Temperature Monitoring in Piping-Prone Hydraulic Structures

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S. Bersan and A.R. Koelewijn

Abstract

Backward piping erosion poses a threat to dikes and dams with a permeable foundation layer. This has been tested in large scale tests in the Netherlands. As part of the testing of alternative monitoring techniques, several temperature-based measurement methods have been tested in an experiment carried out in 2012. Test set-up, monitoring techniques and measurements are described, as well as the resulting practical possibilities with these methods. For the geometrical, stratigraphic and climatic configuration of the test performed, Distributed Temperature Sensors (DTS) demonstrated the capability of detecting the occurrence of piping below a dike with almost equal accuracy as more traditional pore pressure sensors, which are much more costly to install at a sufficient density.

Keywords

Internal Erosion • Piping • Dike Monitoring • Distributed Temperature Sensors

249.1 Introduction

Backward piping is a kind of internal erosion that occurs under hydraulic structures lying on a foundation layer of high hydraulic conductivity. Despite not many cases of piping-induced collapse have been recorded, it is nowadays considered a big threat to dikes and dams (Wan and Fell 2004).

During the last 20 years temperature sensors have been installed in dams and dikes with the aim of detecting internal erosion. The functioning principle is based on the fact that a leakage through an embankment dam changes its temperature field as a consequence of a concentrated increase of the flow velocity. Recently, advanced data interpretation techniques have been developed (Beck 2010).

Although the application of temperature sensors for the monitoring of piping-prone dikes looks promising, the temperature variations induced by the leakages are of little extent, so that piping detection is not straightforward and further research is needed.

The effectiveness of monitoring systems based on temperature measurements has been tested in a full scale failure test. This has been carried out in August 2012 at Booneschans, the Netherlands, with the aim of testing dike sensor systems. Other goals of the test were to verify the effectiveness of countermeasures for the prevention of the collapse and to increase the knowledge on failure mechanisms.

249.2 Test Dike and Monitoring System

The test dike was designed to collapse either by backward piping or by instability of the sand core caused by liquefaction (micro-instability). The dike was 3.5 m high, 18 m long and 15 m wide, on top of a 3 m sand layer. At its shoulders a reservoir was created by rising embankments on three sides. The dike was composed of a 60–70 cm thick compacted clay layer with a 1.7 m high clay dike on top on the upstream side, backed up with a sand core and overlain by organic clay up to

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the crest level (Fig. 249.1). Countermeasures consisted of two controllable drainage tubes placed respectively in the sand core, right behind the clay dike, and at the top of the sandy foundation layer, running parallel to the downstream toe at a distance of 3.7 m from the latter. The longitudinal axis of the dike was aligned with the east-west direction and all distances were measured from east to west.

Conventional reference monitoring consisted of pore pressure sensors placed during construction of the test dike both in the foundation—at the sand/clay interface—and in the sand core, right above the clay layer. Five lines of 17 sensors each have been installed in the foundation and three lines of three sensors each in the core. Visual inspection was performed at regular intervals; position and size of the sand-boils was noticed and documented by pictures.

Distributed temperature and strain sensors, made of optic fibers encased in geotextile strips, were deployed at the interface between the foundation layer and the clay base as well as on the downstream slope, a few centimeters below the clay cover. Five strips at progressive distance from the toe were deployed at the base of the dike and three strips on the slope. Thanks to the distributed nature of the sensor, the temperature was measured along the entire cable and an average value was provided each meter with a frequency of 30 min and a resolution of 0.1 °C. Moreover, an infrared camera was used to map the surface temperature of the downstream slope.

249.3 Monitoring Data

249.3.1 Visual Inspection and Pore Pressure Measurements

The test was performed by increasing the water level in the upstream basin in steps, while the downstream basin was maintained at almost constant level (Fig. 249.2).

Traces of sand transport induced from seepage flow, consisting of grain movements or spots of turbid water, were recorded since 21.5 h, yet the first proper sand boil was only discovered at 45 h, placed at 5.2 m from the east side.

The trace of the first pipe was detected 2 h earlier in the pore pressure measurements: the sensors placed at 4.8 and 5.8 m in the first line, located at about 0.9 m from the downstream toe, showed a drop soon after the hydraulic load had been raised to 1.5 m (Fig. 249.2). The limited extent of the pressure drop is due to the fact that the sensor was likely not located exactly in the piping channel and the draining effect of the pipe decreases very fast sideways with distance.

At 55.5 h, after a further increase of the upstream water level, the first pressure drop occurred in the second line of pore pressure meters, placed at 2.5 m from the downstream toe, indicating that one piping channel had grown that far.

From that moment on, sand transport occurred continuously, as revealed by the size of the sand boils increasing with time.

The opening of the lower controllable drainage tube, starting at 67 h, had a clear effect on the pore pressures under the test dike and, in turn, an effect on the sand transport that suddenly stopped.

After closing the controllable drainage tube at around 94 h, the pore pressures were restored again and the piping erosion process restarted. However, from the pore pressure measurements it is possible to assert that none of the pipes reached the third line of sensors, placed at about a quarter of the seepage length.

The dike failed after 112 h (4.6 days) from the beginning of the test, after the saturation line in the sand core had touched the toe and caused its liquefaction.

249.3.2 Temperature Measurements

Figure 249.3a shows the temperatures at the interface with the foundation, where the pipes developed, as measured by the first line of DTS. Every line represents a position along the dike, 1 m apart one from the other. Temperature values start to diverge after 55 h, that is when the second line of pore pressure

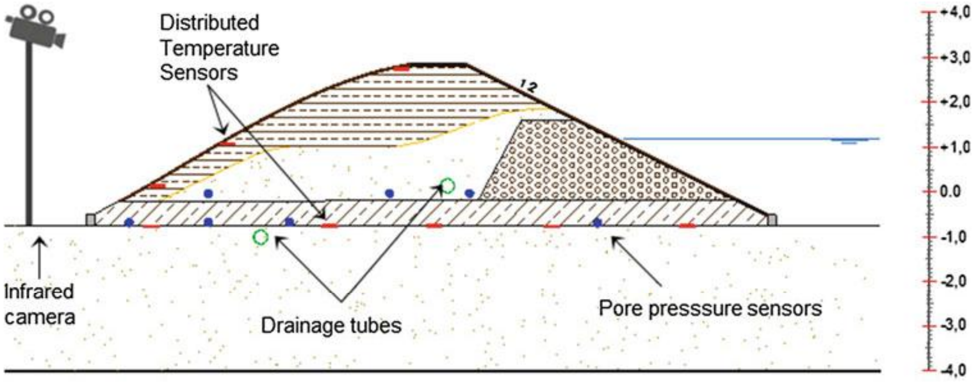
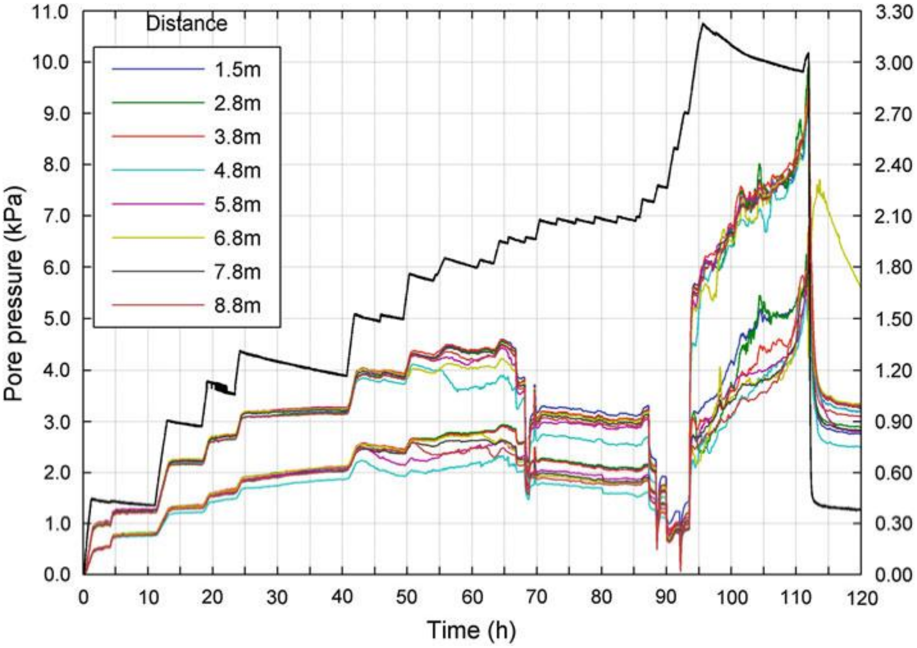


Fig. 249.1 Dike geometry and position of pore pressure and temperature sensors

Fig. 249.2 Hydraulic load applied to the dike (*right axis*) and response in terms of pore pressures measured by the first eight sensors of the first and second line (respectively *lower* and *upper sheaf of curves*)

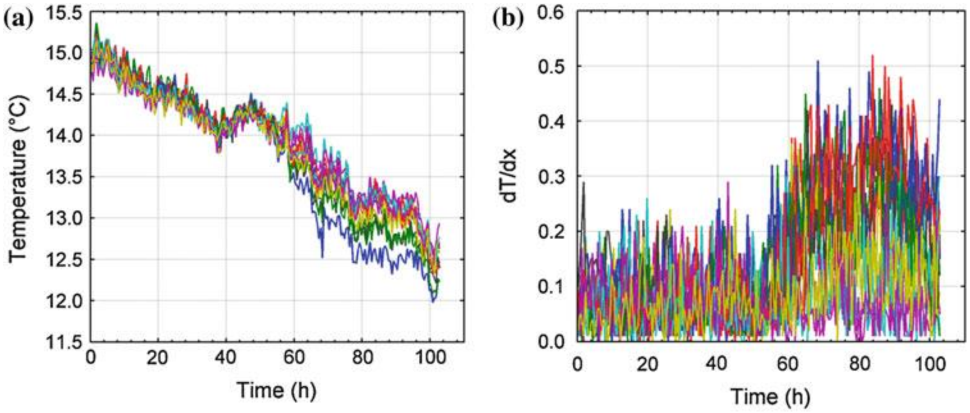


meters is reached by the pipes, while no sign is detected when the first line is reached at 43 h. The divergence is lower than 1 °C. Temperature generally decreases during the test, initially as the pure effect of the interaction with the atmosphere, later on also as an effect of concentrated flow through the pipes. We remember that the air temperature propagates in the soil with a certain delay and damping, therefore the temperature measured during the test also depends on the temperature trend in the days preceding the test.

From these temperature values the spatial gradients have been calculated and reported in Fig. 249.3b. Despite they are quite oscillating, a clear threshold of 0.3 is identifiable, which is clearly exceeded after the pipes reach the location of the sensor. Temporal gradients did not show a univocal correlation with the development of the pipes as they were affected by many other factors, such as the opening and closure of the drainage tube that caused, respectively, a general decline and increase in temperature.

The data showed in Fig. 249.3a can also be represented in a pseudo-color plot which may be very effective for the identification of the pipes (Fig. 249.4a). A monochrome (we chose a grey one) works better (Fig. 249.4b). The pipes appear as areas of lower temperature, detected from 55 h at the approximate location of 5.5, 11.5 and 17.5 m. The data recorded by the second line did not show any anomaly. This is in accordance with the pore pressure measurements, since the second line of temperature sensors is upstream of the third line of pore pressure sensors, which was not reached by the pipes.

Fig. 249.3 Temperature measured by the first line of DTS at the interface with the foundation: absolute values (**a**) and spatial gradients (**b**). Every line represents a position along the dike, 1 m apart one from the other



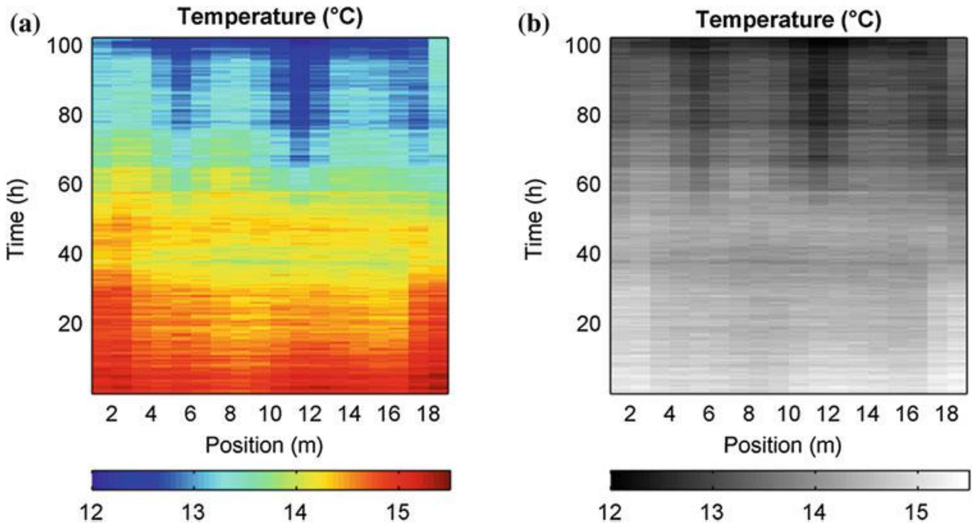


Fig. 249.4 Color plot of the temperatures measured by the first line (**a**) and second line (**b**) of DTS at the interface with the foundation

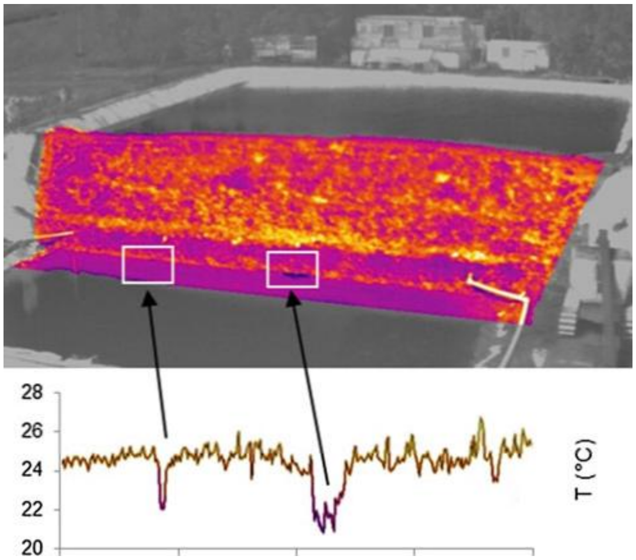


Fig. 249.5 Surface temperature of the downstream slope and temperature at the toe (*graph*) measured by the infrared camera at 94.5 h from the beginning of the test

The presence of the pipes can also be identified as a drop in the surface temperature measured at the downstream toe of the dike by the infrared camera (Fig. 249.5). At the exit points of the flow, the temperature decreases up to 3 °C compared to the surrounding region.

249.4 Conclusions

Although piping was not the mechanism that brought the dike to failure, the erosion process developed to such an extent to provide useful information on the effect of piping on pore pressures and temperatures.

The measured pressure drop was around 10 % of the initial value. The influence on the pore pressure decays very fast sideways with distance from the pipe. For a small length of the pipe and a configuration without landside blanket, as in tested dike, the radius of influence is less than 1 m. This means that to detect the process in its initial stage it is necessary to place a sensor every meter, which is very costly.

When piping occurred, a temperature drop of the order of 0.5 °C was registered at the sensors closer to the affected area. Good agreement was obtained among the anomalies detected by the temperature sensors, the pore pressure sensors and the evidence from visual inspection. Analysis of the spatial gradients seems to produce useful information for early warning purposes. For an installation on a real dike a period of observation is necessary to calibrate the threshold alarm value and identify local non-homogeneities that could produce not piping-related variability. Integration with the information from the temporal gradients, which by themselves are not very informative, could be of help to generate more reliable alarms.

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