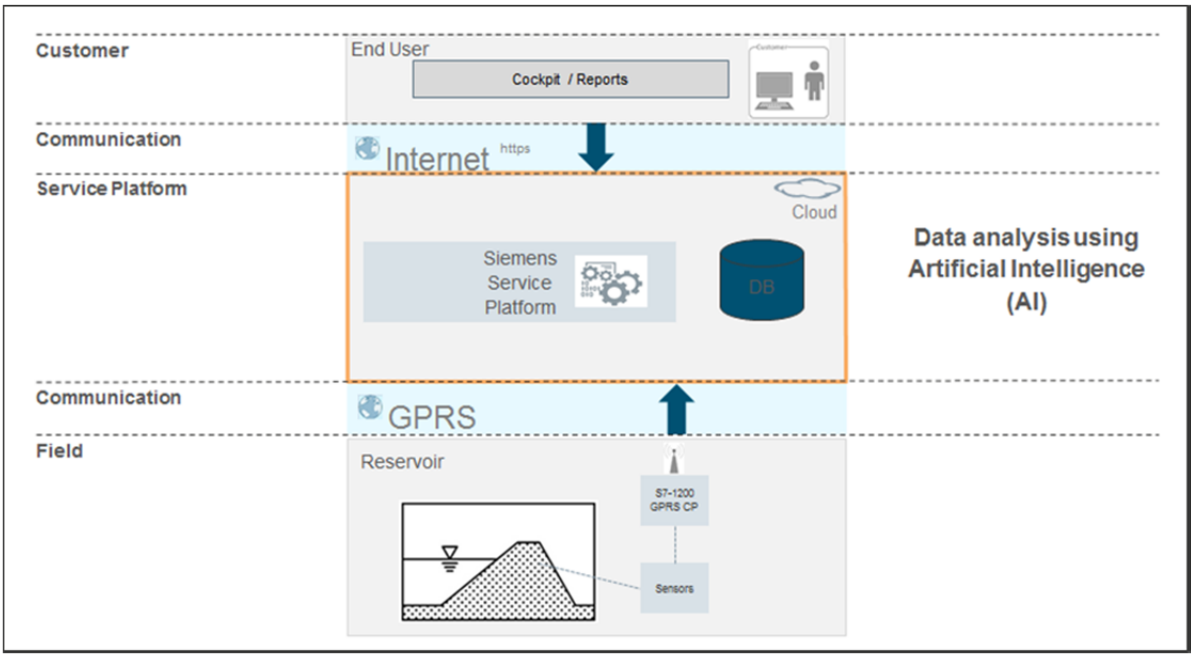

Figure 5 Block diagram of the RTIM system

3.2. Sensors

The system allows for total flexibility in the sensors that can be deployed for any dam, as all the data will be captured by a single operating system. Sensors could include, for example:

- Piezometers,
- Flow meters on drainage flows;
- Tilt meters that if connected by a semi rigid casing, can measure movement ;
- Temperature sensors to indicate seepage;
- Pore water pressure sensors to measure seepage;
- Fibre optic fabric to monitor settlement (See Fig. 2) – although at present this is not real time monitoring;
- Shape acceleration arrays to measure horizontal movement;
- Reservoir water level sensors;
- Rainfall gauges;
- Crack gauges;

- CCTV video feed.

Data are sent electronically to the Reservoir Manager and operators and the Artificial Intelligence software provides a continuous assessment of the data. This will be based on emergency triggers specified by the operators to highlight any potential changes in the reservoir behaviour.

3.3. Data capture and storage

The current specification is to capture data on an hourly basis, but other frequencies can be used. The data will be in simple analogue format which is then digitised and transmitted using the wireless HART communications protocol. This is an industry-proven standard, and provides a robust wireless network for data transmission. Outlying measurements which are beyond normal line of sight communications to the data gathering control station can also be transmitted reliably via the wireless mesh back to the desired control point.

The network uses IEEE 802.15.4 compatible radios operating in the 2.4GHz Industrial, Scientific, and Medical radio band. The radios employ direct-sequence spread spectrum technology and channel hopping for communication security and reliability, as well as TDMA synchronized, latency-controlled communications between devices on the network. This technology has been proven in real plant installations across a broad range of process control industries. For flexibility to meet the application requirements, wireless Hart supports multiple messaging modes including one-way publishing of process and control values, spontaneous notification by exception, ad-hoc request/response, and auto-segmented block transfers of data sets. These capabilities allow communications to be tailored to the application requirements thereby reducing power usage and overhead.

Communications for data transfer from the Programmable Logic Control would be provided via GPRS over mobile phone network to the Siemens data control centre. Where there is no mains power supply, the RTIM system can operate either a hybrid solar and wind power system or a micro hydro power scheme. The main benefit of a hybrid system is that it can take advantage of all climatic conditions. This approach has particularly successful on off grid monitoring and data acquisition.

The data once transmitted from site will be stored on a secure remote server platform. Rules will be applied for security and safety which are in place for remote monitoring and diagnostics services for confidential data from clients. The system separates the role of the data server and the web server. The role of the web server is to provide access to online visualisation only. The role of the data server is to store the data and carry out the real-time analysis and calculations.

3.4. Data analysis

The reservoir owner and operators are able to access the stored data via a series of ‘cockpit’ screens that are configured to the particular needs of the surveillance exercise (see Figure6). In addition to viewing the raw monitored data, the system can also display other derived values that come from algorithms or engineering calculations that turn the data into useful information. Again, there is great flexibility in what can be derived and displayed on the consoles. By combining analytical and real time data a continuously monitored and analysed assessment of the data can be achieved which will alert operators to emerging and potentially emerging trends and situations. Emergency triggers can be set up on all the monitoring sensors to highlight any potential changes in the reservoir behaviour. In order to eliminate system failures, as distinct from reservoir behaviour, software for sensor data validation shall be applied for the data which are collected in a central database at a data server.

Analysis of the raw data uses software based on the principles of artificial intelligence, where the software is ‘trained’ on historical data series, so that the expected variation over time and space is captured fully. The AI software uses the observed deviations to define trigger levels, which can then be used to report anomalous behaviour. The AI is able to distinguish between variations in environmental variables such as weather or reservoir levels, versus that recorded in the dam, such as leakage rate.

The main goal of the AI is signal processing of all online measurement streams gathered from sensor network installed within the dam. Application of data driven methods allows detection of deviation of the system from previously known normal behaviour. Any detected deviation can be interpreted as onset of failure or sensor fault (Simm et al. 2013). The artificial intelligence software will continuously read all measured data of the sensors, calculate the one-side classification and provide an output, which is a classification result. The classification result is a so-called confidence value between 100% and 0%. Such a confidence value will be classified into three classes based on level of deviation: information, warning, alarm. Such information will be visualised on the screen and/or directly sent to the dam owner.

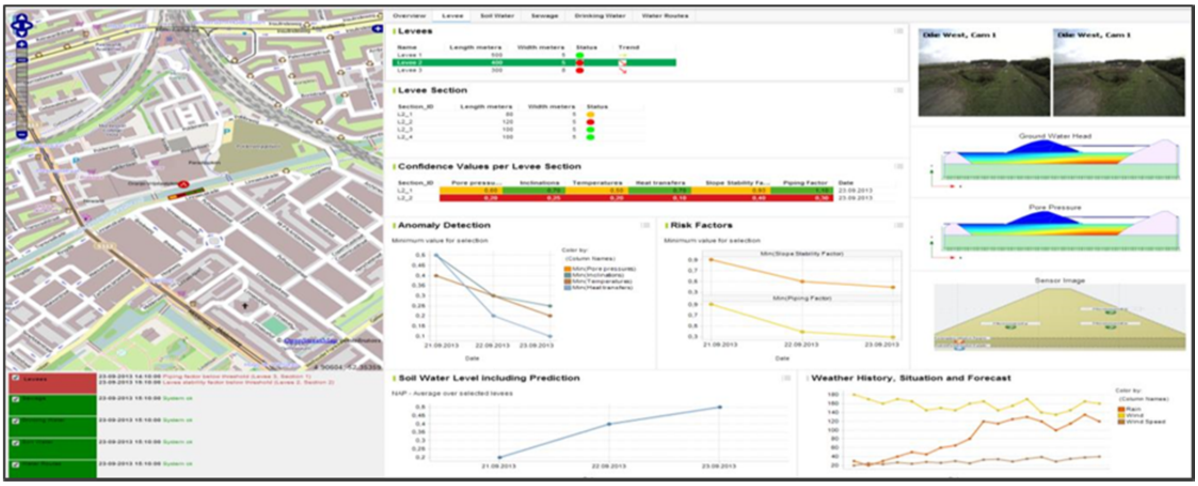

Figure 6 Pre-configured RTIM cockpit screen

3.5. System benefits

The modular nature of this system means that owners can choose to add additional levels of anomaly investigation support. This could also include the linkage to predictive models, as was demonstrated in the UrbanFlood project. So dam breach models, flood routing and the Life Safety Model can all be triggered to run on the basis of an anomalous reading.

The flexible nature of the system means that after the initial set up, it becomes relatively cost-effective to add additional dams onto the RTIM system. This means owners would be able to monitor multiple dams simultaneously, continuously, and easily from the same user interface.

Dwr Cymru Welsh Water (DCWW), a major UK water company, is the first company to install the RTIM system on a dam. DCWW selected Ffynnon Llugwy, which is located in a remote part of the Snowdonia National Park. On a number of occasions access to the site in the winter months is difficult and often treacherous, leading to the reservoir not being visited for several consecutive weeks. There is no power at the site, and poor communications, an ideal pilot site for the system.

The network of sensors designed for the site is based on the monitoring requirements set out in the Inspecting Engineers S10 report. Communications will be improved on site with the use of mobile antenna boosters, and power in the form of a discrete wind power turbine, 2 solar panels and a hydropower unit installed within the compensation pipe. The installation of the RTIM system is due to be completed in September 2015.

4. The life safety model

4.1. Recent developments

LSM was developed originally as a tool to aid analysts to determine the loss of life associated with the flooding from a hypothetical dam failure. HR Wallingford first applied the model as part of the major EC research project FLOODsite (www.floodsite.net), to investigate evacuation along the Thames Estuary. Since the beginning of 2012, we have formally taken over the responsibility for its future development, licensing and promotion on behalf of BC Hydro. In this role we undertake a programme of agreed model developments, jointly-funded by our two organisations, as well as support a number of commercial and academic users. We also undertake consultancy studies using the model, some of which are outlined in the next section.

For a given population at risk, LSM can:

- Estimate the potential loss of life and building loss from an extreme flood event
- Produce a series of virtual representations of how a flood emergency could evolve
- Support emergency management analysis, which aims to develop and test mitigation strategies that could reduce the potential life loss (this could include provision of warnings and safe havens, designated evacuation routes).

Figure 7 provides a conceptual representation of how the LSM is applied, combining 2D water flow with a 2D ‘people flow’.

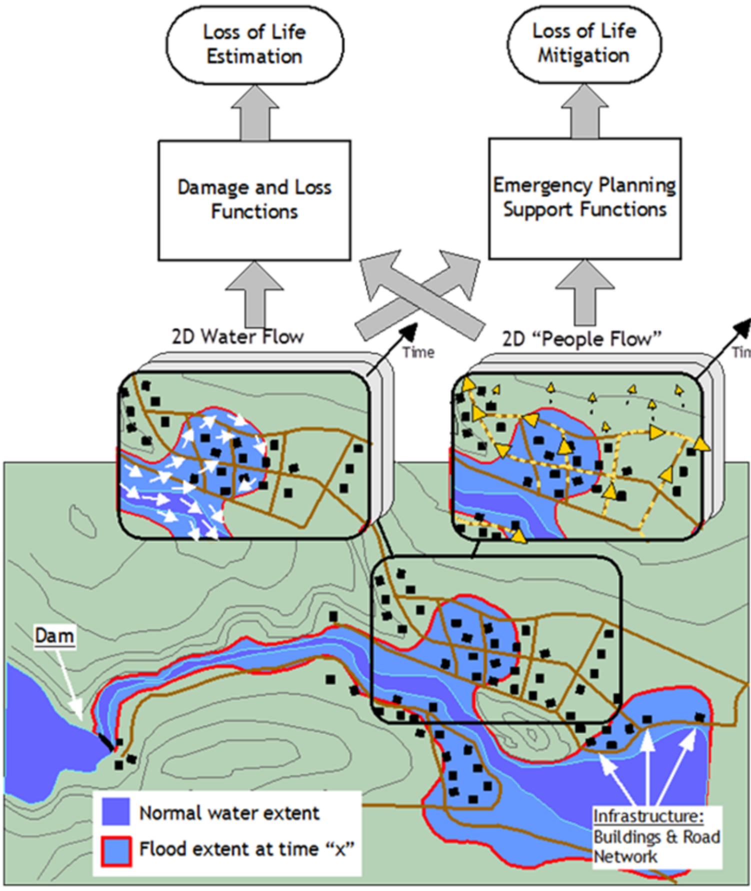

Figure 7 High-level concept of LSM simulation (from BC Hydro 2006)

Working with BC Hydro and other core users, the LSM has been enhanced over the past few years to include:

- Building losses due to high water depth and low velocity
- A mechanism for loss of life when buildings fill with water but are not destroyed
- A mechanism for people to shelter in buildings when the water depth reaches a threshold
- Improved traffic flow
- Improved traffic monitoring and monitoring the number of people that reach each safe haven
- 64 bit application for modelling large geographic areas and populations.

These features are available in version 3.1 of the software which will be released in the autumn along with improved documentation.

There are commercial licence holders of the software in Canada, Italy, Australia and Malaysia, with a restricted number of academic licences within the core LSM user community.

4.2. Current applications

The LSM was developed originally to estimate loss of life for dam risk assessment, and has now been successfully applied to other flood hazards. The model supports emergency planning for floods from dams, rivers and the coast because it includes the interaction between people, vehicles and the flood water and can test a number of scenarios. Scenarios for emergency management can include:

- The lead time of flood warnings
- Evacuation routes and location of safe havens
- Assumptions on traffic density and speed
- Seasonal populations.

The following provides a summary of recent applications of the model.

The Humber Estuary, UK (sea surge)

The East Coast of the UK is at risk from large scale inundation in a low probability extreme storm surge. In the last few years the relevant Local Authorities have developed plans for mass evacuation of the low lying areas in such a scenario. These have involved high level (macro) calculations of evacuation times through to micro scale analysis of evacuation using LSM. The LSM was used as part of a tiered traffic modelling approach to investigate how long it would take for mass evacuation of the area in advance of a major storm surge (such as happened in 1953). The 'micro' modelling carried out by LSM for the east of the City of Hull showed that congestion would take place on the local road network, which had not been modelled in the other two approaches. Overall, LSM produced consistent evacuation times to the other traffic models.

Pennines dam, UK (dam failure)

As part of the European-funded research project, FIM FRAME (www.fimframe.net), a range of tools were used to consider the development and use of flood emergency plans. A dam in England formed one of the case studies, which considered the issue of warnings in the event of potential failure. Although the dam is extremely unlikely to fail, the model application showed that the number of fatalities could be significantly reduced if a warning was provided at the dam site. The application of LSM also raised issues such as omission of evacuation routes and safe havens in the local flood plan.

Windsor, NSW, Australia (river flooding)

An LSM study was commissioned by the State Emergency Service of NSW in May 2013. This was to act as a pilot study to demonstrate the model's capabilities for the community of Windsor. Windsor was chosen as the pilot location because:

- It is a self-contained population centre which needs to be completely evacuated in extreme floods.
- There is reasonably good data on the locations of each of the existing buildings.
- There are proposals for additional major development.
- There is one evacuation route through the town and out onto the main highway.
- A previous macro assessment of evacuation times has identified that there are capacity issues on the evacuation route.

Simulations to date have been 'in the dry', pending receipt of the flood model outputs. This has looked at the time needed for everyone to reach safety (the Olympic Stadium in Sydney) prior to the flood arriving. Running the model 'dry' is a recent feature that avoids the need for 2D flood modelling output, and can be used to test existing evacuation plans.

Pilot application Grand River (dam failure and river flooding)

The LSM was applied to two pilot sites in the Grand River watershed to investigate the suitability of the model for consequence analysis for loss of life and building damage. The St Jacobs pilot site model was run for a dam failure scenario and the Schneiders Creek pilot site for a river flood scenario.

OPG pilot application (dam safety)

OPG have undertaken a pilot study in Canada using LSM as part of an overall risk safety framework to estimate consequences of potential dam failure. A range of population scenarios were determined to account for the high seasonal variation in the population at risk.

Japan (dam failure)

The LSM was used as part of a risk assessment to estimate the consequences of failure for two dams in Japan. The potential failure modes were identified on site visit and desk assessment, the most likely of which were simulated with a breach model and 2D hydraulic model to determine the flood depths and velocities. The LSM produced estimates of loss of life for the most likely dam failure scenarios for a no warning scenario and a scenario with warning.

5. Conclusions

This paper has provided a brief overview of the successful EU project UrbanFlood, which demonstrated the use of sensor technology, linked to a predictive model cascade, to investigate the behaviour of flood embankments. This technology has now been commercialised with a pilot application underway for a UK dam owner. Having real time monitoring can increase the probability of spotting signs of potential failure at an early stage, which in turn can lead to improvements in preventative maintenance of the reservoir, and reductions in reactive maintenance.

The Life Safety Model is one of the predictive models that were demonstrated as part of the early warning system, and this has undergone recent development, and is now finding widespread use in flooding studies around the world.

6. References

BC Hydro. 2006. “BC Hydro Generation, Life Safety Model System v1.0; Guidelines, procedures, calibration and support manual.” Report No. E310.

Bennett, Oliver, and Hartwell-Naguib, Sarah. 2014 “Flood defence spending in England”, House of Commons Library. Internet accessed June 28, 2015.

http://researchbriefings.files.parliament.uk/documents/SN05755/SN05755.pdf

Gouldby B., Sayers P., Mulet-Marti J., Hassan M. & Benwell D. 2008. “A methodology for regional-scale flood risk assessment”, Proceedings of the Institution of Civil Engineers-Water Management 2008, 161, (3), 169–182.

Lhomme J., Sayers P.B., Gouldby B.P., Samuels P.G., Wills M. & Mulet-Marti J. 2008. Recent development and application of a rapid flood spreading method. In: FLOODrisk 2008, 30 September – 2 October 2008, Keble College, Oxford, UK.

Lumbroso, D., Sakamoto, D., Johnstone, W., Tagg, A., and Lence, B. 2011. “The development of a Life Safety Model to estimate the risk posed to people by dam failures and floods”, Dams and Reservoirs Journal, British Dam Society.

Morris, M.W. Hassan, M.A.A.M. and van Damme, M. 2012. “Recent Improvements in Predicting Breach through Flood Embankments and Embankment Dams”, Dams: Engineering in a Social & Environmental Context. Thomas Telford, London, 2012

Simm. J., Jordan. D., Topple.A., Mokhov.I., Pyayt.A., Abdoun.T., Bennett.V., Broekhuijsen.J., Meijer.R. 2013. “Interpreting sensor measurements in dikes – experiences from UrbanFlood pilot sites, Comprehensive Flood Risk Management” – Klijn & Schweckendiek (eds), Taylor & Francis Group, London, Pp. 327-336