

Levee Failure Due to Piping: A Full-Scale Experiment

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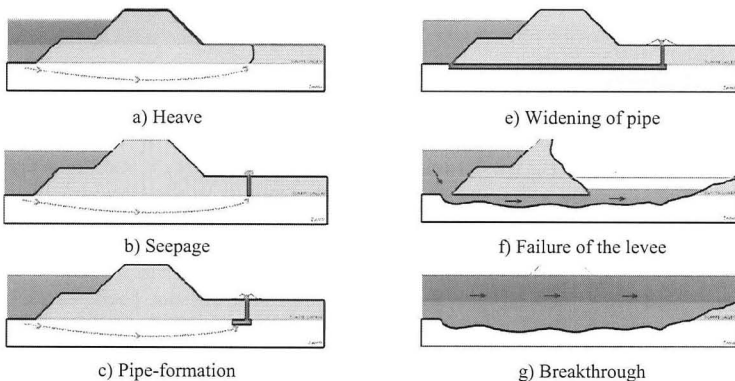
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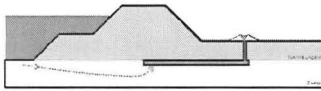
ABSTRACT

Piping is considered as an important failure mechanism for water retaining structures in the Netherlands. A recently performed study on the safety of Dutch levees raised some doubts with respect to the validity of the current calculation model. A large research program has therefore started to investigate the process of piping in more detail. After laboratory experiments and desk studies, the model was validated in a full-scale experiment (seepage length 15 m). This paper describes the piping process as observed in this experiment. Different phases were found: seepage, retrograde erosion, widening of the channel and failure. Once sand craters were formed, stabilization of sand transport was not observed, although quantities of transported sand were very low. Ongoing erosion resulted in a piping channel from the downstream to the upstream side in a few days. Widening of the channel due to continued erosion finally resulted in significant deformation and failure of the levee.

INTRODUCTION

Piping, the process of retrograde internal erosion in sandy layers underneath clay levees, is considered one of the most dominant failure mechanisms of levees in the Netherlands (VNK1, 2005). The process starts with heave and cracking of the soft soil top layer at the land side of the levee, caused by high water pressures which are easily transferred through the permeable sand layer (Figure 1a-b). The cracks in the top soft soil layer allow for seepage. In case the water level difference between river and land side (the hydraulic head) is large enough, sand grains may be transported along with the water flow, thereby creating a pipe underneath the levee (Figure 1c-d). Continuing erosion may finally lead to failure of the levee and breakthrough (Figure 1e-g).





d) Retrograde erosion

Figure 1a-g. Process of retrograde erosion

Several calculation models and empirical relations are available to predict the occurrence of piping by retrograde erosion in order to assess the safety of levees. The most well-known prediction tools are the empirical rule of Bligh [1910] and the model of Sellmeijer [1988], of which the latter describes the process in most detail. However, a discrepancy emerged between calculated probabilities of failure and the opinion of levee managers of the actual resistance to piping (VNK1, 2005) in a recently performed safety assessment of Dutch levees using the model of Sellmeijer. Scepticism existed on whether piping would actually result in failure of the levee and the validity of the model was questioned. A large research program was started to validate and possibly improve the model.

This programme is part of a larger research programme called Strength and Loading of Flood Defence Structures (SBW), in which improvement of prediction models on different failure mechanisms for levees is pursued, in order to improve testing methods for the 6-yearly safety assessment of Dutch levees. SBW Piping specifically focuses on the improvement and applicability of prediction methods for piping. Experiments have been performed to study the process of piping in more detail.

After series of small-scale, medium-scale and centrifuge experiments (Van Beek, 2010^a, Van Beek 2010^b), in which the process of piping and the influence of sand characteristics and length on the critical head was studied, the calculation model was validated in a full-scale experiment (seepage length 15 m). Three objectives were combined in a total of four tests: validation of different aspects of the calculation model, investigation of the failure process and testing of monitoring equipment. The objective of testing of monitoring equipment is part of the research program of the IJkdijk Foundation (described in De Vries et al., 2010). A cooperation between different parties allowed for the experiments to be performed. In this paper the process of piping in the full-scale experiments is described and compared with the expected process based on the model of Sellmeijer.

The model of Sellmeijer

The model of Sellmeijer is based on the equilibrium of forces of sand grains, flow in the developing channel (pipe flow) and the flow through the aquifer (Darcy). The model of Sellmeijer gives the relation between the pipe length and the hydraulic head at which the sand grains are in equilibrium, resulting in the curve as shown in figure 2. This graph shows the head at which the grains are just in equilibrium (ΔH_{eq}) for different relative pipe lengths (l/L). The graph shows that the growth of the channel will stop at a certain equilibrium length, as long as the critical head (ΔH_c , the maximum head at which grains can be in equilibrium) has not been reached; an increase of hydraulic head is necessary to obtain further growth of the pipe. The growth of the channel will continue once the critical head is reached; no equilibrium is possible unless the hydraulic head is lowered. It is assumed that the continued erosion will lead to failure of the levee within a relatively short time.

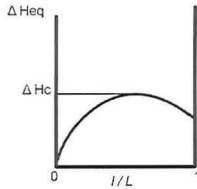


Figure 2. Hydraulic head at equilibrium as a function of the ratio between pipe length (l) and seepage path (L)

The equilibrium curve is of importance for field inspection. Sand transporting seepage wells are often observed and it is important to know whether the sand transport may stop as a result of equilibrium of the sand grains. The equilibrium curve is one of the important items of validation. In the laboratory experiments this curve has not been clearly observed, possibly due to scale or configuration. Below the critical head continuous sand transport has not been observed, although there had been some small signs of sand transport below the critical head, like individual grain transport or formation of very small channels.

FULL-SCALE EXPERIMENT SET UP

The full-scale experiment was performed at the location of the IJkdijk in the Northeast of the Netherlands. Two large basins were created (size 30x15 m), which were filled with two different sands. The sands had a d_{50} of 150 μm and 200 μm and are denoted in the following text as 'fine sand' and 'coarse sand' respectively. The dry sand was applied in layers and densified until a relative density of at least 50% was achieved. After densification, the sand layer was saturated. A clay levee with a height of 3.5 m and slopes of 1:2 was built on top of the sand by densification of smaller clay lumps. A levee with a seepage length of 15 m was obtained.

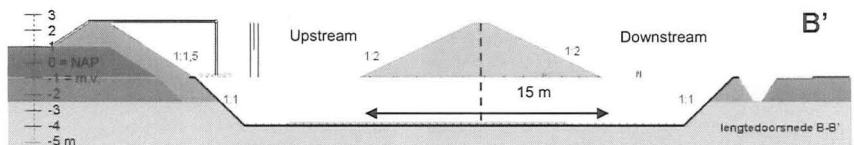


Figure 3. Cross-section of the full-scale experiments

At the downstream side, an overflow was created to keep the downstream water level at a constant level (approx 0.10 – 0.20 m above the sand layer). At the upstream side, the water level could be raised to a level of 3 m above the sand layer and was kept constant. Pumps were installed with a discharge capacity of 150 m^3/h at maximum to keep the water level constant.

Several rows of pore pressure gauges were placed at the interface of sand and clay to be able to monitor the pipe formation. In addition, fiber optics were placed at the interface to measure temperature and strain differences. In two of the four experiments additional monitoring equipment was tested, which is more extensively described in by de Vries et al., (2010). Monitoring wells were placed to measure the

head difference and water pressure at both upstream side and downstream side, at depths of 1 and 2 m. A flow meter was connected to the overflow unit.

To fulfill the three objectives of the project, validation of different aspects of the calculation model, investigation of the failure process and testing of monitoring equipment, a total of four tests was performed. Next to validation of the model two types of sand were applied in two different basins. Next to validation of the model, monitoring techniques were tested. As some of the monitoring techniques were invasive and might interfere with the objective of validation of the model, a test program as shown in table 1 was defined.

Table 1: Test program

Test nr.	Sand type	Monitoring equipment	Objective
1	Fine sand	Low disturbance techniques	Validation of model and process / Testing monitoring techniques
2	Coarse sand	No additional monitoring	Validation model and process
3	Fine sand	No additional monitoring	Validation model and process
4	Coarse sand	High disturbance techniques	Testing monitoring techniques

In this article only test 1-3 will be discussed, as the monitoring techniques in test four might have been disturbing for analysis of the process. Each test has been performed in the same way: the head difference was increased with 0.1 m every hour (15 minutes of filling and 45 minutes of monitoring) until sand transport took place. When sand transport was observed, the increase of hydraulic head was delayed until sand transport had ceased. In some cases the hydraulic head had been increased, despite of ongoing sand transport, as a result of time constraints. Sand craters that occurred at the water level were removed by hand to keep a constant gradient through the dike.

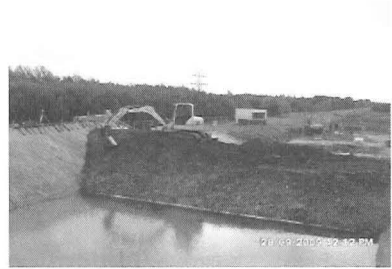


Figure 4: Filling the basin with sand and build-up of the clay levee

PIPING PROCESS – FROM SEEPAGE TO FAILURE

Based on observations in the full-scale experiments, the phenomena in the experiment can be divided into four phases: seepage, retrograde erosion, widening of the channel and failure.

Seepage

Seepage underneath the levee was observed during the first steps of increase of hydraulic head, but no transport of sand. This stage allowed for accurate determination of the permeability of the sand layer. Based on the flow measurement,

grain size distribution, laboratory permeability measurements and the relative density it was concluded that the degree of saturation was good.

Table 2: Properties of sand layer in test 1-3

Test nr.	Sand type	Relative density [%] ¹⁾	Permeability [m/s] ²⁾
1	Fine sand	60	8E-5
2	Coarse sand	75	1.4E-4
3	Fine sand	60	8E-5

1) +/- 10% 2) T=12°C

Retrograde erosion

The retrograde erosion manifested itself in different forms. Sand traces occurred in an early stage of the experiment (first observed at hydraulic head of 0.10 m to 1.4 m depending on the experiment (gradients of 0.007 – 0.09)). Sand traces are spots of sand, which suddenly appear without any visual movement of sand. No boiling of sand or sand craters were observed. The amount of transported sand is limited (spots are generally around 0.1-0.3 m in diameter with barely any height). Although no sand transport is visible, the sand traces may slightly increase in size, and fines were found to be in suspension near these locations. The sand traces do not notably affect the water pressures and are present at various locations along the downstream toe.

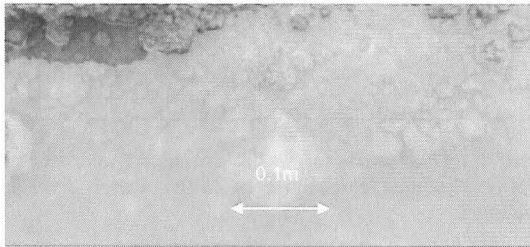


Figure 5. A sand trace

After increase of hydraulic head until 1.6-2.1 m (gradients of 0.11-0.14), depending on the experiment, wells with boiling sand may occur. These wells do lift the sand grains in (small) sand craters, but sand grains are not deposited at or over the rim of the sand crater. A short channel must have been present as the pore pressure meters located near the downstream toe indicated a decrease of water pressure near these wells.

In some cases the wells with boiling sand started to deposit sand over the rim of the crater, after increase of hydraulic head. It also occurred that new wells were created that immediately started to transport sand. In experiment 1 and 3 several well locations were present along the toe of the levee, but in experiment 2 only one well transported sand. It is striking that sand transport at this stage does not cease. Although quantities were limited (approx 0.5 kg/hr) the transport of sand continued at a more or less stable pace.

At this stage the hydraulic head was maintained at a constant level for about 24 hours in each experiment, without any notification of decrease of sand transport. Due to time constraints, the hydraulic head was increased in an attempt to speed up the process. The amount of transported sand increased with each step. Once the

transport is such that it was expected that the channel would reach the upstream side within a certain timeframe, the hydraulic head was kept constant.

The channel formation was monitored by the water pressure measurements. A local decrease of water pressure is an indication for channel formation (Figure 7).

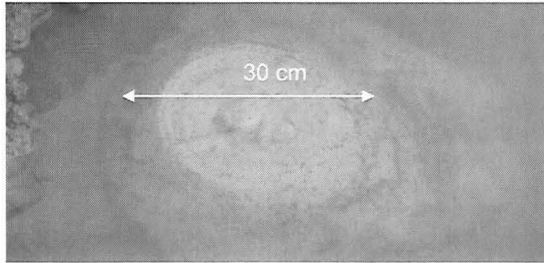


Figure 6. Sand transporting sand boil (sand crater)

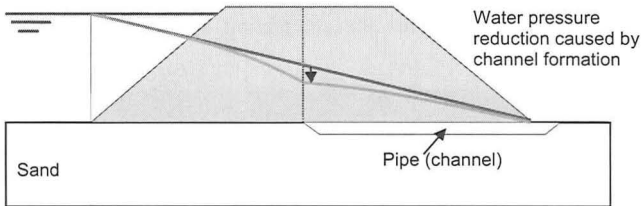


Figure 7. Sketch Local decrease of water pressure (pale blue line) caused by retrograde piping channels compared to initial water level before channel formation (blue line).

Widening of the channel

As soon as the channel reaches the upstream side, a different process starts: widening of the channel. In this process, the channel is enlarged from the upstream side towards the downstream side. The sand, eroded as a result of the widening and deepening of the channel, is pushed forward, causing the backward formed channels to clog. This process therefore takes a considerable amount of time, dependent on the seepage length.

The start of this process cannot be observed in the behavior of the sand boils, as the amount of transported sand does not change initially (Figure 8). The measurement data stops when the widening of the channel reaches the downstream side. It can be seen that no significant increase in transported sand occurs in the transition from retrograde erosion to widening of the channel.

However, the widening process can be observed in the water pressure measurements, as an increase of pressure is observed, caused by the low hydraulic resistance of the enlarged channel, spreading from the upstream side towards the downstream side (figure 9).

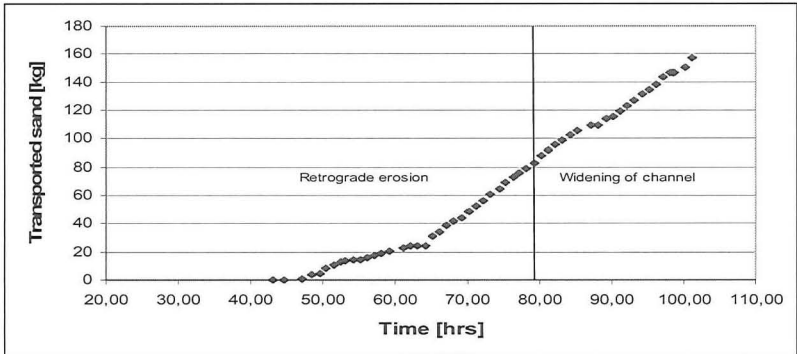


Figure 8: Cumulative amount of transported sand in experiment 3

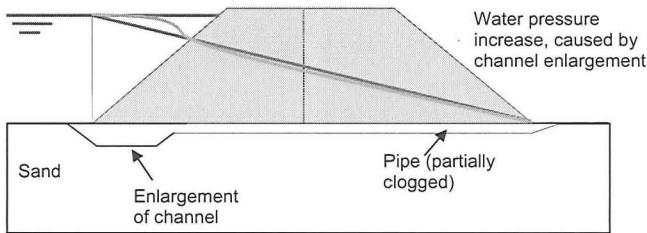


Figure 9: Sketch Change of water level in the sand as a result of channel enlargement (red line) compared to initial water level before channel formation (blue line)

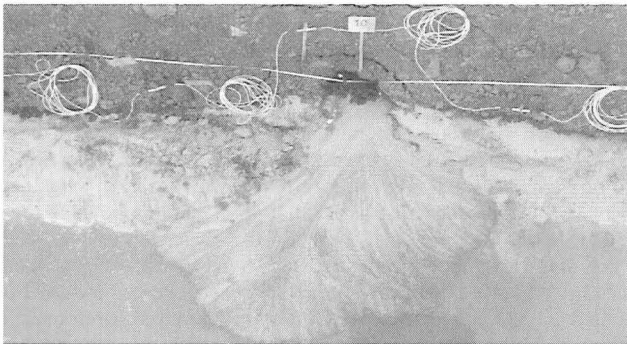


Figure 10: Widening of channel has reached the downstream side, resulting in an increase of sand transport, in this case followed by deformation

A change in the amount of sand transport is observed as soon as the widening process reaches the downstream side: a connection is created between the up- and downstream side of the levee. At this point two things may happen: either the flow and sand transport increase further until the levee fails (which happened in experiments 1 and 3), or the levee deforms (which happened in experiments 2 and 4), thereby partially closing the channel, causing the sand transport to decrease (figure 10). Cracks appear

in the levee. In the latter case, it is only a matter of time until the connection between the upstream and downstream side has re-established and sand transport and flow increase again. Several phases of reconnection and deformation may take place before the levee fails.

Failure

In all experiments failure of the levee took place. The process of failure starts with a large increase of turbulent flow and sand transport (mud flow), affecting a large area. Cracks appear in the levee and parts of the toe of the levee are eroded. Due to the large discharge, the water level at the upstream side could not be maintained, a drop of at least 0.60 m was observed in all experiments. In reality this drop of water level will not occur, thereby possibly even further increasing the damage to the levee.

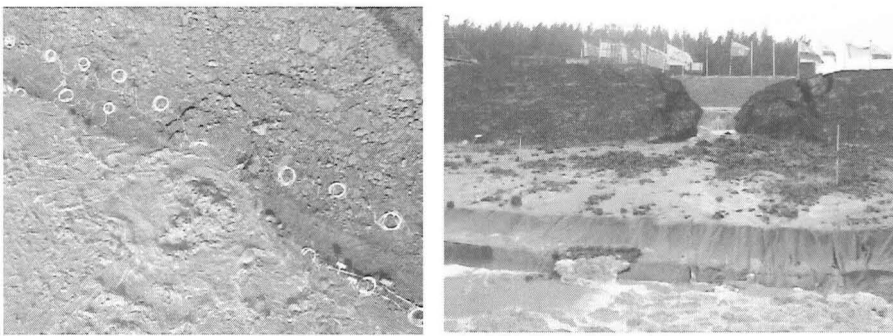


Figure 11: Increase of sand and water transport (mud flow)(left) leading to failure and breakthrough of the levee (right)

Processes in relation to hydraulic head and time

In figure 12 the named processes are related to the applied hydraulic head and the calculated bulk permeability for experiment 2. In table 3 the relation between observed processes, time and hydraulic head is given for test 1-3. An important finding, which results from both figure 12 and table 3, is the fact that the critical head is (almost) reached as soon as sand transporting wells appear. In the experiments the head is increased due to time constraints (after 45, 55 and 65 hours in the test shown in Figure 12), but it is expected that finally the channel would have reached the upstream side at the level at which the first sand transporting wells were observed. As this is uncertain, the critical head is expected to be somewhere between 1.6 and 1.9 m for experiment 2 (gradients 0.11-0.13). The critical head is therefore defined as the head at which it is expected that the channel will reach the upstream side. For the three tests the critical head is estimated to be 2.3, 1.75 and 2.1 m respectively.

Comparing the experimentally obtained critical head with the calculated critical head, it appeared that there was good agreement for the 'fine sand' test. The agreement was less for the 'coarse sand'. The critical head of experiment 2 (coarse sand) is lower than the critical heads of experiment 1 and 3 (fine sand). Based on small-scale experiments (Van Beek, 2010), this was expected, but according to the model of Sellmeijer (1988) the dependency is in the opposite direction. This aspect will be subject to further study.

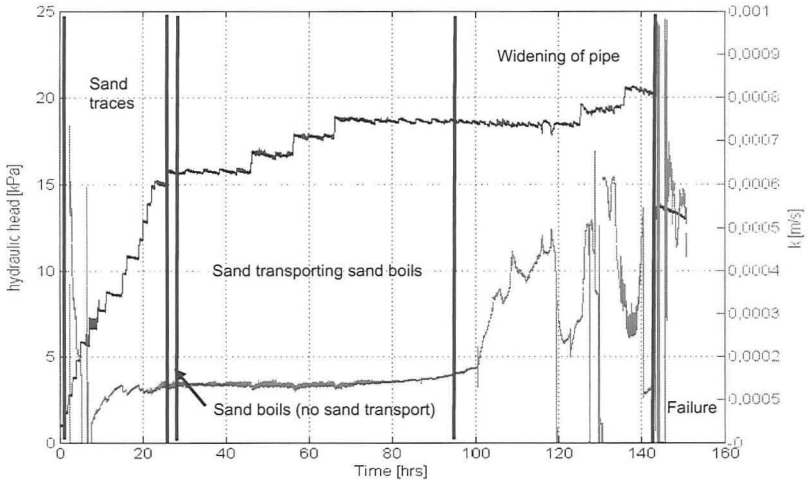


Figure 12. Experiment 2, Relation between processes, time, bulk permeability and hydraulic head

Table 3: Overview of time and hydraulic head in relation to processes in test 1-3

Test		Sand trace	Sand boil	Sand boil	Widening	Failure
1	Time [hrs]	5.3-20.5	20.5-25.7	25.7-95*	95-100.3	100.3
	Head [m]	0.6-1.6	1.6-2.0	2.0-2.7	2.7	2.7
2	Time [hrs]	2-26.3	26.3-27.5	27.5-94.5	94.5-143.3	143.3
	Head [m]	0.2-1.6	1.6	1.6-1.9	1.9-2.1	2.1
3	Time [hrs]	24.6*-42.5	-	42.5-79.2	79.2-111.8	111.8
	Head [m]	1.5-2.1	-	2.1	2.1-2.3	2.3

* value unclear due to limited monitoring

The retrograde erosion phase takes several days, but will proceed faster when the head difference is further increased. Exceeding the critical head with more than several tens of centimetres could possibly result in rapid failure. The relation between time and erosion should be investigated.

The equilibrium curve, as shown in figure 2, might still be correct, although the amount of transported sand is very limited until the critical head is reached. In practice, this amount of transported sand may even not be visible.

It was expected that as soon as the channel reaches the upstream side, the flow and sand transport would increase significantly, quickly followed by failure of the levee. In figure 12 and table 3 it can be seen that the time necessary for the widening process can take up to a few days, which is longer than expected. The process can be well monitored using pore pressure transducers, but in a field situation, without any monitoring equipment, there may be little warning for the failure, as the situation may suddenly change from small sand boils to mud flows and failure. It would therefore be recommended to take immediate measures as soon as sand boils appear.

CONCLUSIONS

The process of piping was studied in a full-scale experiment at the location of the IJkdijk in the Netherlands. Four phases have been observed: seepage, retrograde erosion, widening of the channel and failure of the levee. The phase of retrograde erosion is modelled by Sellmeijer (1988). In this phase channel formation is observed as sand traces, clean wells and sand transporting wells (sand craters). Sand traces, which are sandy spots without any crater formation, appear at a hydraulic head that is below the critical head. In contrary to what was expected, the amount of transported sand below the critical head was very limited. As soon as sand transporting craters appear, the critical head was (almost) reached. The start of the next phase, widening of the channel (cleaning of channel from upstream to downstream), can be monitored only by using pore pressure transducers. The amount of transported sand increases only significantly when the channel reaches the downstream side. The widening process may directly result in failure as soon as the channel reaches the downstream side, but may also result in deformation of the clay levee, partially closing the channel, thereby extending the duration of the widening phase. Failure takes place by significant increase of sand and water transport and deformation of the levee. It appears that failure caused by piping is a realistic threat for levees.

As soon as sand craters appear in the field, most likely the critical head has been reached, and it is recommended to take measures. Based on the amount of transported sand the time to failure cannot be predicted. Water pressure measurements give an indication of the phase.

ACKNOWLEDGEMENTS

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