# Full-scale field validation of innovative dike monitoring systems

## Validation de systèmes de surveillance innovants pour digues à grande échelle

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ABSTRACT: Three large scale field tests on dikes have been carried out at the IJkdijk test site in the Netherlands. Two tests involved piping, micro-instability of the sand core and erosion from overtopping. Both dikes failed on micro-instability. The third test involved slope stability with a deep sliding plane. All tests were done to validate monitoring systems and dike safety information systems. Several systems performed well.

RÉSUMÉ : Trois essais à grande échelle sur digues sont exécutés sur le site de l'Ijkdijk aux Pays-Bas. Deux essais étaient concernés par un phénomène de renard, de déstabilisation par fluidisation de sable du cœur de la digue et d'érosion par surverse. Ces digues s'éffondraient par fluidisation de sable. Le troisième essai impliquait le mode de rupture de pente. Tous les essais ont été effectués pour valider les systèmes de surveillance des digues. Plusieurs systèmes ont donné de bons résultats.

KEYWORDS: dike, embankment, full-scale test, slope stability, piping, microinstability, monitoring, information systems.

## 1 INTRODUCTION TO THE IJKDIJK TESTS

### 1.1 *The IJkdijk research program*

The IJkdijk (Dutch for 'calibration dike') is a Dutch research program with the two-fold aim to test any kind of sensors for the monitoring of levees under field conditions and to increase the knowledge on dike failure mechanisms.

Since 2007, several purpose-built dikes have been brought to failure at the IJkdijk test site at Booneschans, in the North-East of the Netherlands. Past experiments include a large stability test (Zwanenburg et al. 2012) and four field tests on backward seepage erosion or piping (van Beek et al. 2011). The tests presented in this article include these and other failure modes. For the near future, a test on static liquefaction is planned.

Meanwhile, the outcome of these tests has been implemented in practice by instrumenting several regular dikes, i.e. embankments with the function to protect the hinterland against flooding. By the end of 2012, this advanced surveillance by sensor equipment had been placed in ten different dikes in the Netherlands, United Kingdom, Germany and China.

### 1.2 *All-in-One Sensor Validation Test*

The main purpose of the All-in-One Sensor Validation Test (AIO-SVT) was to test the predictive power of full-service dike sensor systems, i.e. sensor in and on dikes combined with data processing and an information system providing a timely, reliable warning in case failure may occur. The application of such systems into practice will be a major improvement to the current state-of-the-art of dike management. In addition, contributing sensor systems were also tested and validated on their own. Another reason to carry out this test, in accordance with the two-fold aim of the IJkdijk,is to learn more on dike failure mechanisms, including failure prevention methods.

The AIO-SVT involved three dikes, which were all brought to failure. First, the geotechnical design of each dike is described, followed by the instrumentation. Next, the results are described, first regarding the failures of the dikes, then for the monitoring systems and finally for the information systems. Finally, conclusions are drawn.

## 2 DESIGN OF THE EXPERIMENTS

The experiments were designed in such a way that each dike could fail to different failure modes. The duration of each experiment was planned to be at least several days, with a maximum of one week, to allow the participating companies to collect a reasonable amount of data under varying conditions.

### 2.1 *West and East dikes*

The West and East dikes, named after their respective locations on the test site, were in many ways comparable. Both test dikes were 3.5m high, 15m long and 15m wide at their base, see Figure 1. The lower part of each dike was made of a 0.7m well-compacted clay layer, with a 1.7m high less-compacted small clay dike at the upstream side on top, a sand core behind this small clay dike and a cover of organic clay. This composition is found in many smaller dikes around the country. The base consisted of a uniform sand with a thickness of 3m with an impermeable foil below, to separate this test layer from the subsoil. Under the West dike, the sand has a $d_{50}$ of 0.296mm and a uniformity coefficient $U=d_{60}/d_{10}$ of 1.69. Under the East dike, the $d_{50}$ is 0.180mm and U=1.73. The upstream reservoir is enclosed by a 3.7m high dike. The size of the reservoir is about 2000m$^3$.

By design, failure could occur from piping through the base, micro-instability of the sand core and overtopping of the crest

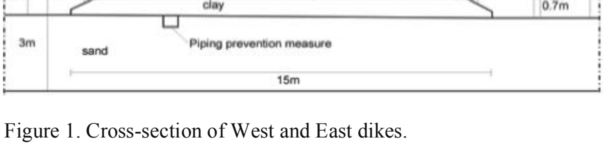

Figure 1. Cross-section of West and East dikes.

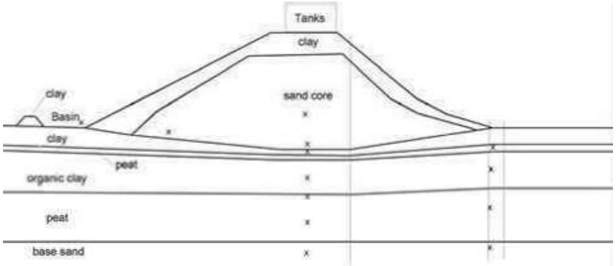

Figure 2. Cross-section of South dike at start of test, showing settled geometry and indicating positions of reference monitoring.

and subsequent erosion of the downstream slope. The earlier tests on piping had a similar configuration, but with a more sound clay dike (van Beek et al 2011). Those tests failed to piping at reservoir levels ranging from 1.75m to 2.3m. In order to make piping less likely this time, in each test dike a piping prevention measure has been placed. In the West dike, piping is controlled by a controllable drainage tube at 3.7m from the downstream toe, while in the East dike a coarse sand filter has been placed as a rectangular box 0.5m wide, 0.5m deep around 3.5m from the downstream toe. The grain size of this filter varies from 1 to 2 mm, the grain size distribution is such that excessive loss of particles through this filter is prevented (Burenkova 1993).

### 2.2 *South dike*

The South dike was built on a 4.5m thick composition of soft peat and clay. After construction, it was 4m high, 50m long at crest level, with a crest width of 3m and side slopes of 1:1.5 (V:H). The core was made of sand, with a 0.5m thick clay layer. Figure 2 shows a cross-section of the dike at the start of the test, i.e. after consolidation resulting in a settlement of 0.99m.

The designed failure modes of this dike were slope stability with a deep sliding plane through the subsoil with a minimum deformation of 20cm and rupture of the clay cover by high pore pressures inside the sand core as a result of saturating this core with water.

## 3 INSTRUMENTATION

For the instrumentation a clear distinction is made between the reference monitoring and the instruments of the participating companies. The reference monitoring was required (and sufficient) to closely monitor the course of the tests, while the other instruments were validated and the measurements were used to make updated predictions of the failures.

A total of nine companies participated with their instruments – some in all tests, others in only one or two. Each of these companies were invited to use their own measurements to give an initial prediction of the failure mode and the conditions at which failure would occur, and to update this prediction at least every 24 hours.

Three companies providing dike safety information systems participated in all three tests. These companies had access to the data of the monitoring systems being validated through a central data base. The data of the reference monitoring was not disclosed during the tests.

### 3.1 *West dike*

The reference monitoring was primarily carried out with pore pressure meters: two to record the water levels in the upstream and downstream reservoirs, four lines of 17 meters each at the interface between the lower sand and the well-compacted clay layer at 0.9m, 2.5m, 4.3m and 11.2m from the downstream toe and a 3 by 3 grid of pore pressure meters at the bottom of the sand core: right behind the small clay dike and at 1.8m and 6.0m downstream, respectively. In addition, visual inspections were carried out at regular intervals, an HD camera facing the downstream slope taking one frame every five seconds was used, rainfall data was recorded and the upstream and downstream discharges were measured.

The following instrumentation was installed by the seven companies participating in this test:

- glass fibre optics woven into geotextile, measuring temperature and strain approximately every metre in eight lines parallel to the toe of the dike, five at the sand/clay interface and three in the downstream slope;
- a Fast Ground Based Synthetic Aperture Radar system, measuring a two-dimensional displacement field of the downstream slope every five seconds;
- two vertical tubes, installed at the upstream crest line, measuring temperature and strain profiles over depth employing glass fibre optics;
- a thermic infrared camera facing the downstream slope, with a resolution of 640x480 pixels and an accuracy of 0.05 K;
- a ground penetrating radar system at 100 MHz, operated by moving it across the crest of the dike;
- two controllable drainage tubes with measurements of pore pressure, temperature and discharge, located close to the sand/clay interface at 3.7m from the downstream toe (lower tube) and right behind the small clay dike at the bottom of the sand core (upper tube);
- six pore pressure meters at the sand/clay interface, three at 0.5m from the downstream toe and three at 2.2m.

### 3.2 *East dike*

The reference monitoring at the East dike was almost identical to the West dike, but with four lines of 16 instead of 17 pore pressure meters at the sand/clay interface.

The six companies participating in this test installed the following:

- glass fibre optics woven into geotextile, measuring temperature and strain approximately every metre in eight lines parallel to the toe of the dike, five at the sand/clay interface and three in the downstream slope;
- two vertical tubes, installed at the upstream crest line, measuring temperature and strain profiles over depth employing glass fibre optics;
- an electric resistivity system employing two rows of 14 electrodes on the downstream slope;
- a thermic infrared camera facing the downstream slope, with a resolution of 640x480 pixels and an accuracy of 0.05 K;
- a ground penetrating radar system at 100 MHz, operated by moving it across the crest of the dike;
- ten pore pressure meters at the sand/clay interface, five at 0.7m from the downstream toe and five at 2.2m.

### 3.3 *South dike*

The reference monitoring at the South dike consisted of 34 pore pressure meters and six automatic inclinometers. Twentysix pore pressure meters were installed in two cross-sections each 13m from the centre line, as indicated in Figure 2, six pore pressure meters were installed in six water tanks on top of the crest and the remaining two were installed in the basin on the non-failing side of the dike and in the ditch which was excavated during the test to reduce the overall stability. The inclinometers were distributed along the centre line and both instrumented cross-sections.

The seven companies participating in this test installed the following:

- glass fibre optics woven into geotextile, measuring temperature and strain approximately every metre in three parallel lines along the whole length of the dike, on ground level and on two higher levels;
- a system of six extremely accurate inclination instruments, each mounted on top of a 5.6m steel rod placed on the slope of the dike (three on the side of the failure, three on the other side);

- a Fast Ground Based Synthetic Aperture Radar system, measuring a two-dimensional displacement field of the slope at the side of the failure every five seconds;
- a total of four tubes measuring temperature and strain profiles over depth employing glass fibre optics: two vertical tubes 5.5m long halfway the slope at the side of the failure, one vertical tube 3.5m long at the toe at the same side in the centre line and one horizontal tube along the whole toe of the dike;
- a thermic infrared camera facing the downstream slope, with a resolution of 640x480 pixels and an accuracy of 0.05 K;
- one controllable drainage tubes with measurements of pore pressure, temperature and discharge, located inside the sand core, close to the toe at the side of the failure;
- eight instruments measuring pore pressure, temperature and local inclination distributed over two cross-sections 10m away from the centre line, in each cross-section one instrument in the sand core close to the toe and three instruments distributed over depth in the soft soil deposits under the toe.

## 4 RESULTS OF THE EXPERIMENTS

### 4.1 *West dike*

The test on the West dike started on August 21st at 4:30 pm. Filling the reservoir about 1m already caused serious cracks in the upper part of the dike. Also, leakage through the small clay dike occurred. Compaction of this clay was not sufficient. Once the situation stabilized, the upstream level was increased again. At a head drop of 1.56m the first wells appeared and sand producing wells (piping) appeared at a head drop of 1.79m.

At 66.7 hours after the start of the test (t=66.7hrs), at a head drop of 2.02m, the lower drainage tube was partly opened as piping had already been detected at the third line of pore pressure meters, i.e. upstream of this tube. This had a clear effect on the pore pressures, as shown in Figure 3, and the piping process stopped.

Meanwhile, the sand core became saturated, as measured by the upper pore pressure meters. At t=63.6 hrs, the upper drainage tube was opened and the pore pressures in the core were controlled. At t=94.0 hrs, both tubes were closed and the pore pressures rised sharply. From t=97.6 hrs, sliding of the downstream slope started to occur.

At t=110.1 hrs, considerable sliding of the downstream slope had occurred. Piping had resumed too, but the continued sliding from micro-instability of the sand core caused so much settlement of the crest that at t=111.9 hrs (August 26th at 8:24 am) failure occurred.

### 4.2 *East dike*

The test on the East dike started on August 21st at 3:20 pm and ran parallel to the test on the West dike. In many ways, both tests were similar, although the controllable drainage tubes were missing at the East dike. Wells occurred at the downstream slope at a head drop of 1.60m and piping started at a head drop of 2.02m. However, piping was detected only in the two lines of pore pressure meters downstream of the coarse sand filter, upstream no piping could be traced. Apparently, this measure worked.

As the last stages of the hydraulic load were delayed in comparison with the West dike, severe settlements from micro-instability of the sand core occurred later. Here at t=138.9 hrs (August 27th at 10:18 am) failure from micro-instability occurred. Figure 5 shows an overview of both failures.

### 4.3 *South dike*

The test on the South dike started on September 3rd at 12:12 pm, by infiltration of water into the sand core. The next day, a small excavation was made in front of the dike. This had a limited effect on the dike, as shown in Figure 6 by the horizontal displacements at the toe of the dike. The next day, a final excavation was made and on the basis of slope stability calculations it was decided to continue by hydraulic loading only. In order to acquire a lot of measurement data, several days were taken to raise the phreatic surface in the sand core and to fill the water tanks on top. Finally, failure occurred on September 8th, at 2:27 pm, after 122.26 hours, see Figure 7.

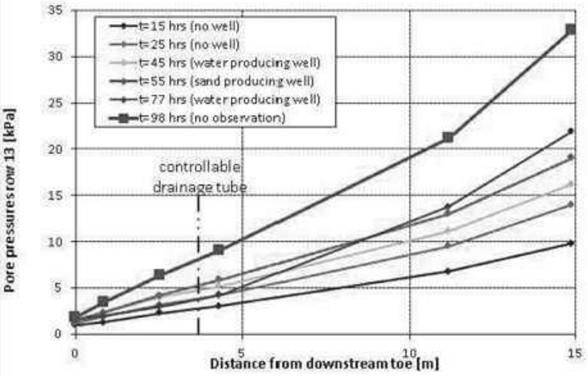

Figure 3. Pore pressures at sand/clay interface West

Figure 4. West dike close before failure.

Figure 5. West and East dikes after failure.

Table 1 shows the results of slope stability calculations at characteristic moments applying the models of Bishop (1955) and Van (2001). The latter is a geometrically more flexible variant to Bishop's model. The results correspond well to the deformation behaviour shown in Figure 6: close to the critical value of 1, the deformations quickly increase. These results may even draw some suspicion, but it should be borne in mind that quite advanced soil investigations had been carried out prior to the test (Zwanenburg et al. 2011, Koelewijn and Bennett 2012) and detailed actual measurements of pore pressures were available. Moreover, the model by Bishop has already long ago been described as surprisingly accurate for conditions close to failure (Spencer 1967).

Table 2 gives the measured values of the horizontal deformations during the last phase of the test for all inclinometers except one at the East side, which failed. The preset deformation criterion for a successful test was exceeded at the moment the maximum pore pressures were recorded.

Table 1. Safety factors calculated for the South dike.

| Situation, date, time | Van | Bishop |
|---|---|---|
| Dike completed, June 26, 5:00 pm | 1.46 | 1.50 |
| Start of test, Sept. 3, 12:12 pm | 1.74 | 1.82 |
| Before last excavation, Sept. 5, 9:00 am | 1.24 | 1.38 |
| After last excavation, Sept. 5, 5:00 pm | 1.05 | 1.08 |
| Start of last infiltration, Sept. 8,1:53 pm | 1.01 | 1.05 |
| Maximum pore pressures, Sept. 8, 2:13 pm | 0.92 | 0.95 |
| Visible failure, Sept. 8, 2:27 pm | 0.94 | 0.98 |

Table 2. Horizontal deformations measured by inclinometers around failure, in mm.

| Time | East in toe | Middle - crest | Middle in berm | West in berm | West in toe |
|---|---|---|---|---|---|
| 1:53 pm | 115 | 145 | 160 | 140 | 135 |
| 2:13 pm | 145 | 190 | 200 | 175 | 155 |
| 2:27 pm | 180 | 430 | 470 | 310 | 320 |
| 2:30 pm | 225 | 1450 | 1650 | 900 | 830 |

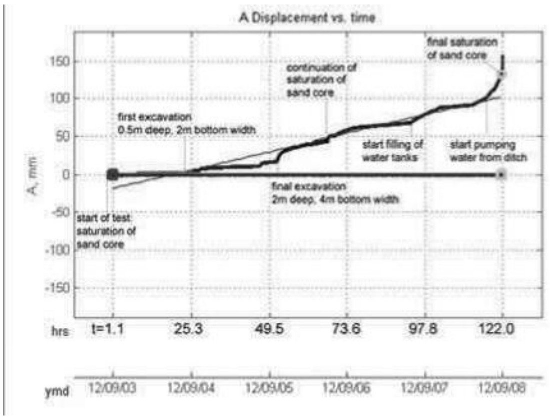

Figure 6. Horizontal displacements at toe of dike until close to failure.

Figure 7. South dike during failure: fracturing of slope of ditch.

## 5 PERFORMANCE OF THE MONITORING SYSTEMS

All monitoring systems were judged by their accuracy, range, density of measurements, measurement frequency, redundancy, robustness, time to install and adjust, processing time, interpretation and quality of prediction. Note that several of these factors are not only influenced by the instrumentation, but also by the strategy adopted by the company. It should also be noted that successful application of any technique depends on the actual conditions and environment.

An extensive evaluation of the results by the above criteria indicated a good to excellent performance in these tests of the controllable drainage tubes, the thermic infrared camera system for piping and micro-instability (although faster processing of the measurements seems, in general, a point of improvement), the tubes measuring strain and temperature profiles (design could be improved) and the ground based SAR (robustness to field conditions could be improved). The other systems performed as expected or worse.

## 6 PERFORMANCE OF THE INFORMATION SYSTEMS

The information systems were judged by their ability to combine data of different sources, the application of various techniques and methods to arrive at meaningful information, the clarity of statements and the quality of prediction.

Two companies performed well, one employing advanced data driven modelling and anomaly detection to improve finite element calculations, the other one focused more on an engineer's approach employing both modern technology and visual observations to update their predictions during the test.

The third company restricted its efforts mainly to producing all kinds of graphical presentations of the measured data, but hardly combining data of different sources.

## 7 CONCLUSIONS

Each of the three test dikes failed according to one of the designed failure modes. Instrumentation of nine companies was tested, indicating a novel technique to measure strain and temperature, a thermic infrared camera system to detect piping and micro-instability and fast ground based SAR as promising new monitoring techniques, as well as a controllable drainage tube capable of preventing failure. Employing monitoring data led to an improvement of the prediction of failure, especially if different types of monitoring were used. Real-time advanced modelling further improves the knowledge on the actual and expected condition of dikes.

## 8 ACKNOWLEDGEMENTS

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