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Chapter 2. Description of the Monitored Flood Defence Structures*

Several levees and dams are analysed in this work. This chapter presents sensor technologies and schemes of sensor installation inside the monitored flood defence structures.

2.1. *Short description of the projects*

The flood defence structures presented in this work were monitored within two projects: *UrbanFlood* and IJkdijk All-in-One Sensor Validation Test.

2.1.1. *UrbanFlood* project

The *UrbanFlood* (www.urbanflood.eu) European project investigated the use of sensors within flood protection systems (levees, dikes, dams) to support an online early warning system, real time emergency management and routine asset management (see Figure 2.1). One of the main goals of this project was the development of an early warning system (EWS) platform validated for flooding.

The internal workflow within the *UrbanFlood* EWS is presented in Figure 2.2. The "Sensor Monitoring" component receives measurements from the sensor network installed in the dike. Raw sensor data are filtered by the "AI Anomaly Detection" block (or Artificial Intelligence (AI) component) that identifies anomalies 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 2.2) and the "Evacuation Simulator" calculates the escape routes from the affected areas.

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1. Pyayt, A.L., Kozionov, A.P., Mokhov, I.I., Lang, B., Meijer, R.J., Krzhizhanovskaya, V.V., Sloot, P.M.A. Time-Frequency Methods for Structural Health Monitoring. Sensors (MDPI), 14, pp. 5147-5173 (2014), doi:10.3390/s140305147.

2. Pyayt, A.L., Mokhov, I.I., Lang, B., Krzhizhanovskaya, V.V., Meijer, R.J. Machine Learning Methods for Environmental Monitoring and Flood Protection, Proceedings of the International Conference on Artificial Intelligence and Neural Networks (ICAINN 2011), Amsterdam, the Netherlands, July 13-15 2011, pp. 118-124, pISSN 2010-376X and eISSN 2010-3778.

3. Simm, J., Jordan, D., Topple A., Mokhov, I., Pyayt A., Abdoun T., Bennett, V., Broekhuijsen, J., Meijer, R. Interpreting sensor measurements in dikes - experiences from UrbanFlood pilot sites. Comprehensive Flood Risk Management – Klijn & Schweckendiek (eds). 2013 Taylor & Francis Group, London, ISBN 978-0-415-62144-1. Proceedings of the 2nd European Conference on FLOODrisk Management. 20-22 November 2012, Rotterdam, The Netherlands, pp. 327-336.

4. Pyayt, A.L., Kozionov, A.P., Kusherbaeva, V.T., Mokhov, I.I., Krzhizhanovskaya, V.V., Broekhuijsen, J., Meijer, R.J., Sloot, P.M.A. Signal analysis and anomaly detection for flood early warning systems, Journal of Hydroinformatics, IWA publishing, 2014, doi: 10.2166/hydro.2014.067 (in press).

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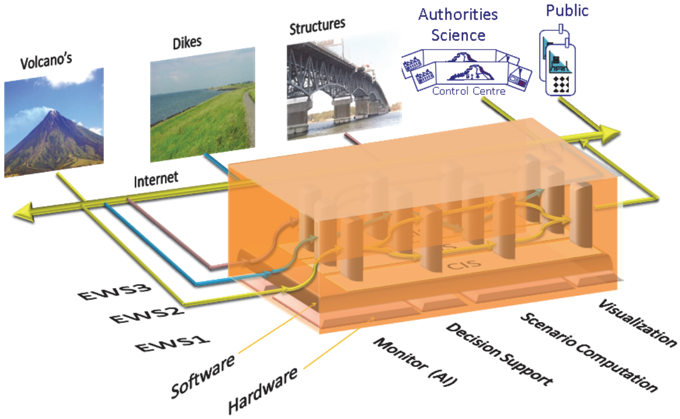

Figure 2.1. *UrbanFlood* monitoring concept [12].

Information from all the modules is fed into the interactive "Decision Support System" (Figure 2.2). This is a multi-touch device that visualises levee cross-sections with installed sensors, raw measurements and results of data analysis.

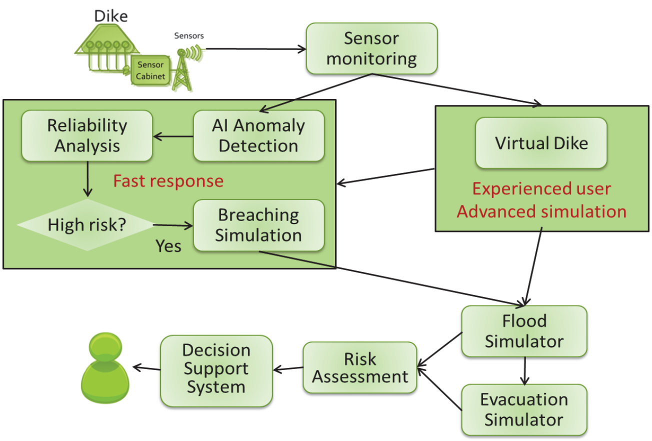

Figure 2.2. Workflow of the *UrbanFlood* early warning system [69].

More details on the *UrbanFlood* early warning system and computational modules can be found in works [92], [32], [114].

2.1.2. IJkdijk All-in-One Sensor Validation Test (AIO SVT)

IJkdijk consortium (http://www.ijkdijk.nl/) organised in 2012 several full-scale levee destructive experiments (Booneschans, the Netherlands). This means that several full-scale dikes were constructed and were affected by abnormal conditions that led to collapse of these objects.

The main goal of these experiments was to test ability of sensor technologies (remote and in situ monitoring) to identify the onset of levee collapse. Collected sensor measurements were analysed and visualised by several partners of the consortium.

The planned experiments have been carried out at three levees: the West levee piping experiment (21-26 August), the East levee piping experiment (21-27 August), the South levee macro stability experiment (3-8 September).

The West/East levees are presented before start of the experiment in Figure 2.3. The main difference between the East and West levees was that DMC drainage system was installed into West levee that made process of piping more "controllable". If this system is turned on, the water that is leaking through the levee will be pumped out of the levee that will postpone time of levee collapse. More details can be found on official website [14].

Figure 2.3. Photo of the West (left) and East (right) levees before start of the experiments (14 Aug 2012).

Pore pressure measurements were provided to the IJkdijk consortium in these experiments. There were installed 3 cross-sections with 2 sensors within each cross-section at different depth for the West levee, 5 cross-sections for the East levee (Figure 2.4). More details about the sensor supplier are presented in the next Sub-Section.

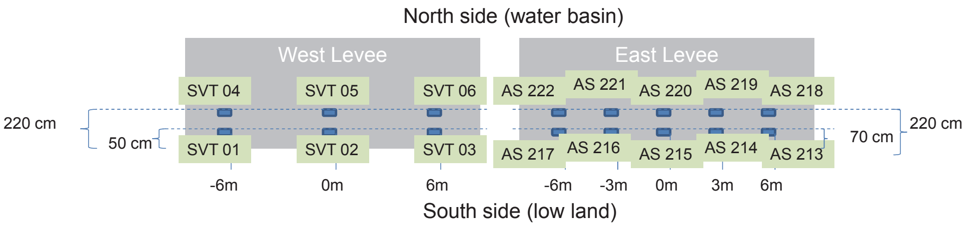

Figure 2.4. Alert Solutions sensors installed into the West/East levees.

2.2. Description of the sensor technologies

2.2.1. Alert Solutions

In 2008, Alert Solutions introduced its sensor network, GeoBeads, to monitor levee and slope stability monitoring. GeoBeads was developed “to provide all essential dynamic parameters for the determination of soil stability” [97] (Figure 2.5(a)).

a) b) c)

Figure 2.5. (**a**) GeoBeads sensor string with integrated bentonite shells for hydraulic isolation between measurement depths. (**b**) Installation of a GeoBeads string using a light weight direct push-in rig with a sonic drilling head. (**c**) Schematic overview of a GeoBeads sensor string installed vertically to obtain multilevel measurements of levees, mountain slopes and construction activities [101].

GeoBeads consists of fully digital sensor modules (nodes) that are based on robust semiconductor technologies and can be scaled to a wide network area for measurements. Each small-sized node in the network can simultaneously house various measurement devices. The set per node commonly includes a piezometer, an inclinometer and thermal sensors [96], [97]. Pore pressure, inclination and temperature are measured as a result. Local contractors execute the installation with regular drilling or push-rig equipment (Figure 2.5(b)).

Data are immediately available on the Internet.

2.2.2. GTC Kappelmeyer

GTC Kappelmeyer uses distributed fibre optic temperature sensing technology that can accurately measure the ambient temperature along fibre optical cables with high accuracy. This measuring method is based on the fact that the optical properties of the fibre depend on the ambient temperature.

Fibre optical cables suitable for applications in hydraulic engineering usually consist of a core with at least two fibres and a mechanical strength member that is covered by an outer jacket (Figure 2.6).

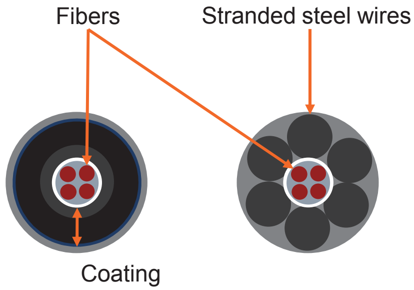

Figure 2.6. Cable structure and measuring principle. Schematic display of different cable types [101].

Distributed fibre optical temperature measurements are most suitable for levee seepage detection due to their high information density [26]. Essentially, there are two measurement methods [27], the gradient method and the heat-pulse method.

The gradient method requires using the temperature differences between the reservoir water and the dam material to successfully detect leakage. The leakage is detected when the temperature gradient significantly drops between the water and the ground temperature.

GTC Kappelmeyer uses a heat-pulse method [15] that provides robust leakage detection in the autumn and spring, when the ground (T_G) and water (T_W) temperatures are nearly equal (Figure 2.7). The area of leakage is presented as a blue arrow in the central area of the pictures in the centre and right in Figure 2.7. The fibre optic cable is heated up (central picture in Figure 2.7) by sending an electrical current through the metallic cable coating (e.g., rodent protection, shielding). The temperature increase immediately surrounding the cable depends on the heat capacity and heat conductivity of the outcrop. However, during seepage flow, the poorly conductive heat transport is superimposed by the much more effective advective heat transport. Therefore, clearly visible temperature anomalies occur in these areas during the heating process (the temperature difference is shown using red figures in the right picture of Figure 2.7): the temperature in the seepage area is lower than in the dry soil.

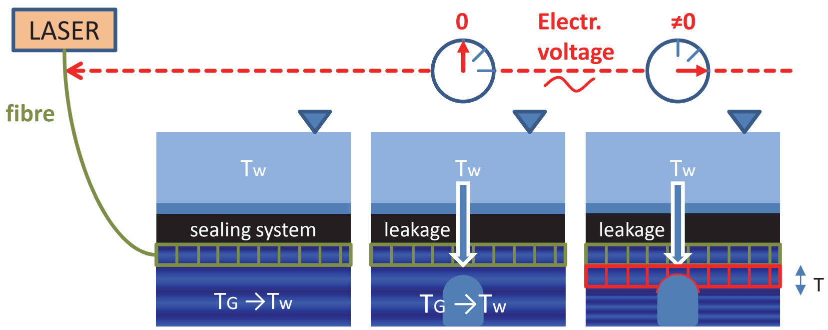

Figure 2.7. Heat-pulse method for leakage detection [101].

2.3. The monitored levees

2.3.1. Stammer dike in the Netherlands

The “Stammerdijk” (or Stammer dike) lies along the Gaasp River near the A9 motorway in Amsterdam, the Netherlands. The Gaasp River is a canal with a controlled water level (variations of no more than 0.2 m throughout the year). The dike is constructed on 5 to 6 meters of peat layers and on 3 m of sand.

This levee is equipped with a detailed network of GeoBeads sensors that continuously measure the pore water pressure, temperature and inclination. Sensor modules have been installed at two cross-sections at depths of up to 10 meters below sea level in the various soil layers (sand, clay and peat) [105]. The distance between the cross-sections is approximately 100 meters.

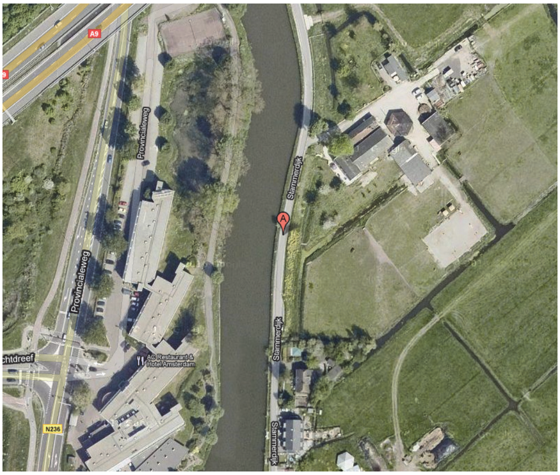

Figure 2.8. Stammer dike.

The scheme of one of the two cross sections is presented in Figure 2.9.

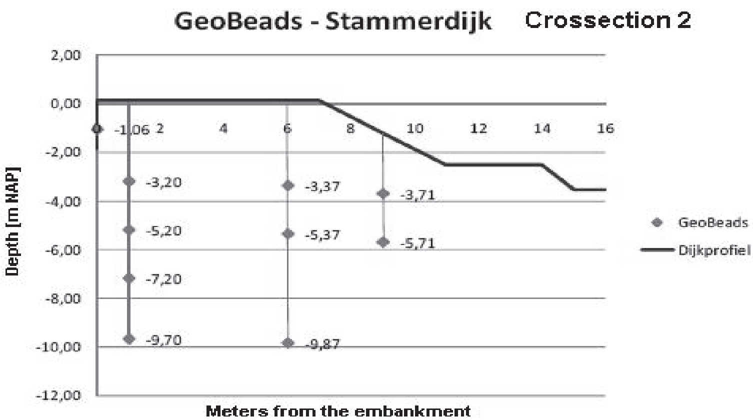

Figure 2.9. Stammer dike cross section #2.

2.3.2. Boston dike in the United Kingdom

The Boston dike is located in the town of Boston, Lincolnshire, which is located in the eastern region of the United Kingdom. The crest of the dike is covered with large trees and has shown various stages of failure in the past. The dike is constructed on layers of fine clays and sands that overlie boulder clays (see Figure 2.10). This levee was equipped with 3 cross sections of GeoBeads sensors [114].

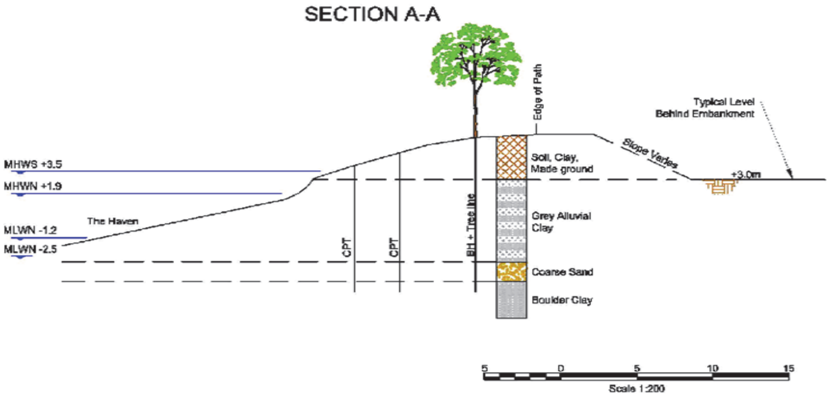

Figure 2.10. Boston dike cross section A-A [114].

2.3.3. Rhine levee in Germany

Two types of sensors were installed in the Rhine river levee, Alert Solutions (GeoBeads) were installed in 2 cross-sections and a GTC Kappelmeyer fibre optic cable (250 m) was installed across the levee (Figure 2.11 – orange line). One of the two Alert Solutions cross-sections is presented in Figure 2.11. The fibre optics cable provides spatio-temporal temperature measurements across the levee [101].

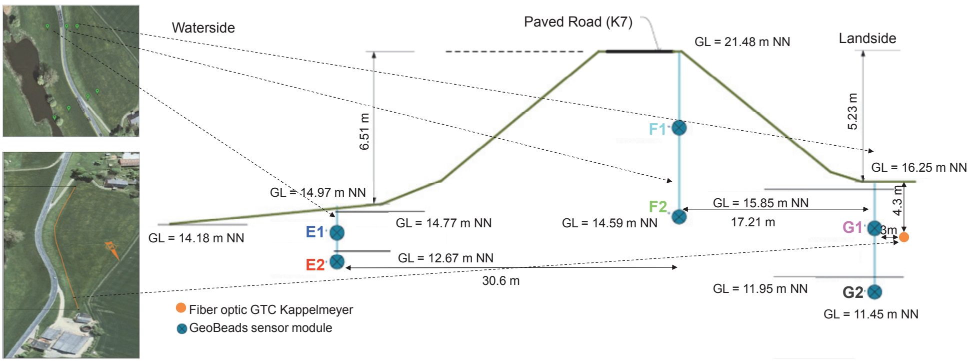

Figure 2.11. Alert Solutions sensors (marked with green balloons in the left portion of the picture, and marked with blue circles in the right part of the picture) and GTC Kappelmeyer fibre optic cables (marked with orange line) installed into the Rhine levee in the second cross-section, the left slope on the waterside slope of the levee, and the right side on the landside slope [101].

2.3.4. Retaining dam

GTC Kappelmeyer provided an anonymised data set. Because the description of the monitored object is confidential, it was not provided.

2.3.5. Zeeland dike in the Netherlands

Zeeland dike or "Oost Zeedijk" (East SeaDike) is presented in Figure 2.12. A cross-section of the Zeeland dike is presented in Figure 2.13 [99].

(a) (b)

Figure 2.12. (**a**) Map of the Zeeland dike; (**b**) the enlarged image of (a).

Several sensors have been installed, including a temperature sensor inside the drainage pipe (T). In Figure 2.13 P1 corresponds with the water level sensor inside the drainage pipe and P2 corresponds with the water level sensor at the back of the dike (before the road and the ditch).

This dike is affected by constant weak piping, which requires the installation of a drainage pipe with the pump (Figure 2.13) that removes water from dike. The pump is automatically turned on and off when certain water levels are measured in drainage pipe.

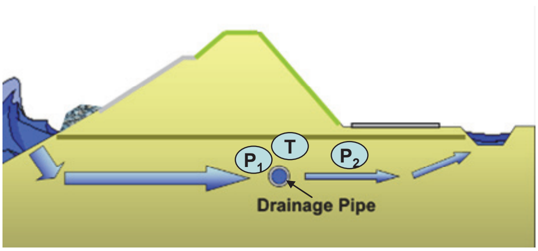

Figure 2.13. Zeeland dike cross-section with approximate sensor positions and arrows showing the piping direction. Excess water is pumped out through the drainage pipe to prevent piping.

2.4. Conclusions

Two different sensor technologies were applied for levee monitoring, GeoBeads sensors (Alert Solutions) that measure a wide range of parameters at a single point and distributed fibre optic temperature cables (GTC Kappelmeyer). The GeoBeads technology requires the installation of sensors at several cross-sections to monitor different parts of the levee. In contrast, the second technology provides a full set of information for the entire dike, but only for a limited set of parameters (e.g., temperature). The installation of GeoBeads sensors is required for detecting most levee failure scenarios. However, a fibre optic cable is useful for detecting potential leaks.

GTC Kappelmeyer sensors were installed into the Rhine levee and the retaining dam (both in Germany). Alert Solutions sensors were installed into the Stammer dike (Netherlands), Boston levee (UK), and Rhine levee (Germany). The Zeeland dike was equipped with several sensors for measuring the water levels and temperatures inside of the levee. Alert Solutions sensors were also used for levee behaviour analysis during the IJkdijk experiments (see Chapter 6).

Analysis of measurements collected from sensors installed into Rhine levee, Stammer dike, Zeeland dike and Boston levee was carried out within the *UrbanFlood* project. The results of the data analysis are described in Chapter 3 and Chapter 4.

Short description of the IJkdijk experiment is presented in this chapter. Chapter 6 presents results of this experiment analysis.

All the described in this chapter flood defence structures are the earth-fill dams.