Robust monitoring

- 2009.02.01.1 Added value of sensor streams in dike monitoring systems

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Document Management

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Management summary

In the FC2015 project “Robust Monitoring” sensor values from various sensors in real levees are coupled to models on dike stability. This is illustrated with two cases: IJkdijk and LiveDijk.

A wide variety parameters is measured by sensors in and on levees. These include water tensions, temperatures, tilt, strain, self potential, acceleration, heat and hydraulic heads. There are a limited number of (validated) models on dike stability, e.g. Mstab for macro stability and Mpiping for piping. These models have been adjusted to cope with real time sensor data. The water tensions are used in the model calculations in the module of FEWS-DAM.

For the parameters other than water tensions, there are no models available which link the measured parameter to dike stability. A simple virtual sensor was constructed based on the difference in average values between two time windows. A large difference is considered to be an indication of changes in the levee which might be related to the stability.

The IJkdijk case is representative of a crisis situation. During the controlled experiment failure of the levee was achieved. The water tensions were converted to pipe lengths by the adjusted model FEWS-DAM. Also, temperatures and tilt angles were monitored real time and linked to the simple average-difference model. The virtual sensor could be linked to events reported in the logbook of the experiment.

The LiveDijk Eemshaven case is representative of an operational levee. Sensors were installed to monitor the levee during at least two years in order to get a better understanding of the normal behavior of levees. The real time measured water tensions were converted by the adjusted FEWS-DAM to safety factors. The LiveDijk Eemshaven levee is stable, as expected. For this levee, temperatures and accelerations were monitored as well using the simple average-difference model. Virtual sensor values hardly vary, which is to be expected of a stable levee.

For future work, new models need to be constructed to link the various parameters to dike stability. Also, new and existing models have to be able to cope with anomalous sensor readings without giving erroneous values for the virtual sensors. Finally, a combination of different types of sensors will improve the robustness of a flood control system.

1 Introduction

This deliverable, which is part of the project “Robust monitoring”, describes the added value of sensor streams and sensor data with respect to the current standard in dike monitoring. Until recently, dike monitoring usually consists of visual inspection. During the last years, several experiments with dike sensors systems were performed. This deliverable is called “*Inzicht meerwaarde sensorstreams ten opzichte van de huidige situatie*” in de FloodControl project plan Tranche 2009.

In this document the use of sensor data in combination with adjusted models is evaluated. The sensor streams of two real dikes where used for this: the piping experiments of the IJkdijk (Nieuweschans, the Netherlands) and the LiveDijk location at the Eemshaven (Delftzijl, the Netherlands).

The aim of this part of the project “Robust monitoring” is threefold:

1. To investigate the added value of using several types of sensor data.
2. To investigate which models for dike stability are available that can be adjusted to cope with sensor data.
3. To design virtual sensors based on the different roles and users of information in the water safety chain.

2 Approach

In order to design a flood control system that meets the requirements of the end users, the information needs of various end users are investigated (§ 2.1). The combination of raw sensor data and models can provide that information (§ 2.3). Therefore, the available sensors in dikes and models on dike stability are investigated (§ 2.2 and 2.4). In order to make these models suitable for incorporation in the flood control system, they have to be fast enough for real time processing and able to cope with sensor input as a substitute for expert knowledge.

2.1 Information needs

In the water safety management chain in the Netherlands, several roles among various organizations have different information needs. The roles and users of information are depicted in Figure 2-1 and Figure 2-2. The focus of this document is on the red boxes in the figures. The view on the FCS of a specific user depends on his role. Two different users can get information from the same model, but the results can be presented and visualized in two different ways. Another possibility is that the underlying models are different as well.

For instance, a dike manager (*dijkbeheerder*) needs far more detailed information from a location than a dike grave (*dijkgraaf*) during daily operation. In case of an emergency, the information needs change again. The roles and information needs are described in more detail in FC2015 report “Visualisation of levee quality based on sensor data” (2009.02.02.1).

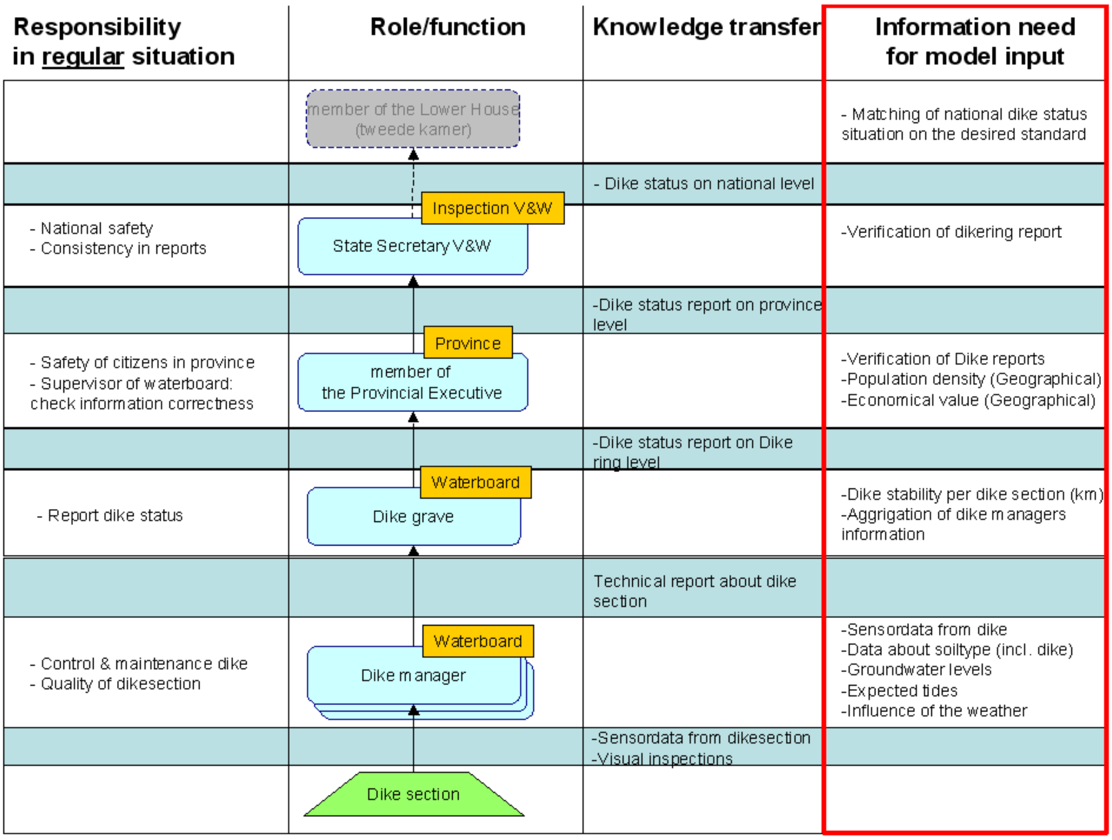


Figure 2-1: Information needs, roles and levels in normal maintenance situation.

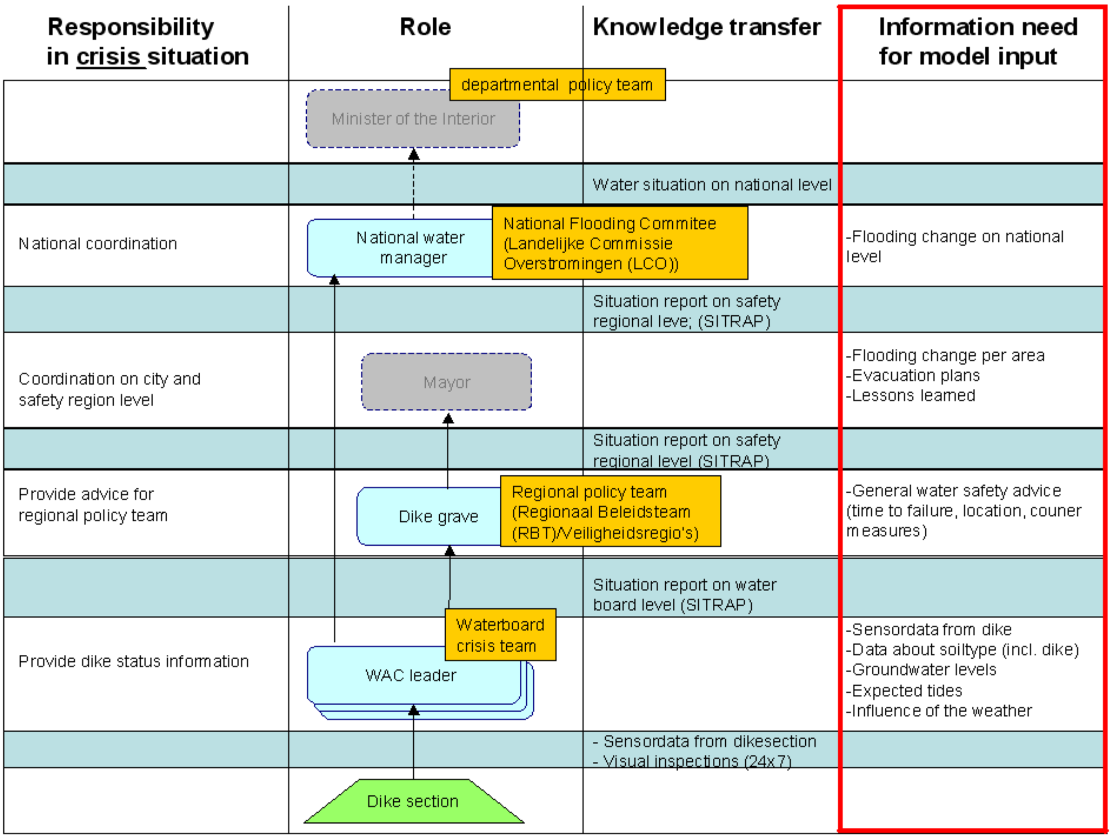


Figure 2-2: Information needs, roles and levels in a crisis situation

2.2 Available sensors

Several levees in the Netherlands are equipped with sensors. Among them are the (artificial) IJkdijk for the piping (and other) experiments at Nieuweschans and the LiveDijk at the Eemshaven, both in the northern part of the Netherlands. The instruments in these levees are summarized in Table 2-1 and Table 2-2.

Table 2-1: Sensors in LiveDijk Eemshaven

Party	Sensor	Parameter	Unit
Alert Solutions	GeoBeads	Temperature	°C
		Inclination	degrees
		Water tension	mbar
GTC Kappelmeyer	Optic fiber cable	Temperature	°C

Table 2-2: Sensors in IJkdijk piping experiment

Party	Sensor	Parameter	Unit	Experiment			
				1	2	3	4
Intech	Infrared camera	Heat		x	x	x	x
ITC	?	Self potential	V		x	x	x
Fugro	?	Self potential	V				x
2M	?	Electromagnetic conductivity	S/m				x
Deltares	Water tension meter	Water tension	kPa	x	x	x	x
	Piezometers	Hydraulic head	kPa	x	x	x	x
		Temperature	°C	x	x	x	x
Dike Survey	Optic fiber cable	Movement	Mm	x			x
Alert Solutions	GeoBeads	Temperature	°C	x			x
		Water pressure	kPa	x			x
		Tilt angle	Degrees	x			x
Inventec - Ten Cate	Optic fiber cable	Temperature	°C	x	x	x	x
GTC Kappelmeyer	Optic fiber cable	Temperature	°C	x			x
Landustrie	Flow sensor	Water flow	M^3/hour	x	x	x	x
TNO	Weather station	Radiation (average, maximum, minimum)	W/m^2	x	x	x	x
		Wind speed average (m/s)	m/s	x	x	x	x
		Wind direction (degrees)	degrees	x	x	x	x
		Wind gust maximum (m/s)	m/s	x	x	x	x
		Temperature (average, maximum, minimum)	°C	x	x	x	x
		Humidity (average, maximum, minimum)	%	x	x	x	x
		Rainfall total (mm)	mm	x	x	x	x
	Luisterbuis	Acoustic signal		x			x
		Temperature	°C	x			x
		Water pressure	kPa	x			x

2.3 Virtual sensors

In order to make the raw sensor data useful for end users, the raw data has to be converted. The result of the conversion is in fact a new – virtual – sensor. A virtual sensor is a value of a relevant parameter which has not been measured as such by a sensor, but is derived from a (combination of) sensor reading(s) after data processing[fc09b]. This data processing is called “link to model”. Different types of virtual sensors are:

- Processing of measured sensor data by filtering, subsequent input for modeling and model output. The model output can be regarded and visualized as a virtual sensor.

- Prediction: link of sensor data, predicted water discharge and rainfall in model can give prediction of dike stability for next 24 hours.
- Interpretation/expert judgments: numerical processing, rule of thumb or complex interpretation is linked to sensor data or model result. This step is needed for the end user.
- Visualization: to make the result visually appealing, the result is shown on a color scale linked to ‘warning levels’. The visualization is depicted as a virtual sensor.

Based on a selection of sensors from the IJkdijk and LiveDijk, a number of virtual sensors are defined in the cases. These are described in § 3.2 and § 4.2.

2.4 Available models

Failure of levees can occur through a number of mechanisms, such as overtopping, macro-stability, micro-stability, instability of levee cover, instability of foreland, piping and heave. Only for a limited number of these failure mechanisms validated models are available.

For the failure mechanisms of macro-stability and piping, the models which predict dike stability are mature. These models were used in the Dijksterkte Analyse Module (DAM) developed in 2008 by Deltares [kno08a]. The underlying models are Mstab and Mpiping. These models use a geometry and several geotechnical parameters of the levee and a freatic water line or the difference in water pressure at both sides of the levee as input parameters for dike stability calculations. In Mstab and Mpiping, the output of the model is a safety factor or a piping factor respectively. In DAM the result of the calculation is coupled to alert levels with a traffic-light code. An example of the traffic-light for the stability factor (macro-stability) is [kno08b]:

- Green, value > 1.17: dike stability sufficient.
- Yellow, value between 1 and 1.17: dike stability does not conform to norm.
- Orange, value between 0.85 and 1: dike stability severely decreased, awareness for possible crisis.
- Red, value below 0.85: dike stability insufficient, intermittent danger of failure, crisis.

An example of the traffic-light for the piping factor (piping) is [kno08c]:

- Green, piping factor > 3: dike stability sufficient.
- Yellow: piping factor between 1.5 and 3: dike stability does not conform to norm.
- Orange: piping factor between 1-1.5: dike stability severely decreased, awareness for possible crisis.
- Red: piping factor between 0 and 1: dike stability insufficient, intermittent danger of failure, crisis.

The available models have been adjusted to be able to cope with real time sensor data. The software DAM which was developed in 2008 had a long computation time. For real time data, fast answers are needed. Therefore, the kernel of the DAM software was improved in project FC2015 2009-05 [fc09f]. In effect, it is now fast enough to consider it (almost) real-time. A computation on the stability of a dike of considerable length now takes 15 minutes, instead of one day.

Furthermore, three adjustments were made in order to incorporate sensor data:

1. For macro-stability in Mstab: instead of theoretical freatic lines based on expert knowledge, the measured water tensions were used to calculate the freatic line. Based on the freatic line derived from water tension sensors, the stability of the levee with respect to macro-stability is calculated.
2. For piping: the length of pipes is derived from the measured pattern of the water tensions. This length can be compared to the one calculated using Sellmeyer’s rule [fc09f], which is based on the water level difference on both sides of the levee.
3. The module of DAM is coupled to FEWS to FEWS-DAM. FEWS is a Flood Early Warning System, which is developed by Deltares. In FEWS, sensor data can automatically imported, model calculations and predictions can be made and visualized and output can be generated. In FEWS-DAM, FEWS is the platform for data import and output and visualization. DAM is the module which performs the model calculations on dike stability.

Based on the IJkdijk experiment, the model which predicts failure by piping will be improved. In the current project, we used the latest available state-of-the-art model.

The sensors in the levees measure a wide variety of parameters. However, for a number of measured sensor data, the corresponding models which predict dike stability are not developed yet. For example, in the macro-stability experiment at the IJkdijk location of 2008, temperature and electrical conductivity were measured. Changes in these parameters were observed during the experiment, but models which link these changes to stability of the dike are not yet made. For these sensor parameters, new models need to be designed. For now, changes from trends can be regarded as an indication of changes in the stability of the levee. For data import and output and calculation of averages of sensor values, a FEWS configuration is set up. For next year, a more advanced analysis of the new types of parameters will be performed.

3 Case Emergency situation - IJkdijk

3.1 Description of case

The case of the piping experiment IJkdijk corresponds to scenario 2 in FC2015 report 2009.02.02.1 [fc09a]. In the piping experiment the levee is forced to fail by the failure mechanism of piping under controlled conditions. It therefore contains all phases of alert during an emergency situation.

Near Nieuweschans in the northern part of the Netherlands, a full scale levee test location is situated. In 2008, a macro-stability experiment was performed. In this experiment a full scale levee was constructed and forced to fail under controlled conditions by the mechanism of macro-stability. The levee was prepared with several types of sensors from 13 different companies. In this experiment it was demonstrated that sensor information provides a valuable contribution in the assessment of levee stability, in addition to the usually performed visual inspection.

In the fall of 2009, a new experiment was planned. In this experiment, the failure mechanism of piping was investigated as part of the Rijkswaterstaat research program SBW, Revalidation Piping and part of the FC2015 program [fc09c-e]. Again, the levee was equipped with a number of sensors. At the test location, four individual experiments were performed. These experiments were designed to be performed twice and with more (experiment 1 and 4) or less (experiment 2 and 3) expected influence of the sensors on the formation of pipes. In Table 3-1, the experiments at the IJkdijk location are summarized. For the Robust Monitoring project, we concentrated on experiments 1 en 4.

Table 3-1: Piping experiments at test location IJkdijk

Experiment	Start	Failure	Number of sensors
1	29 September 2009	3 October 2009 16:20h	Many
2	19 October 2009	25 October 2009 11:00h	Few
3	11 November 2009	14 November 2009 6:35h	Few
4	30 November 2009	5 December 2009 16:24h	Many

3.2 Models used emergency situation

The models used in the emergency case are shown in Table 3-2. Based on the available models for piping in relation to the sensor parameters (§ 2.4), FEWS-DAM is implemented as the basic model in the IJkdijk experiments. This is a validated model, which is being improved during and after the experiments.

In order to simulate information streams from different levee sections, the WAC leader receives information from different types of sensors.

In order to simulate different roles and information needs, based on Figure 2-1, the WAC-leader receives information from different types of sensors. In addition to the converted water tension readings (resulting in pipe lengths), deviations from average behavior for temperature and orientation of GeoBeads are also provided. The sensor data were converted to the following virtual sensors:

1. The water tensions were converted to pipe lengths by FEWS-DAM.

2. The temperature was converted to average temperature. The virtual sensor is the difference in average temperature between the time window of the last 2 hours and the time window of 2 to 4 hours before the last measurement.
3. The three angles measured by the inclinometer were combined to a total angle. The virtual sensor is the difference in average total angle between the time window of the last 2 hours and the time window of 2 to 4 hours before the last measurement.

The last two virtual sensors are not based on validated models. When the difference is larger than a certain level, it is considered to be an indication of some processes in the levee which are possibly linked to the stability of that levee.

The sensors, models and virtual sensors for different roles are schematized in Table 3-2. The italic entries are included in the prototype of the FCS.

Table 3-2: Inputs and outputs on different levels, crisis situation

Role - level	Input	Model	Model description	Output /virtual sensor
WAC leader	*Schematic composition of dike* *Surface line* *Water tensions from sensors*	*Validated*	*FEWS-DAM, based on Mpiping and Sellmeyer*	*Pipe length on individual locations*
	Temperature of GeoBead	*Simple*	*Deviation of current value from running average*	*Difference between average values between two time windows for each sensor*
	Angles of GeoBead	*Simple*	*Deviation of current value from running average*	*Difference between average values between two time windows for each sensor*
Dike grave	Pipe length on individual locations	Simple	Aggregation into dike sections and coordinate of problem	Locations of critical pipe lengths
	Location of problem	Advanced	Predictions on flood areas and evacuation times	Map of problem area, evacuation times
	Location of problem	Simple	Link to existing emergency counter measures plans	Counter measures
National water manager	Output of dike grave	Advanced	Aggregation of various problem areas and definitions of priorities	National overview of problem areas with counter measures and evacuation times

3.3 Experiments

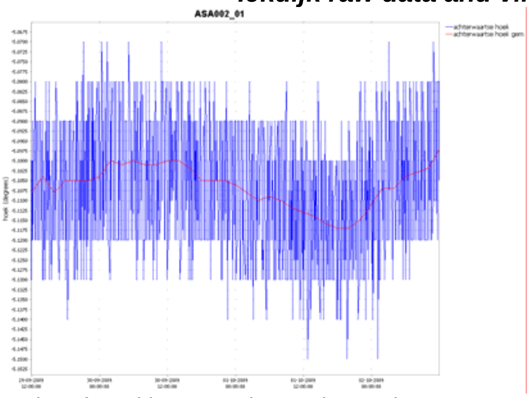
During the first experiment, a first version of the FEWS-DAM configuration was running on a laptop at the IJkdijk location. However, the module did not function properly and needed to be improved for the next experiments.

During the second and third experiment, FEWS-DAM was running and calculating pipe lengths based on water tension readings from the sensors. FEWS-DAM was linked to AnySense Connect for data input (water tensions from sensors) and data output (pipe lengths). Anysense Connect was connected to the FCS at IBM. The results are visualized in the FCS [fc09a]. The results were not always reliable, because several sensors did not function properly during (part of) the experiment. Their values were included in the model nonetheless, resulting in unrealistic pipe lengths. The malfunctioning sensors need to be removes manually from the FEWS-DAM configuration in order to give sensible results. The model is not (yet) able to recognize incorrect values. In this sense it is not robust.

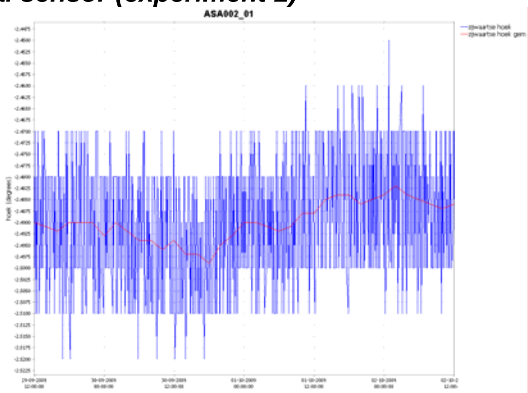
During the fourth experiment, FEWS-DAM was not used. The operators at the levees needed to focus all their attention to the experiment in order to make it successful. They did not have time to install and maintain the FEWS-DAM configuration during this experiment.

The second stream of sensor data was implemented in a separate FEWS configuration. For these sensors, temperature and tilt (angles) from the GeoBeads were selected. In Figure 3-1 an example of the raw data, the averaged data and the virtual sensor are visualized for one sensor (ASA002_01, angles from GeoBeads) during experiment 1.

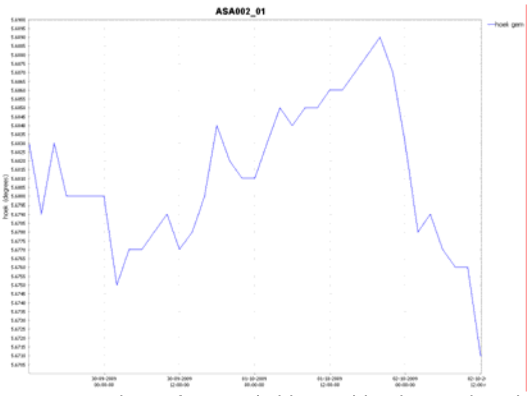
IJkdijk raw data and virtual sensor (experiment 1)



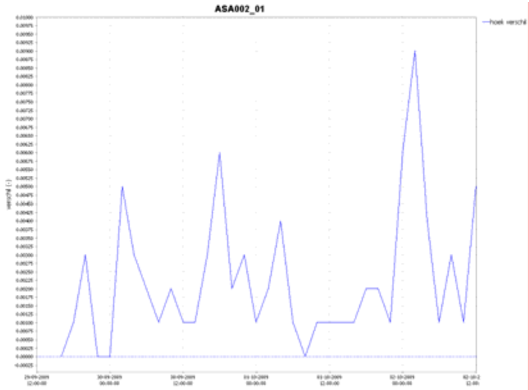
Angle to front: blue = raw data, red = running average over 2 hours



Angle to side: blue = raw data, red = running average over 2 hours



Average angles to front and side combined to total angle



Virtual sensor: difference in total angle between two time windows

Figure 3-1: Example of raw sensor data and construction of virtual sensor. Horizontal axis is date and time, vertical axis is angle in degrees.

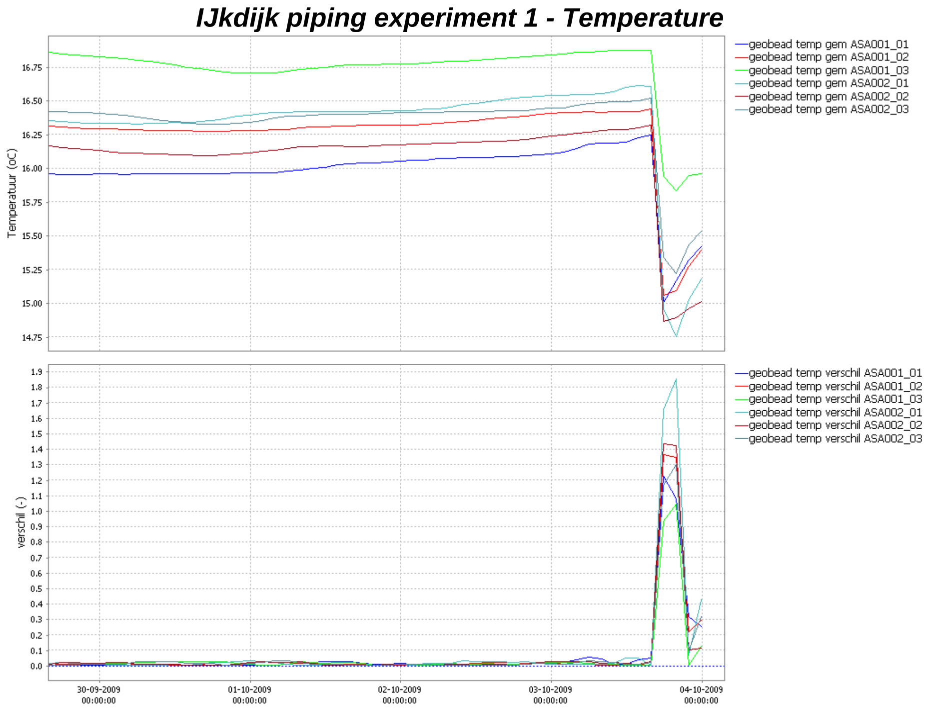
3.4 Analysis of case IJkdijk

3.4.1 Experiment 1

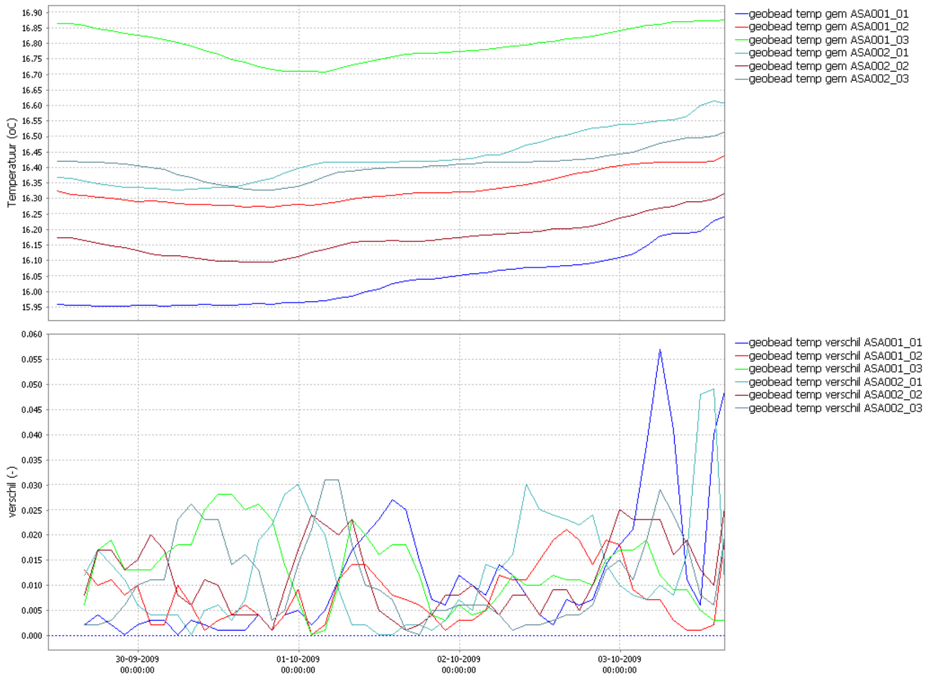
In this paragraph, a global overview of the case IJkdijk, experiment 1 is given. A full description of the experiment and the results from the reference measurements performed by Deltares is given in [fc09 d and e]. Here, the sensor values are coupled to events that reported in the logbook of the experiment.

The experiment started at Monday 29 September 2009 at 12:00 h. The water level was increased in steps of approximately 10 cm. At a water level of 0.52 m, the first well appeared on 29 September at 17:21. When the water level was 1.99 m, the first wells which transported sand appeared (30 September, 13:41h). A few hours later, the sand transport starts in another well. This sand transport is still discontinuous. At 19:00h, a new phase starts where sand is transported continuously though several wells with a water level of 2.29. During the next days several wells appear and disappear again. On 3 October at 7:00 a well appears on the position of the later breach. At that moment, the water level was at 2.67m for some time. From 10:30h onwards, the flow through the wells increases. At 14:00h the water becomes colder. At 16:20 the levee failed.

During experiment 1, the FEWS-DAM module was not functioning properly. Therefore, the virtual sensor values of pipe lengths derived from water tensions are not included. The temperature and angles are shown in Figure 3-2 and Figure 3-3 for 6 sensors which were located close to the breach. At the breach location, no sensor was present. From the top panels it is clear that the sensors registered the levee breach. The differences in temperature prior to the breach can be linked to events in the logbook. For example, on 30 September a well appeared close to sensor AS002_03, which started transporting sand and later on transported only water and disappeared again. This can be linked to differences in the temperature. Some time closer to the breach time, several sensors give indications of changes: when the well appeared at the breach location at 3 October 7:00h, the sensor nearest to it (AS001_01) already registered differences in temperature for some hours. When the water though the well became colder (felt by hand), there was another peak in temperature measured by the sensor. The total tilt angle appears to be less sensitive. However, there is a difference in total angle from about 12:00h, so about 4 hours before the breach. In a more advanced analysis, alert levels can be determined.



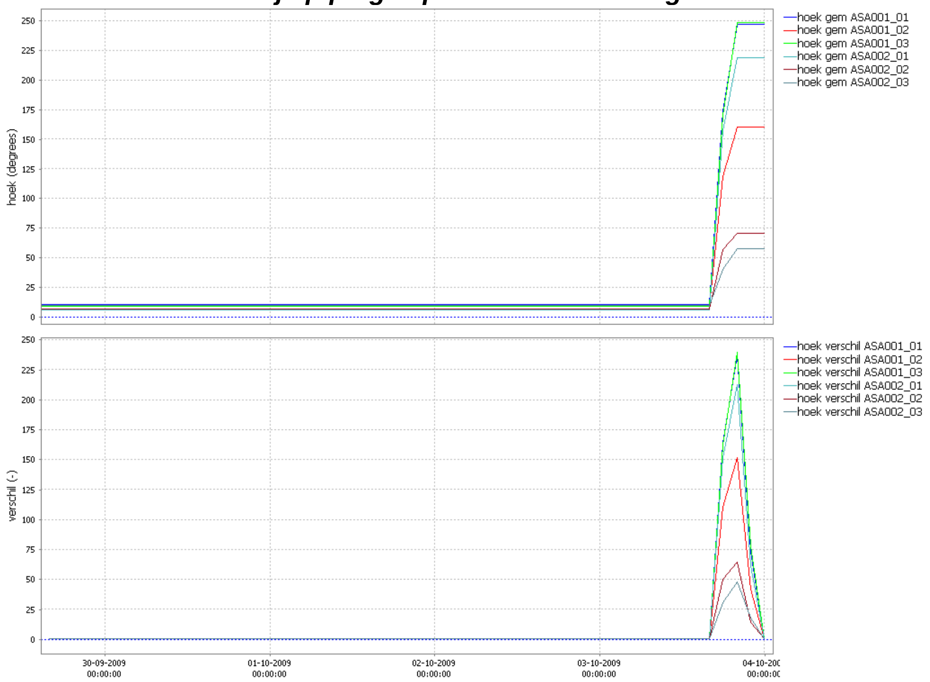
Temperature (top) and difference in temperature (bottom) including breach



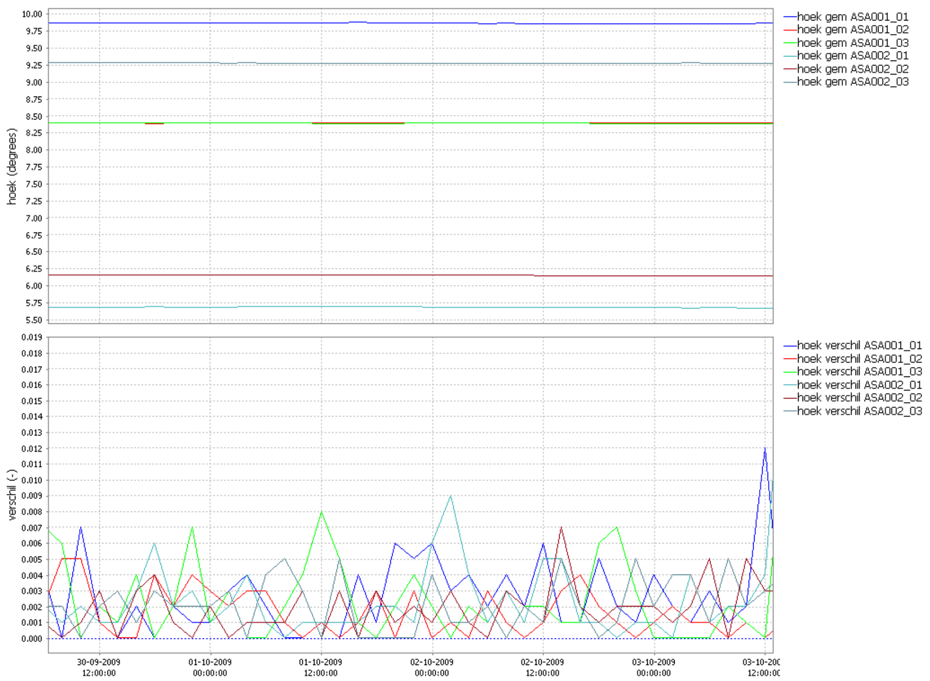
Temperature (top) and difference in temperature (bottom) prior to breach

Figure 3-2: Sensor data and virtual sensors (near breach location) for temperature derived from GeoBeads. Top panel shows data including the breach and bottom panel shows the data before the breach. Period: from 29 September to 3 October 2009.

IJkdijk piping experiment 1 – Tilt angle



Total angle (top) and difference in total angle (bottom) including breach



Total angle (top) and difference in total angle (bottom) prior to breach

Figure 3-3: Sensor data and virtual sensors (near breach location) for tilt angle derived from GeoBeads. Top panel shows data including the breach and bottom panel shows the data before the breach. Period: from 29 September to 3 October 2009.

3.4.2 Experiment 3

In this paragraph, a global overview of the case IJkdijk, experiment 3 is given. A full description of the experiment and the results from the reference measurements performed by Deltares is given in [fc09c and e]. Here, the sensor values are coupled to events that reported in the logbook of the experiment.

The start of the experiment was on Monday 9 November at 15:00h. The water level was increased in steps of approximately 10 cm. At a water level of 1.50 m on 10 November at 15:25h the first wells appear. These are not continuous and no sand is transported. The first sand transporting wells are observed on 11 November at 9:20h at a water level of 2.10 m. From then on several wells appeared and disappeared. At some locations the pipes retreated. On 14 November at 5:50h the sand transport of a particular well suddenly increased. The water level was increased to 2.30 m. One of the wells started to transport clay instead of sand. Approximately 20 minutes later the levee failed

During experiment 3, FEWS-DAM was functioning properly. Apart from the reference water tension sensors there were only a limited number of sensors available during this experiment. The GeoBeads from Alert Solutions were not included. Therefore, in this section only the water tensions and pipe lengths from FEWS-DAM are presented.

In Figure 3-4 the water tensions are shown for part of a line of water tension sensors. These readings were combined to calculate a pipe length in FEWS-DAM. From Figure 3-4 it is clear that some sensors (in this case sensor 7.5/63.3) give jumpy readings. The virtual sensors of pipe length, calculated from lines of water tension sensors is shown in Figure 3-5. Because of the jumpiness of some sensor readings, the calculated pipe length also looks jumpy. The results are not always realistic, because of (temporary) malfunctioning of several sensors. The model is not yet robust in the sense that it does not recognize erratic values.

During the experiments, the operators derived the fall of the water line in the levee from the water tensions. They discarded erratic readings by hand. Several episodes of rise and fall in the water line were linked to the presence of wells and the stage of piping. The last increase in water tension before failure started at 4:00h, failure followed at 6:36 h. Because of the noisy behavior of the virtual sensor of pipe length, we were not able to link the episodes to the virtual sensor. In order to do so, the model needs adjustment by automatic discarding, smoothing or filtering of the raw data.

IJkdijk piping experiment 3 – Raw data: water pressures

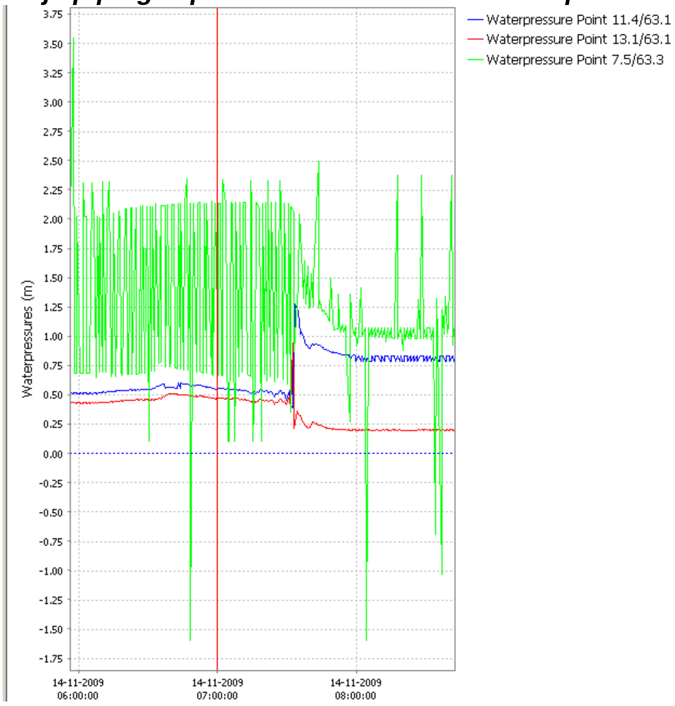


Figure 3-4: Sensor data for water pressures measured in experiment 3, for three sensors at the side of the levee. Period: 14 November 2009 from 6:00 to 8:40h.

IJkdijk piping experiment 3 – Virtual sensor: Pipe lengths

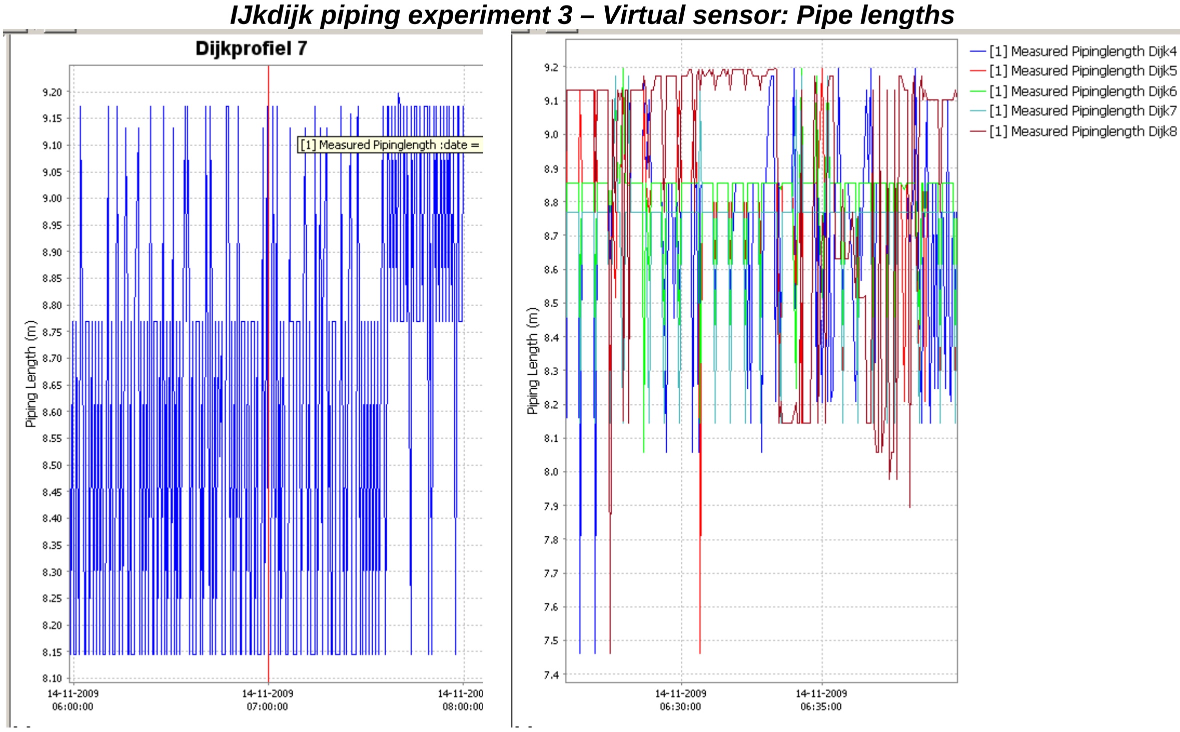


Figure 3-5: Virtual sensors (pipe length) derived from the water tensions measured in experiment 3. Left: for one profile (corresponding to Figure 3-4) Period: 14 November 2009 from 6:00 to 8:40h. Right: for several profiles, for a time interval of several minutes around the breach at 6:36h on 14 November 2009.

4 Case Operational levee – LiveDijk Eemshaven

4.1 Description of case

The case of the LiveDijk Eemshaven corresponds to scenario 1 in FC2015 report 2009.02.02.1 [fc09a]. In 2009, the consortium of Stichting IJkdijk, Water Board Noorderzijlvest and STOWA has equipped an operational levee with sensors. This "LiveDijk" is situated at the Eemshaven and consists of a section of 600 m of a sea dike. This dike does not form part of the direct sea barrier, but is still in contact with the sea. Therefore, it provides a realistic test site. Water Board Noorderzijlvest has made the dike available for the test.

A full description of the levee and its sensors can be found in [liv09]. The sensor system of Alert Solutions (GeoBeads) and optical fiber cables of GTC Kappelmeyer were installed in September 2009. Four lines of Geobeads were installed. The cross-sections are shown in Figure 4-1. The optical fiber is situated parallel to the levee and makes a loop at each GeoBead line to approximately 6 m below the surface of the levee (at red dot in Figure 4-1).

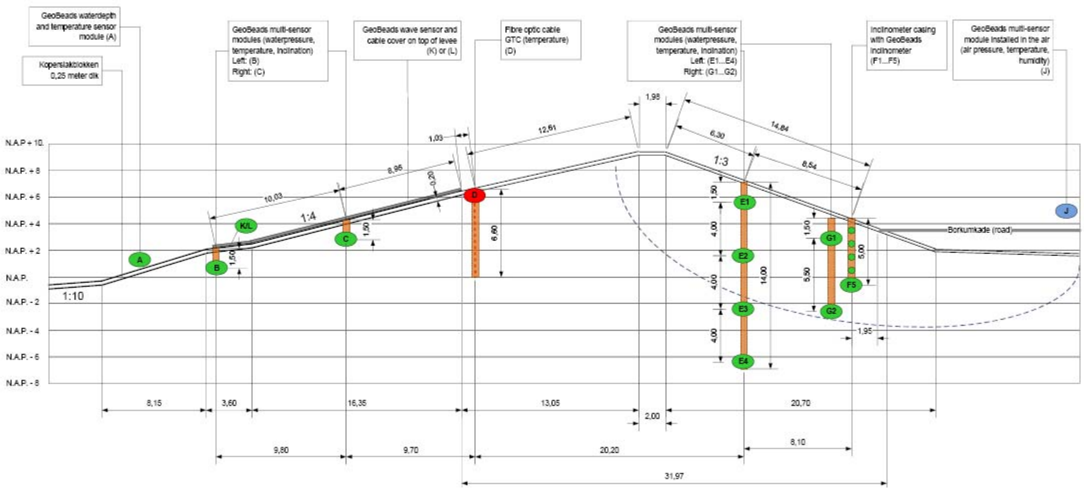


Figure 4-1: Cross section Geobead sensors in LiveDijk Eemshaven.

On 15 October 2009, the sensor system started operation officially. The system will operate for at least two years. This period is sufficiently long to study the normal behavior of the levee, e.g. in relation to heavy winter storms or quiet summer weather. During the project Robust Monitoring, however, sensor data were collected for only a couple of weeks. Still, the case represents an operational levee.

4.2 Models used for operational levee

For the LiveDijk Eemshaven, a validated model for macro-stability is available. For this failure mechanism, the newly developed FEWS-DAM is used. This model was adjusted for usage of real time sensor data.

In order to simulate different roles and information needs, based on Figure 2-1, a selection of additional sensor data was incorporated as well. These were based on the temperature and accelerations which was measured by Geobeads. The sensor data were converted to the following virtual sensors:

1. The water tensions were converted to safety factors. This conversion is based on a validated model (Mstab).
2. The temperature was converted to average temperature. The virtual sensor is the difference in average temperature between the time window of the last 2 hours and the time window of 2 to 4 hours before the last measurement.
3. The accelerations in three perpendicular directions (x, y and z). The virtual sensors are the differences in average acceleration, for each direction.

The last two virtual sensors are not based on validated models. When the difference is larger than a certain level, it is an indication of some processes in the levee which are possibly linked to the stability of that levee.

Although visual inspection is currently a very important information source for the determination of the stability of the levee, we did not incorporate this type of information other than insert an example of an inspection report to the FCS. No model is attached to the visual inspection and no virtual sensor is derived from it.

The sensors, models and virtual sensors for different roles are schematized in Table 4-1. The italic entries are included in the prototype of the FCS.

To simulate the case of more than one dike manager for one dike grave, the various sensor outputs are divided into two dike managers.

Monitoring of this dike will not be very exciting, since this dike is meant to be stable. The exceeding of warning levels can be triggered by an additional artificial model, based on one of the sensor outputs. This artificial model is then only visible in the lowest level (of the dike manager) with a very low reliability. One level higher, it can show up with an indicator of “overruled by expert”. One level higher, it does not show up at all.

Table 4-1: Inputs and outputs on different levels, normal situation

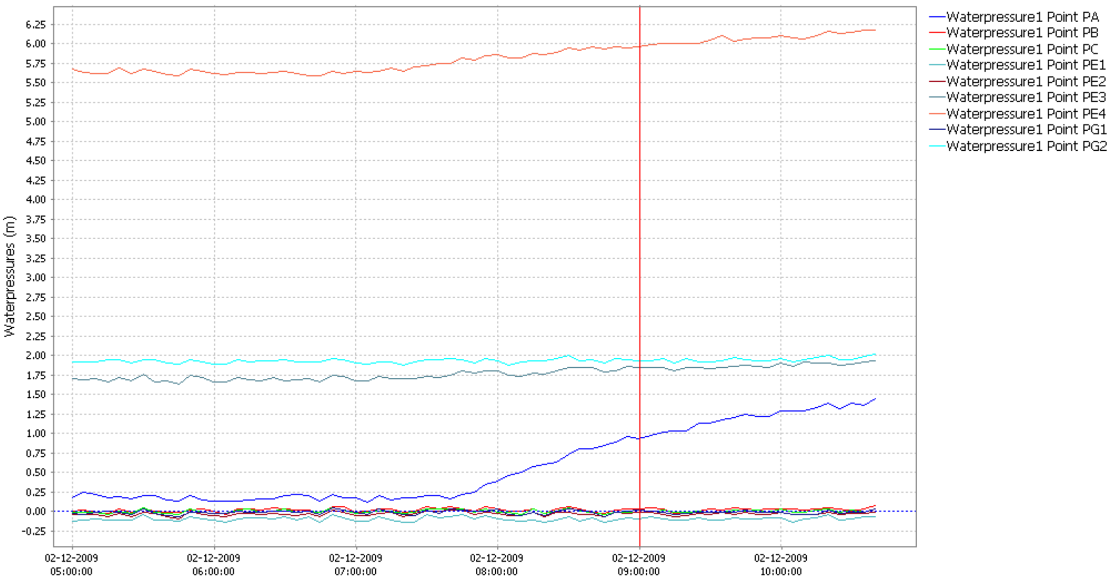
Role – level	Input	Model	Model description	Output / virtual sensor
Dike manager 1	*Schematic composition of dike* *Surface line* *Freatic groundwater level (from water tensions, sensor data)*	*Validated*	*FEWS-DAM, based on Mstab*	*Stability factor for each cross section of sensors*
Dike manager 2	*Temperature of GeoBead*	*Simple*	*Deviation of current value from running average*	*Difference between average values between two time windows for each sensor*
	Acceleration x, y and z of GeoBead	*Simple*	*Deviation of current value from running average*	*Difference between average values between two time windows for each sensor*
Dike manager 3	Visual inspection	-	-	-
Dike grave	Stability factors and other "failure parameters" of all dikes	Simple	Combine algorithm 1: On overlapping sections: weighing of judgments of various dike managers (e.g. 50-50% or 40-40-20%) for each location. Combine algorithm 2: E.g. worst aggregated answer determines answer of the entire section.	Aggregated dike stability for each section, stating "voldoet aan norm" (sufficient), "voldoet niet aan norm" (insufficient) or "geen oordeel" (no judgment). Percentage of length of sections which have sufficient dike stability ("voldoet aan norm").
Member of the Provincial Executive	Output of Dirctor of Water board	Simple	Combine algorithm 3: aggregation of dike sections to dike ring areas	Aggregated dike stability on dike ring areas. Percentage of length of sections which have sufficient dike stability ("voldoet aan norm").
State Secretary V&W	Aggregated dike stability on dike ring areas	Simple	Combine algorithm 4: combine information from all dike rings to national overview	National overview of dike stability. Percentage of length of sections which have sufficient dike stability ("voldoet aan norm").

4.3 Analysis of case

Two sets of data and virtual sensors are made for the LiveDijk. The first virtual sensor is the safety factor from FEWS-DAM based on the water tensions. This is a validated model. The second set consists of the simple model of deviations from the running average, for the temperature and the acceleration.

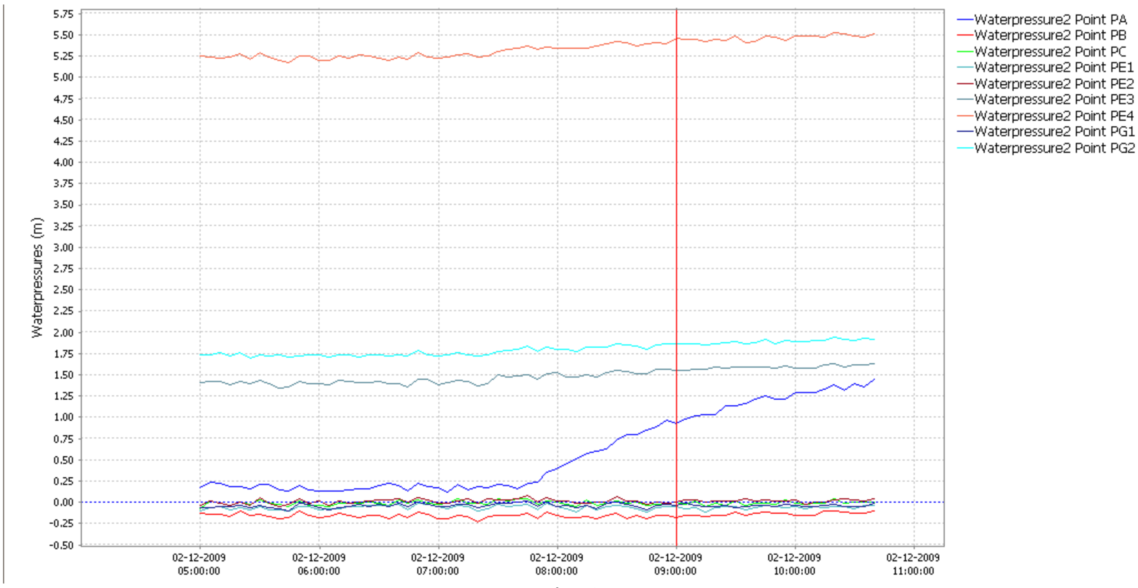
Examples of raw data for water tensions are given in Figure 4-2. In Figure 4-3, the virtual sensor safety factor is shown. In line 4, one of the sensors occasionally gives erroneous water tensions. These strange values are included in the model anyway, which results in safety factors which are not correct. At this stage, the model is not yet able to cope with anomalous readings. Therefore, in this sense the model is not robust. For the other lines, the calculated safety factors are rather constant and well above the critical alert level: the levee is stable.

LiveDijk Eemshaven – Raw data: water pressures

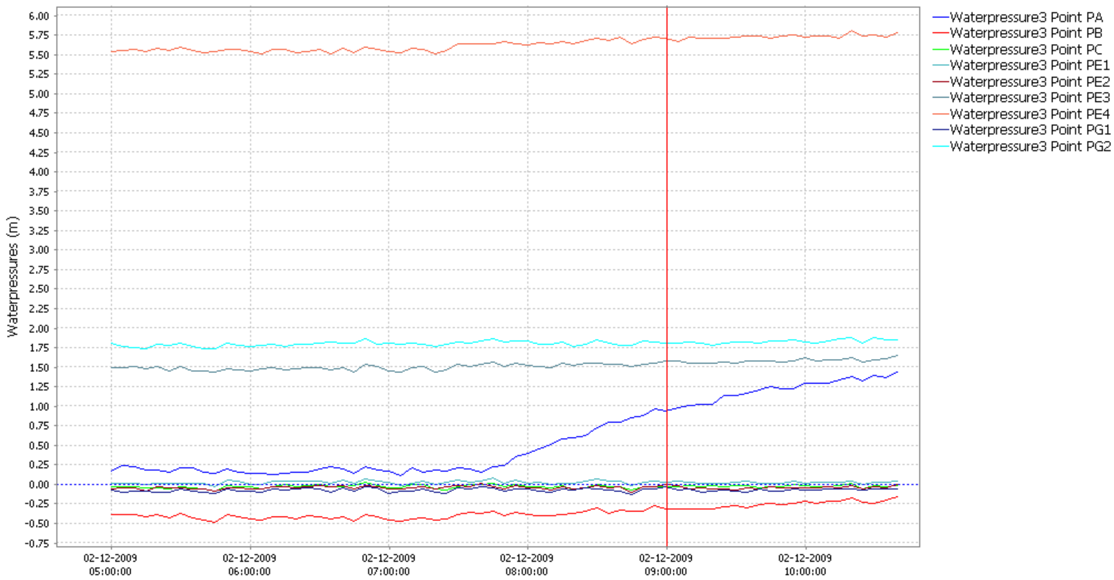


Line 1

Figure 4-2: Example of water tension sensor readings from LiveDijk Eemshaven. Period: 2 December 2009, from 5:00 to 12:00h.

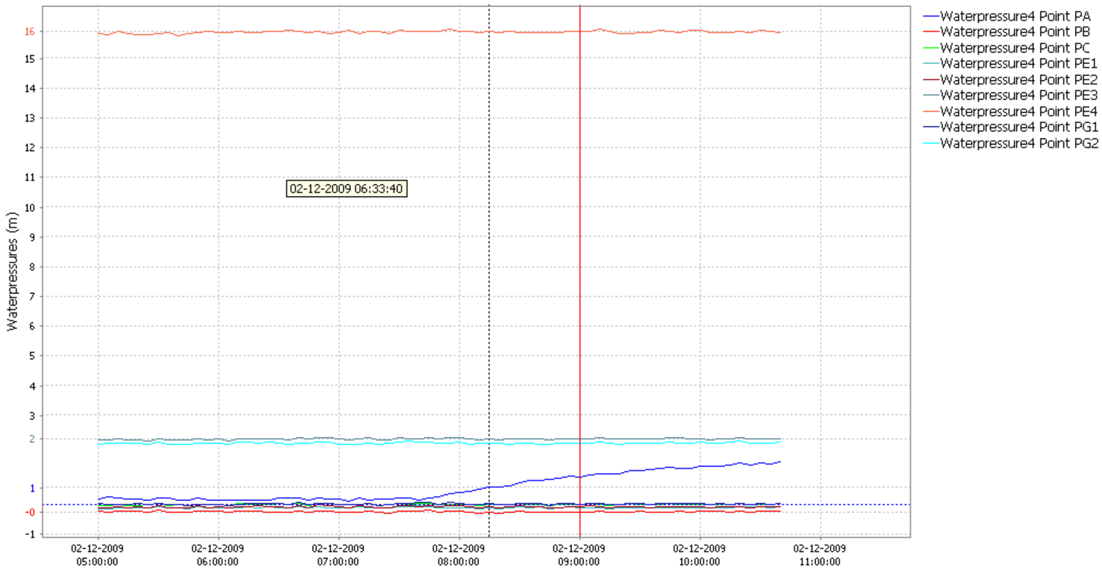


Line 2



Line 3

Figure 4 2, continued: Example of water tension sensor readings from LiveDijk Eemshaven. Period: 2 December 2009, from 5:00 to 12:00h.



Line 4 with erroneous reading (top red line)

Figure 4 2, continued: Example of water tension sensor readings from LiveDijk Eemshaven. Period: 2 December 2009, from 5:00 to 12:00h.

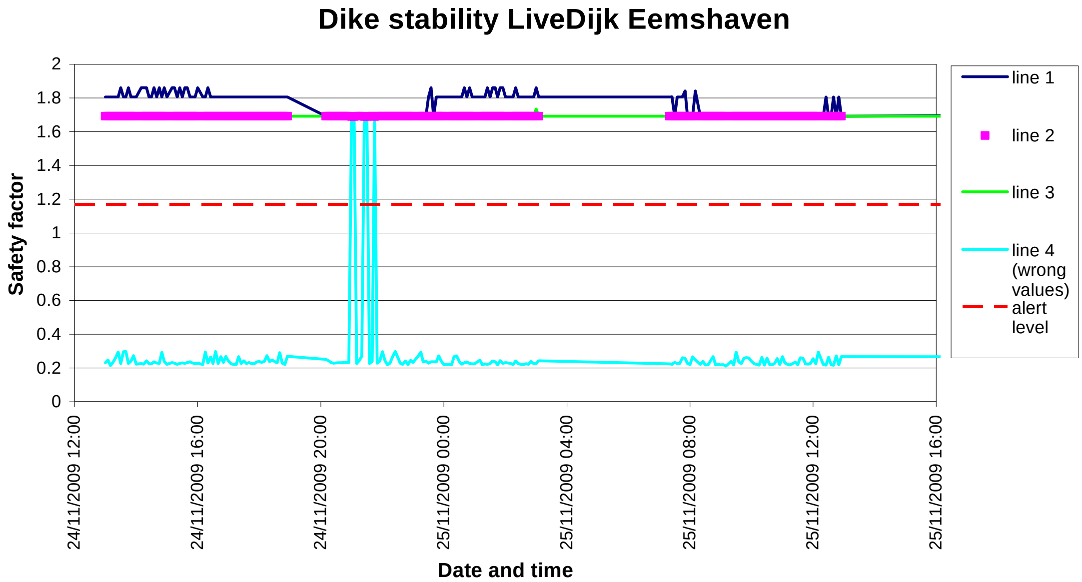


Figure 4-3: Virtual sensor safety factor for the LiveDijk Eemshaven, derived from water tension sensor readings and modeled by FEWS-DAM. Period: 24 November 2009 12:00h to 25 November 2009 16:00h.

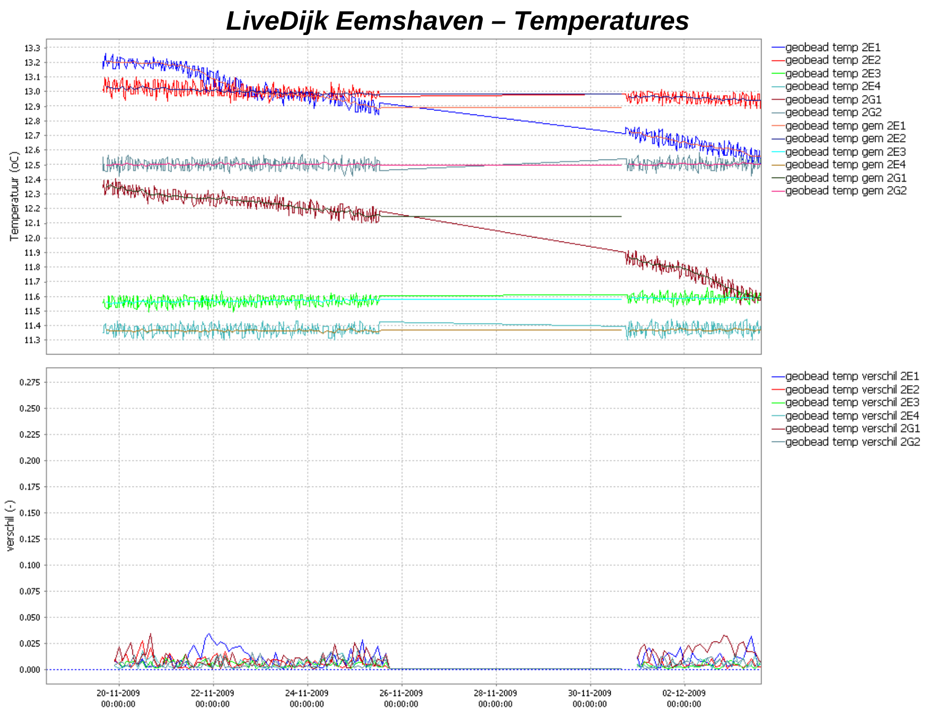


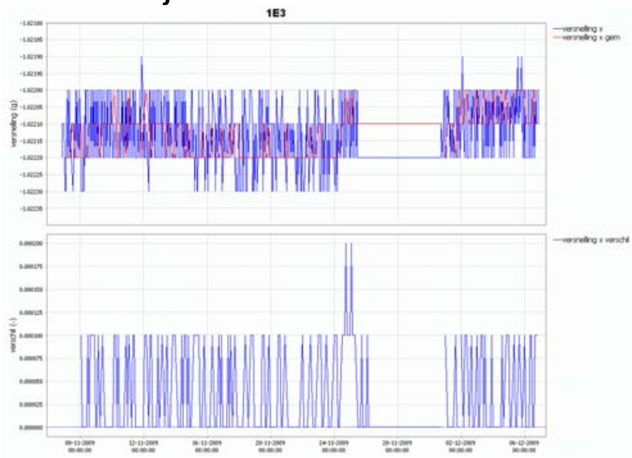
Figure 4-4: Example of sensor readings and virtual sensors based on temperature for the LiveDijk Eemshaven. Top panel shows raw data and running averages. Bottom panel shows the virtual sensor consisting of the difference in temperature between two time windows. Period: 20 November 2009 0:00h to 3 December 2009 0:00h.

In Figure 4-4 and Figure 4-5 examples of sensor readings from temperature and acceleration are shown for selected sensors. The general pattern is the same for all four lines. The virtual sensor consists of the difference between the average readings of two time windows.

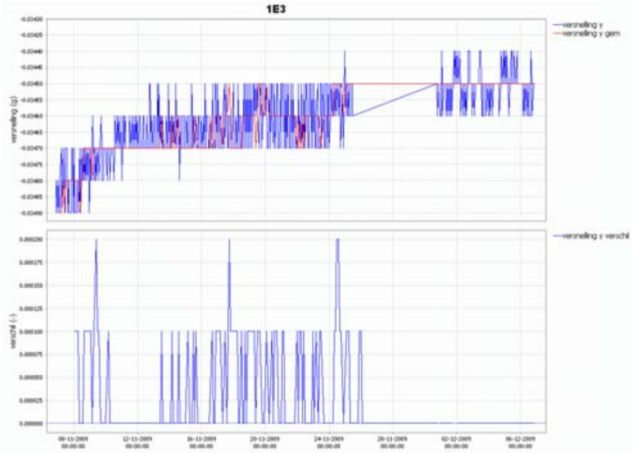
In Figure 4-4, the sensors which are placed close to the surface (blue and brown) show the seasonal decrease in temperature. The sensors deeper in the levee (> 6.6 m below the surface) show very constant values.

In Figure 4-5, the accelerations show very constant values. The jumpiness of the signal and of the derived virtual sensor is related to rounding errors. The sensor readings consist of integers, which are converted to accelerations in m/s by division by a factor.

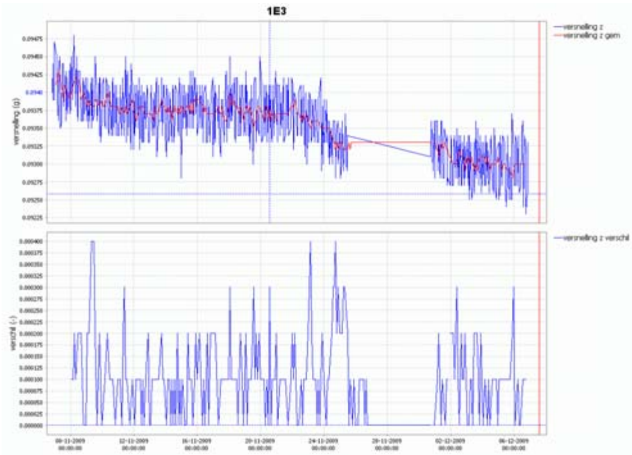
LiveDijk Eemshaven – Accelerations



Direction x



Direction y



Direction z

Figure 4-5: Example of sensor readings for 1E3 and virtual sensors based on accelerations in three perpendicular directions (x, y, z) for the LiveDijk Eemshaven. For each direction the top panels show raw data and running averages, the bottom panels show the virtual sensor consisting of the difference in acceleration between two time windows. Period: 8 November to 6 December 2009.

5 Conclusions

In the FC2015 project “Robust Monitoring” sensor values from various sensors in real levees are coupled to models on dike stability. This is illustrated with two cases: IJkdijk and LiveDijk.

A wide variety parameters is measured by sensors in and on levees. These include water tensions, temperatures, tilt, strain, self potential, acceleration, heat and hydraulic heads. There are a limited number of (validated) models on dike stability, e.g. Mstab for macro stability and Mpiping for piping. These models have been adjusted to cope with real time sensor data. The water tensions are used in the model calculations in the module of FEWS-DAM.

For the parameters other than water tensions, there are no models available which link the measured parameter to dike stability. Two sensors were selected for a simple analysis. The raw readings were converted to average values over a specified time window and a virtual sensor was constructed as the difference in average value between two time windows. A large difference is considered to be an indication of changes in the levee which might be related to the stability.

The IJkdijk case is representative of a crisis situation. During the controlled experiment failure of the levee was achieved. The water tensions were converted to pipe lengths by the adjusted model FEWS-DAM. Also, temperatures and tilt angles were monitored real time and linked to the simple average-difference model. The virtual sensor could be linked to events reported in the logbook of the experiment.

The LiveDijk Eemshaven case is representative of an operational levee. Sensors wer installed to monitor the levee during at least two years in order to get a better understanding of the normal behavior of levees. The real time measured water tensions were converted by the adjusted FEWS-DAM to safety factors. The LiveDijk Eemshaven levee is stable, as expected. For this levee, temperatures and tilt angles were monitored as well. Apart from the near surface temperatures, the raw data and derived virtual sensors give rather constant values. This is to be expected for a stable levee.

6 Recommendations

In several real levees, a variety of parameters are measured by various sensors. However, there are no models on dike stability for each of the measured parameters or for combinations of parameters. These models have to be developed in the future. Deep analysis of the IJkdijk experiments (2008 macro stability and 2009 piping) and the (forming) long-term data set of the LiveDijk should provide a better understanding of the failure mechanisms and of the suitability of various parameters for monitoring dike stability.

One requirement for new models is high speed. In order to monitor real time and also provide real time virtual sensors, the models need to give a fast answer. This means that each individual calculation needs to be fast, but also the computation of e.g. an entire dike ring.

Another requirement for new models is to be able to cope with erroneous readings, which are not caused by instability of the levee. The now available models incorporate all sensor readings, even if a sensor is (temporarily) malfunctioning. In that case, the resulting virtual sensor does not correspond to a realistic value of dike stability. Malfunctioning of a sensor should be detected automatically. The sensor value should be discarded and e.g. replaced by a value interpolated from its neighbors.

In the current project, the models were not yet combined to one virtual sensor on dike stability. In the future, several sources of information (e.g. different types of sensors) can be combined. The reliability of the “total” virtual sensor then depends on the reliability of the individual sensors, the reliability of the models which convert the sensor values to virtual sensors on dike stability and the number of virtual sensors which make up the total virtual sensor. In the ideal flood control system, an answer on dike stability is always available. This should be the case even if some systems fail. Although the reliability will be reduced, decisions can still be made based on the available information.

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