How to create a Smart Levee

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1 Introduction

Many river deltas in the world are of great economic value. However, in general these areas are susceptible to flooding (Figure 1) because of the low level of the land. In the Netherlands, protection against flooding is in the form of artificial levees and flood defence structures like storm surge barriers. Primary levees protect the land against high water levels from the sea and the large rivers. All other levees (most regional) are called secondary levees. The state of the network of primary and secondary levees are all monitored frequently. Traditionally, this monitoring is done by visual inspection and an evaluation of stability based on height and resistance against various failure mechanisms every six to twelve years. Research on weak spots is focused on monitoring of pore pressure inside a levee. During the last couple of years, monitoring has been extended by performing innovative physical measurements inside and on levees. A few examples are given in Ng & Oswalt (2010), Smith & Côté (2011) and Sjödahl et al. (2011).

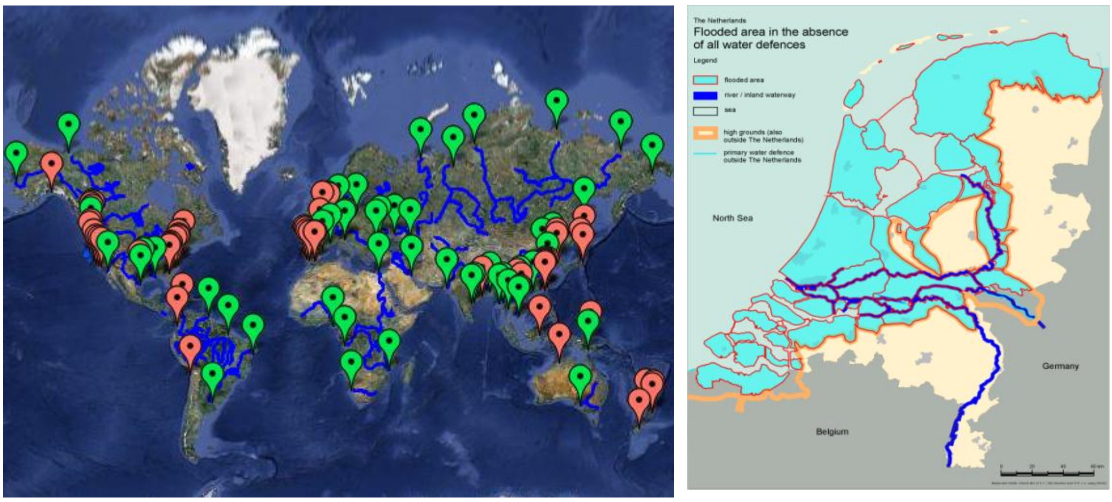

Figure 1 Left: Deltas of the World (Lui, 2011).
Right: The Netherlands, with flood protected area in blue.

In the Netherlands, relevant research in the past few years has been concentrated on full-scale field experiments on levees, mainly related to the so-called ‘IJkdijk’ (Dutch for ‘calibration levee’) and its spin-offs. At a special test site, on one large levee the slope stability failure mechanism has been investigated thoroughly by a wide range of sensors (Koelewijn, 2009; Weijers et al., 2009). Four smaller levees have been subject to backward seepage erosion (piping), again monitored by a large suite of sensors (De Vries et al., 2010; Koelewijn et al., 2010). After these tests on artificial levees, several existing levees have been instrumented in order to assess their real time stability status both in the Netherlands and abroad (Melnikova & Krzhizhanovskaya, 2011; UrbanFlood, 2011).

With emerging possibilities of monitoring levees by measurements, the question arises what kind of monitoring techniques can help the safety assessment of levees. Therefore the “Smart Levee” is introduced. Additionally, an overview of the available techniques is given. We will illuminate the message that sensors alone are only part of the safety assessment.

2 Definition of a “Smart Levee”

A Smart Levee provides intelligence about its past, current and expected condition to its end users to make informed decisions to maintain demanded flood protection levels. In this definition, a Smart Levee is not synonymous to an instrumented levee. The smartness is not only found in the application of sensor technology, but also in knowledge of the potential failure mechanisms of the levee and the coupling of these two elements. The sensors (ears and eyes of the levee) need a brain to combine information and a mouth to communicate the state of the levee. Knowledge about the body (the levee) and its environmental exposure is essential for the right application and placement (where to look at), correct interpretation and decisions based on this information.

In the Netherlands, a vast length of levees protects the country, with a total of about 3200 km of primary levees and 14,000 km of secondary levees. We distinguish between manmade sea and river levees, remnants of peat deposits and natural dunes. Due to the enormous length of the levees, it is not feasible to install sensors inside all levees. Moreover, there is no need to do so. When sufficient knowledge on a particular levee is available, e.g. based on composition, height and observed behaviour, the levee can be sufficiently Smart. Based on several case studies in the Netherlands, three categories of levees that could benefit from the application of sensors are defined:

1. Levees to be used as reference location for specific frequently encountered types of levees, this may cover up to 80% of all levees by instrumenting only a limited number of sections;
2. Problematic levees or weak levees according to calculations, these levees might already be included in a reconstruction plan (spanning several years, sometimes more than a decade);
3. New levees and large scale improvement works on existing levees.

These three types of Smart Levees can be equipped with suitable in situ sensors or monitored with remote sensing (e.g. satellites as sensors). The sensor information about the actual current condition of the levee will help timely decision making in crisis situations and in maintenance. By monitoring weak levees, information will be gathered regarding the actual behaviour of the levee. In this way, improvement works can be planned more efficiently and more effectively. Instrumentation of newly built levees helps to reduce maintenance costs and to improve the design of future levees.

The instrumentation of levees should focus on reducing the uncertainties regarding the potential failure mechanisms threatening a specific levee. Risk reduction should be the prime goal when drawing up the instrumentation plan. Inevitably, this results in a location-specific monitoring solution in situations only where an increase of knowledge from sensor data can help to reduce uncertainties. When there is no risk, there is no need for instrumentation. When the risk is clear (e.g. insufficient height), instrumentation alone will not help to reduce it (but it can aid in the improvement works).

3 Parameters

Historically, monitoring of levees is performed by periodic visual inspection of the levees. The observations indicating possible instability are e.g. horizontal or vertical cracks, signs of excess pore pressures, leakage zones and deformation of pavement, new or illegal objects, new land use, variations in height of the levee and revetment control.

The visual inspections have been standardized and digitized by the Dutch project “Digispectie”, with the use of handheld computers (STOWA, 2007). In a way, the eyes of the person inspecting the levee are a sensor. However, not all indicators of instability are visible from the outside of a levee. It is there that in situ or remote sensors can fill a gap.

Dutch knowledge on the applicability of sensors in relation to monitoring of levees comes from the IJkdijk experiments and from several pilot levees. The IJkdijk experiments served two purposes: to get a better understanding of the failure mechanisms and to provide a platform for sensor parties to develop and validate their equipment.

In the full-scale experiments at the IJkdijk test site, both extensive reference monitoring systems employing proven technology and a variety of new sensor technologies were installed. Table 1 gives an overview of the parameters measured and the sensors installed during these experiments.

Based on experience or understanding of the failure mechanisms, certain parameter can be selected for monitoring purposes. These parameters can be measured with a number of techniques. Temperature, for example, can be measured by MEMS at point locations, by fiber optics in line segments or remotely (surface only) by a thermographic camera. Another example is movement, which can be measured by inclinometers on a fixed rod, by strain in fiber optics or remotely by laser altimetry.

Table 1 Parameters measured by sensors in IJkdijk experiments

Slope stability experiment		**Piping experiment**	
Parameter	**Sensor**	**Parameter**	**Sensor**
Pore pressure	Vibrating Wire Piezometer, MEMS, BAT	Pore pressure	Vibrating Wire Piezometer, MEMS, fiber optics
Temperature	Thermographic camera, fiber optics, MEMS	Temperature	Thermographic camera, fiber optics, MEMS
Movement (Strain/ Tilt/ Consolidation)	Inclinometers, fiber optics, optical camera, MEMS, laser scanning, extensometer, inverted pendulum, Liquid Level Settlement Sensor, Absolute Pressure sensor	Movement (Strain/ Deformation)	Fiber optics, optical camera
Visual inspection	Human eye	Visual inspection	Human eye
Vibration	Fiber optics, microphones, hydrophones	Vibration	Fiber optics, hydrophones
Weather conditions	Weather station	Weather conditions	Weather station
Soil moisture content	MEMS, various agricultural sensors	Flow / discharge	Flow meter
Electrical conductivity	Agricultural sensor	Sand volume	Spoon (manual operation)
		Self Potential	Non polarising electrodes

For slope stability, pore pressure and deformation are key parameters to detect, understand and monitor the process (Bishop, 1955). For backward erosion by piping, the process can be followed both by measuring pore pressures (Van Beek et al., 2010) and temperature (Beck et al., 2010). Advanced analyses showed that the measurement of the discharge and the volume of sand transported through the pipes are valuable too to determine the stage of advancement of the piping failure process (Kruiver & Hopman, 2010).

4 Sensors

4.1 Location and frequency of sensors

Another aspect to Smart Levee technology is the location of the sensor. In general, sensors sample the levee in both time and space. In situ sensors that are pushed into the ground give point measurements in space, from the inside of the levee. Fiber optic cables give information along a line, also from inside the levee. Sensors on the surface can give either point, line or plane information, depending on the type of physical measurement. Remote sensors measure on the outside (the surface) of the levee only.

The required sampling interval in space largely depends on the scale of the failure mechanism. For slope stability of a large river levee, instrumentation of cross-sections 30 metres apart may be sufficient in some cases. For piping, timely detection of the failure mechanism requires a sensor within the sand layer, at not more than 1 metre from the top of this layer. Moreover, measurements need to be taken at least once every 2 metres along the length of the levee, while sufficient redundancy should be applied to be able to discern false signals.

The sampling interval in time of in situ sensors can be adjusted to sufficiently small intervals in time to be able to follow the processes. Whether that leaves enough time to act on the observed changes in stability in time is a different issue, which needs to be adressed by both failure mode analyses on the technical side and (adjustment of) management and organizational issues on the non-technical side.

4.2 Installation of sensors

The placement of sensors in or on a levee is crucial to be able to interpret the sensor values. For instance, an inclinometer does not measure the rotation of the levee body when it is not installed on a rigid rod and connected to a stable reference. Pore pressure might not be measured correctly when the clay seal is not properly applied. Additionally, the sensor needs to be installed in the right layer of the levee. For a sand layer, susceptible to piping erosion, the pore pressure meter needs to be installed in that layer, and not accidentally in the adjacent clay layer. Knowledge of the internal structure of the levee is essential for proper installation of in situ sensors.

Even when the technique and the location of the sensors are decided, the actual positioning of the sensors inside the levee may pose problems. The levee managers still tend to be very cautious about admitting digging or drilling in their levees. They fear damage or instability of the dike due to a new leakage path along the sensor cable.

A possible solution for avoiding damage to levees and for a limited density of observation points in space is remote sensing. The platform for the sensors can be airborne (airplane or helicopter) or spaceborne (satellite). In the case of remote sensing, the sampling in time is the limiting factor. For airborne measurements, the measurement campaigns can be planned, but might be relatively expensive. The revisit time of satellite varies between several days and about one month for the types of satellite measurements which can be valuable for levees. In case of levees facing rather short flood waves, this is generally not enough, but for long term observations at locations with a rather stable water level this can be useful. For leakage, infrared and passive microwave anomalies indicate zones of possible leakage through the levee, related to piping. The deformation of a levee, in the order of 1 to 10 mm/year can be monitored by Persistent Scatterer Interferometric SAR.

4.3 Logistics

Logistic issues which need to be covered include power management (grid power, batteries, renewable energy), datacommunication (wired or wireless), data management (how to handle a huge amount of data in time, get alerted when useful, get alarmed when required) and the robustness of the whole monitoring system. What does it mean if a supplier guarantees a reliability of 99.98%? And what if he is right, but failure of the system tends to coincide with (rare) flood conditions? Issues like these need to be covered before a Smart Levee system is commissioned, to avoid the collection of rather meaningless data on the one side and post-failure investigations on the other side.

5 Smart information

In order to use sensor information for decision making, the raw information has to be transformed into a form that is useful for decision makers at different levels. Figure 2 illustrates this transformation, where pore pressure serves as an example. In the case of an imminent breach of the levee, the person responsible for the safety of the people in the region is not interested in the pore pressure of individual sensors, but in the location of the possible breach and the number of people and the value of economic activity threatened by that. This is depicted by the red area in the right panel. One decision level lower, at the water board, information about the stability of the levee at defined transects is important. This information is derived from the pore pressure measurements. Based on the stability at transects, weak zones can be identified and appropriate measures can be taken. The individual pore pressure readings might only be of interest for the dike manager (one level lower), who checks the stability factors in the portion of the levee under his responsibility.

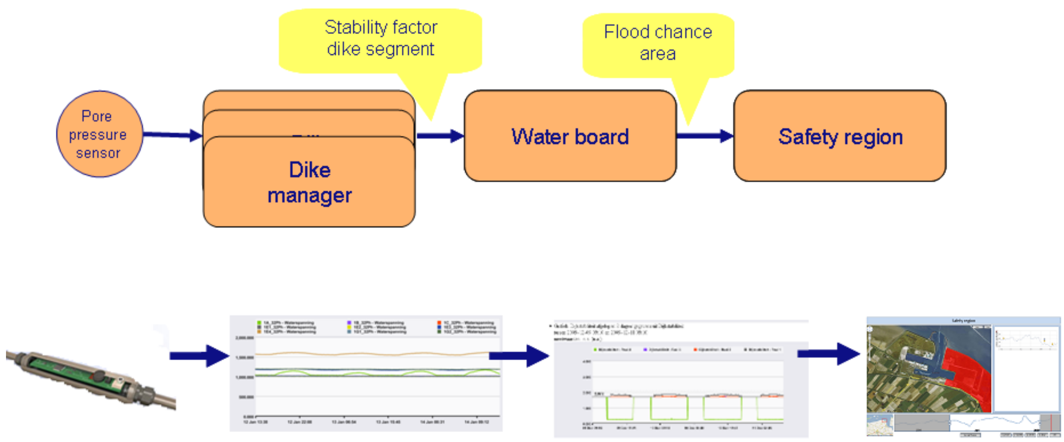

Figure 2 Sensors and virtual sensors in the chain of water safety

The example shows that raw sensor data need to be transformed. The transformed sensor is called a virtual sensor. For the construction of virtual sensors, models are needed. These models link a measurable parameter to a physical process affecting stability of a levee. As indicated before, for pore pressure, models which translate pore pressure to a safety factor (for slope stability) or a pipe length (for piping) are available. These existing models have been made much faster to be able to cope with real time sensor information. For other parameters, such a temperature, such physical models still need some development for application at highly variable water levels. In the case of piping and a temperature difference between the upstream and downstream, contour plots of temperature indicate the location and the extent of a backward eroding pipe. However, more research (including field measurments from various locations and conditions!) is still needed to be able to quantify what amount of temperature anomaly implies a certain amount of piping. For many newly measured parameters, sensor interpretation relies qualitatively on patterns of change. End users at various decision levels cannot use this type of visualisations, because they need quantitative information.

Monitoring for varying purposes demands different types of information. In case of operational monitoring, for the daily maintenance, an update of the situation once a week might be sufficient whereas in the case of flood risk management during high water level events, an update every few minutes might be required. Also, the type of displays based on the sensor data will be different, partly because the end users are different in these situations.

When levee monitoring by sensors will be applied on a larger scale, the transformation of sensor data to virtual sensors needs to be performed in an automated way. With the knowledge of the levee, outlier values can be explained in terms of e.g. malfunction or in terms of real warning of a change in stability.

6 Conclusions

A Smart Levee presents its different end users with selected information needed to assess its current and future safety level for historical and expected flood conditions. For many levees, visual inspection remains a very important sensor. For a yet limited amount of levees, this includes direct or indirect monitoring of key parameters by sensors, either in situ or remotely.

For piping, the key parameter to be measured is the pore pressure in the aquifer. To determine seepage and erosion, this may also be monitored in an indirect manner by observing temperature. Sand volume and discharge (in situ) and passive microwaves (airborne) are also useful parameters. For slope stability, pore pressure and deformation (in situ tilt and strain) are key parameters. Satellite data (PSI) can give additional information.

The transformation from raw sensor values to useful virtual sensors creates the information needed by decision makers. In automated systems, knowledge of the levees is to be valued. Sensors alone do not provide a complete picture of the stability status of a levee.

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