# Piping: over 100 years of experience

## From empiricism towards reliability-based design

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### Introduction

Backward piping is the process of channel formation in a sandy aquifer under river dikes. During high water periods this process manifests itself by the formation of sand boils. A long history of cases and experiments has contributed to the insights into this phenomenon and has improved the ability to predict the safety of levees.

### Early 19th Century

Around the turn of the previous century, engineers became aware of the threat of piping for the stability of levees. Piping, which was a term for all kinds of internal erosion at the time, was found to occur underneath weirs as a result of underseepage.

Clibborn and Beresford were the first to find a relation between the seepage length and the head at which piping could occur (Clibborn and Beresford, 1902). Experience with weirs in India lead to the empirical rule of Bligh several years later (Bligh, 1910), which is also known as the creep theory, in which percolation factors were established for different soil types, thereby determining a safe head to prevent piping.

More engineers followed this empirical approach, such as Griffith (1914) and Lane (1934). Lane (1934) argued that vertical length contributes more to safety than horizontal length and adjusted the empirical rule, based on a total of 200 cases in the US.

In the Netherlands, practice confirmed the danger of a too large degree of underseepage. From this time period, several cases are known in which, according to the observations made, can be attributed to piping. A famous example is the case nearby Zalk. The translated eyewitness report is as follows (COW, 1981):

“In the neighborhood of Zalk, at the 8th of Januari 1926 at around half past seven, a small sand boil was discovered by the levee patroller, which produced clean water. Despite the fact that the sand boil was not significant, it was decided by a company of water board officials to cover up the location with gravel. The company had only scarcely left the location when the levee patroller, who had stayed behind, came running with the announcement that the levee was failing. The company turned around and saw a mud fountain of a man’s height at the location of the observed sand boil.”

The example shows that the failure due to piping can be very sudden. Two other cases are known in which the observation of sand boils was followed by failure of the levee, namely the case of Nieuwkuijk in 1880 and the case of Tholen in 1894. The large number of ‘wielen’ at locations with sandy foundation also show that piping has most likely been the cause of many historical dike failures. From the position and shape of the wiel, the geotechnical situation of the subsoil during the break can be traced. If the center of the 'wiel' is situated in longitudinal profile of the original dike, piping is the likely cause of a dike failure. In that case the subsoil mostly consists of sand and the breach can have grown both vertically and horizontally.

Figure 1 The mud fountain as observed at the location of the sand boil (case Zalk, 1926)

### 1950 to 1990: Experiments and theoretical considerations

For a long time the empirical rule of Bligh functioned as a design rule for dams. In the Netherlands, however, despite several cases of levee failures, design rules were not used to improve the state of the levees. After a breach or overtopping the levee was repaired by filling the gaps and by increasing the crest height slightly above the water level of the latest flood. Until the flood disaster in 1953 existing levees were not evaluated or designed according to the existing piping rules. The disaster caused a turn in the safety philosophy of levees. It was realized that a need existed for safety assessment of levees.

In 1965 the Technical Advisory Comittee for Water-retaining Structures (TAW) was founded to investigate the state of the levees. The alarming finding that during high water periods many sand boils were observed along the river levees, even at levels far below the design level, resulted in new research of piping.

Large research programs were performed in the 1970s and 1980s to create a better understanding of the piping mechanism. In the Netherlands the influence of soil characteristics, such as grain size, porosity, dimensions of the sand bed and type of exit point, on the critical head were investigated by a large number of experiments (Wit, 1984).

The process was studied in detail by laboratory experiments. A sequence of piping phenomena were observed in a box in which sand was retained by a filter at the upstream side and covered by a clay layer, which simulated the levee. At the downstream end the sand bed was not covered, so that water could flow out and sand could be deposited after erosion. A gradual increase of hydraulic head over the sand bed resulted in various phases of erosion. The process started with a gradual expansion of the sand at the inner toe of the levee, followed by small holes (with diameter of several times the grain size), due to local washout of particles. After further increase of head sand boils were observed, which are circular mounds in which sand grains are moved upward and fall back, as if the sand is 'boiling'. A further increase of hydraulic head was necessary for sand to be deposited near the edges of the sand boils and sand craters were formed: rings of deposited sand with boiling sand in the middle. Finally, when the pipe has grown towards the upstream filter, deepening and widening of the pipe was observed, as a result of increase in flow.

It was noted that as soon as sand craters were observed, no equilibrium situation was obtained such that the hydraulic head needed to increase for further development.

Figure 2 Pipe development and crater formation visible after removal of the clay layer

At the same time a German research group investigated the piping phenomenon (Müller-Kirchenbauer, 1978; Hanses, 1985). They looked in detail into the erosion process, which included both fluidisation at the head of the pipe and bed erosion, by which the pipe widened and deepened.

The understanding of the process which emerged from the experiments gave rise to the development of a theoretical model, in which the equilibrium of grains in the bed of the pipe was used as criterium for development of the pipe (Sellmeijer, 1988). The critical head was calculated by combining groundwater flow with the flow conditions in the pipe. Curve-fitting resulted in a formula relating sand characteristics to the geometric properties of the sand bed.

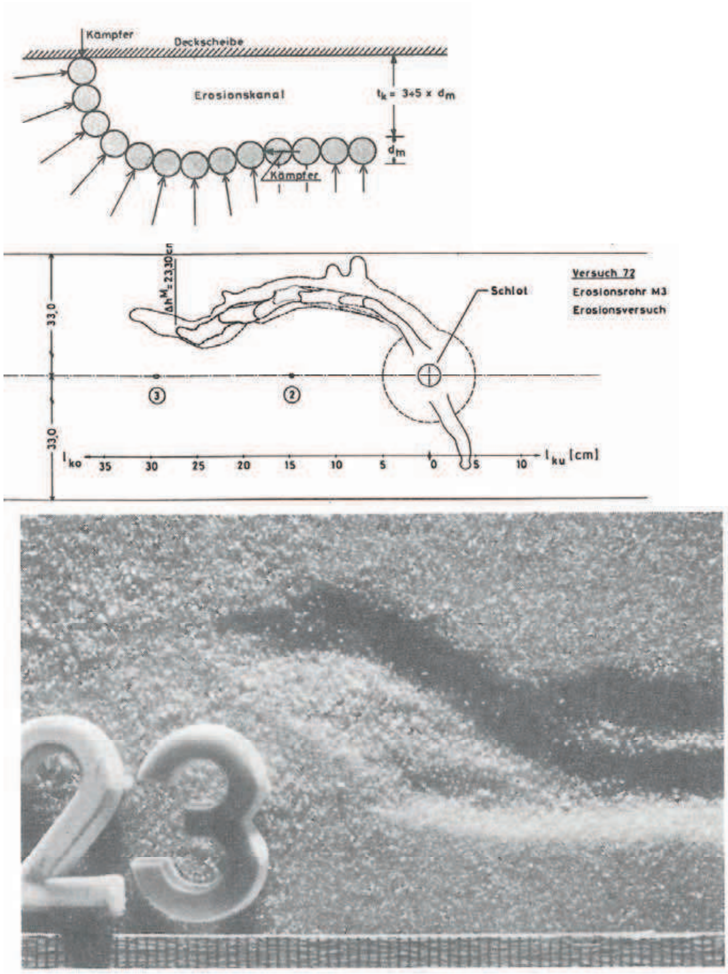


Figure 3, 4 and 5 Detailed study on pipe formation (Hanses, 1985)

Large-scale tests performed in the Delta flume allowed for validation of the model at different scales (Silvis, 1991). Based on values from the literature and these experiments the model was calibrated by adjusting the bedding angle and the final formula (1) was included in the technical report on sand boils (TAW, 1999), which was in use from 1988 to 2010:

$$\frac{H_c}{L} = F_{\mathrm{R}}\, F_{\mathrm{S}}\, F_{\mathrm{G}}\, C \tag{1}$$

$$F_{\mathrm{R}} = \frac{\gamma_p'}{\gamma_w}\, \eta \tan(\theta) \tag{2}$$

$$F_S = \frac{d_{70}}{\sqrt[3]{\kappa L}} \tag{3}$$

$$F_G = \left(\frac{D}{L}\right)^{\frac{0.28}{\left(\frac{D}{L}\right)^{2.8}-1}} \tag{4}$$

$$C = 0.68 - 0.10\ln\left(\eta F_S\right) = 0.82 - 0.10\ln\left(F_S\right) \tag{5}$$

Although the model of Sellmeijer provides a more theoretical explanation of the process than the empirical model of Bligh, it is still an experimental rule. The outcomes of the model of Sellmeijer are limited to the Bligh criteria of 10H and 18H in design guidelines.

During the high water periods of 1993 and 1995, the design level was not reached. In both cases the water level remained about 0.5-1.5 m below design level. Yet in 1993 about 120 sand boils were observed. Most of the sand boils emerged at known problematic locations. For safety reasons, all sand boils were mitigated by building rings of sandbags around the sand boils ('opkisten'), raising the water level in the polder area and by temporary berms ('aanbermen'). During the high water period of 1995, again about 180 sand boils occurred, many of them at the same locations as in 1993. Also new locations were found, as well as locations where the sand boils did not return.

The model showed that sand transport can occur at river levels below the critical head. The presence of many sand boils, even outside the 18H criterium of Bligh, during the high waters of 1993 and 1995 was therefore not necessarily alarming and could be related to local weak points like the presence of a new ditch in combination with a deep sand pit, penetration of the cover layer for drillings and soundings, the presence of sand channels, shortage in seepage length or reduction of the inner slope.

Figure 6 Sand boils during the high water of 1995

**Recent work: Experiment, practice and theory**

Increasing awareness related to rising water levels and the need for knowledge on the safety of the levees resulted in a study which investigated the probability of failure of the Dutch levees flood defences (V&W, 2005). Piping turned out to be the main contributor to the probability of flooding and it was recommended to investigate the reasons for that in more detail. Also, the estimated failure probabilities determined using Sellmeijer's rule raised questions to field experts in the Netherlands. According to calculations with the model of Sellmeijer, the empirical model of Bligh appeared to be unsafe in certain situations. Would piping actually lead to failure of Dutch levees?

The empirical model of Bligh has been compared with cases from the USA along the Mississippi (Ammerlaan, 2007). Figure 7 shows critical sand boil locations observed in 1937, 1947 and 1950. It can be seen that numerous sand boils were observed at H/L values higher than 18. Failure nearly occurred at the Trotters location, where the H/L value also exceeded 18.

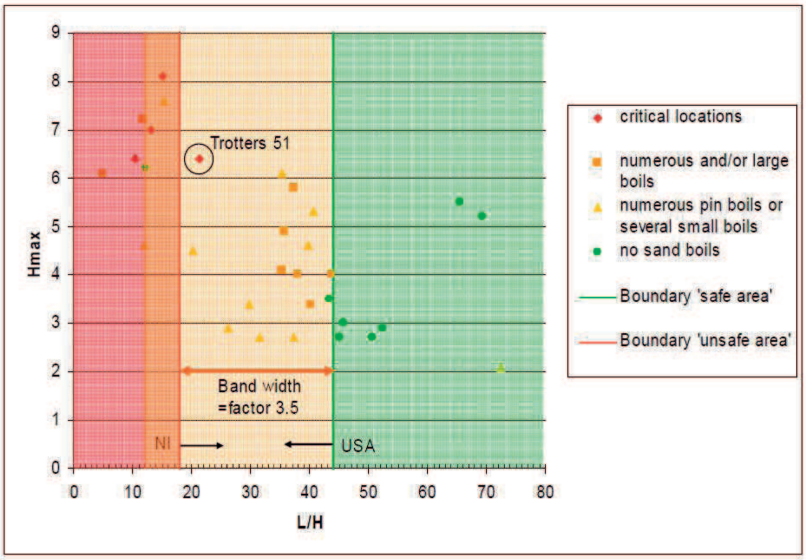


Figure 7 Cases Mississippi River dikes (from Ammerlaan, 2007)

The model of Sellmeijer has been revalidated in a large research program, consisting of a combination of theory, practice and experiments. Small- and medium-scale experiments allowed for the validation of the model for fine sands and for the assessment of the influence of scale-effects on the critical head (Beek, to be published). In these experiments sand was prepared in a PVC box with Perspex cover, retained by two filters. At the downstream side the filter was lower, leaving some space to allow for sand transport. The hydraulic head was increased until a pipe was formed. For coarse sands the original model appeared to overestimate the critical head (Sellmeijer, to be published). Based on these experiments, the model was recalibrated to a new design rule (included in the technical report on sand boils in 2011):

$$\Delta H_c = L \cdot F_{resistance} \cdot F_{scale} \cdot F_{geometry} \tag{6}$$

$$F_1 = F_{resistance} = \frac{\gamma_p^{'}}{\gamma_w}\{\eta \tan(\theta)\} \tag{7}$$

$$F_2 = F_{scale} = \frac{d_{70m}}{\sqrt[3]{\kappa L}}\left(\frac{d_{70}}{d_{70m}}\right)^{0.4} \tag{8}$$

$$F_3 = F_{geometry} \overset{MSeep}{=} F(G) \overset{standaarddijk}{=} 0.91 \cdot \left(\frac{D}{L}\right)^{\frac{0.28}{\left(\frac{D}{L}\right)^{2.8}-1}+0.04} \tag{9}$$

A series of full-scale tests allowed for validation of the adjusted rule as well as the observation of the piping process leading to failure of the levee. In the full-scale test, experiment, practice and theory can be combined, due to the full size, the controlled conditions, available sensor technologies, and available knowledge on the process.

Four full-scale tests were performed, to validate the piping process and to test monitoring techniques. Two types of sand were used ($d_{50}$ of 150 μm and 200 μm), which are denoted as "fine sand" and "coarse sand" respectively. The experiments were performed at the location of the IJkdijk in the Northeast of the Netherlands. Two large basins were created, which were filled with the two different sand types, until the sand bed has a depth of 3m. A clay levee with a height of 3.5 m and slopes of 1:2 was built on top of the sand (figure 8). Accordingly, a levee with a seepage length of 15 m was obtained, as shown in figure 9, over which the hydraulic head can be increased in steps.



Figure 8 and 9 Filling the basins with sand (left) and building the clay levee (right)

Several rows of pore pressure gauges were placed at the interface of sand and clay to be able to monitor the pipe formation. Each test was performed by increasing the hydraulic head difference over the levee, until erosion of sand grains was observed, either by visual inspection or by a change in the water pressures underneath the levee. In all experiments the critical head was determined. The critical head is defined as the head difference at which the pipe grows towards the upstream side without reaching an equilibrium situation.

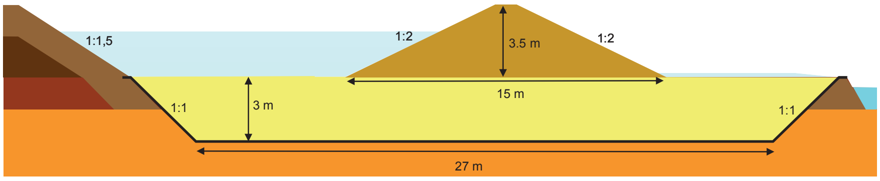


Figure 10 Schematic cross-section of the full-scale experiment

The IJkdijk experiments show that failure of a levee due to piping is certainly possible and that the model of Sellmeijer is able to predict the critical head well (Beek, to be published). The observations made during the experiments correspond well with the observations in the past, both from experimental perspective as well as practice. It is found that the observed processes, despite of differences in scale, are very similar. It is noticed that in all experiments sieved sands are used, where as in practice heterogeneity both at micro-scale and at macro-scale can influence the process. This has not yet been investigated.

Based on the available knowledge, four phases can be observed: seepage, backward erosion, widening of the channel and failure of the levee.

### *Phase 1: Seepage*

Seepage is a precondition for piping. In the full-scale experiments seepage occurred as soon as a hydraulic head fall was applied, as no impermeable soft soil layer was present. In practice wet spots are often observed at the polder side of the levee, when the water pressure is sufficient to create rupture of the cover layer, or when weak spots are present, such as former drill locations.

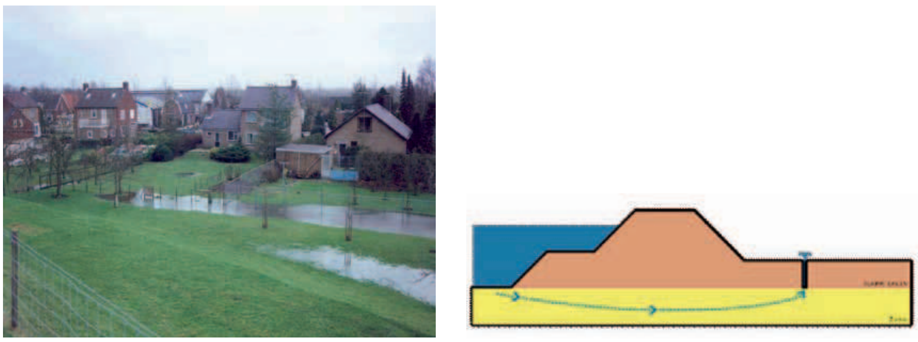

Figure 11 and 12 Wet spots behind the levee (left) and seepage after cracking of the cover layer (right)

### *Phase 2: Backward erosion*

The first indication of erosion consisted of small rearrangements of grains, individual grain movement and the occurrence of tiny channels in the small- and medium-scale experiments. These observations are very similar to the first observations of erosion in the full-scale experiments. These observations consisted of some spots or traces of sand, which were visible across the downstream toe in all tests. The sand traces may indicate a local flow concentration, which flushes out single sand particles, caused by local inhomogeneities or creation of very small pipes. In all of these processes the sand transport reaches an equilibrium situation, in other words, the sand transport stops, unless the hydraulic head fall is increased. In the full scale test, the quantity of sand in the traces remained limited to some cubic centimetres. In practice this amount of sand transport will not always be visible.
After increasing the hydraulic head, sand boils appeared in the full-scale experiment. These sand boils indicate that more water flows out of the aquifer under the levee, probably from a local pipe underneath the levee. The pore pressure measurements show a small decrease at the locations of the sand boils, indicating the presence of a preferred flow path. Sand boils are also observed in the experiments performed by de Wit (1984) and by Müller-Kirchenbauer (1978).

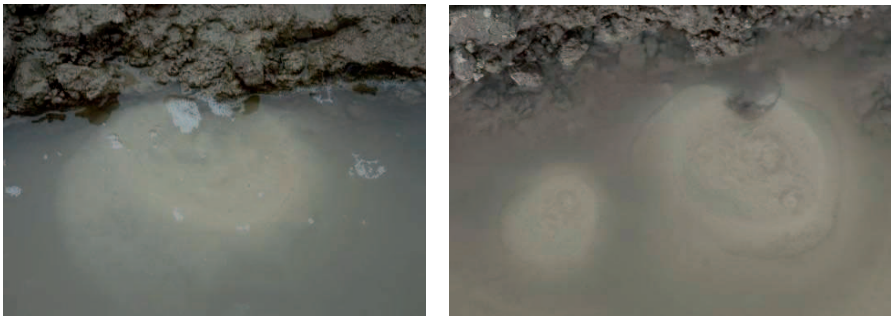

Figure 13 and 14 Sand boils that actively deposit sand at the slope of the crater (test 2)

After further increase of hydraulic head, sand was transported continuously in the small-, medium- and full-scale experiments. A crater formed as a result of sand deposition, with fluidized boiling sand in its centre. Once sand boils are observed in the full scale experiments (figures 13 and 14), the sand transport does not stop.

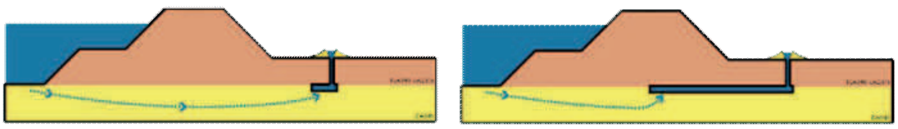

Figure 15 Backward erosion, causing pipe formation

As a result of the sand transport in the small- and medium-scale experiments, a variety of erosion patterns is observed, from a single straight pipe to branching pipes. This variety is also observed in the full-scale experiments, as was found by analysing the water pressure measurements. The location of the pipe is estimated after studying the change in water pressure due to pipe formation. From this analysis, it is concluded that pipe development does not take place across the entire width. One or more groups of meandering pipes grow backwards over a width of several metres.

In all experiments, the flow barely increases as pipe formation takes place. This means that pipe formation has a minimal effect on the bulk permeability and cannot serve as an indicator for piping in practice.

Figure 16 and 17 Sand boils in a ditch

An important finding in this phase is that the sand transport does not cease once it has started. This is observed in both experiments and full-scale tests. This is not in contradiction with the model of Sellmeijer. The model predicts an equilibrium of sand transport until the critical head is reached. An equilibrium situation below the critical head is only observed in the beginning of the experiment, during the occurrence of sand traces. The amount of transported sand is therefore very limited until the critical head is reached (in the order of cubic centimetres). In practice, this amount of transported sand may even not be visible. As soon as sand boils appear, which continue to deposit a significant amount of sand (in the order of cubic decimetres per hour), it is possible that the head is critical.

The amount of transported sand per time unit remains more or less constant as long as the head is kept constant. It is observed that the amount of sand transport increases with increasing head. The backward erosion process may be very slow, but fastens when the head increases.

***Phase 3: Widening of the channel***

The third phase of erosion is widening of the pipe, observed in all experiments. In the small- and medium-scale experiments the process can be observed through the transparent cover, whereas in the full-scale experiments and the experiments by de Wit the process could not be observed visually. In the full-scale experiments the process is analysed from the water pressure measurements. As soon as the pipe reaches with the upstream side, a pressure surge accompanies the flow through the pipe. This pressure surge in turn causes a large quantity of sand to be eroded. In the small-scale experiments, this normally does not lead to considerable blockage of the pipe, probably due to the limited seepage length. However, in the medium-scale and full-scale experiments, blockage took place, due to which the widening process took longer. In these experiments a widened pipe appears to be present upstream of the blockages. The sand in the blockages is subsequently removed during a new process of backward erosion. In this way, the widened upstream pipe becomes progressively longer, moving towards the downstream side of the levee.

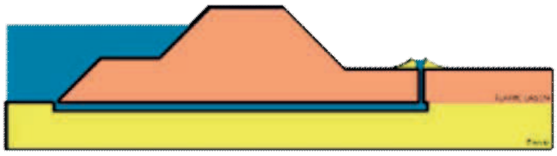

Figure 18 Widening of the channel

During the widening process, the flow and sand transport at the exit point do not increase significantly. Although the process of widening is very fast in the small-scale experiments, it took up to a few days in the full-scale experiments. The process can be faster if the hydraulic head is increased, which has not been investigated yet.

When the widened upstream pipe has almost reached the downstream side, the sand transport and flow increases sharply. The backward and widening processes can be well monitored using pore pressure gauges (figure 19), but in a field situation, without any monitoring equipment, there may be little warning for the failure, as the situation can suddenly change from small sand boils to mud flows and failure.

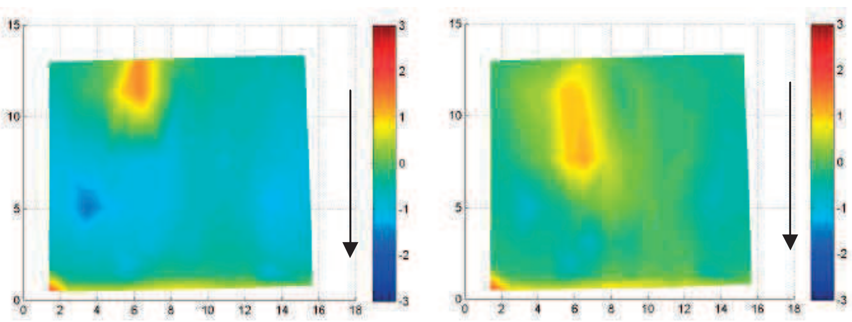

Figure 19 The change in water pressure in the horizontal plane as a result of channel formation, during the widening phase. The increase in pressure at the top of image (orange/red area) shows the presence of a widened (i.e. low hydraulic resistance) area. It can be seen that the pipe widens in the direction of flow (indicated by the arrows). The blue areas indicate a decrease of pressure as a result of backward growing pipes.

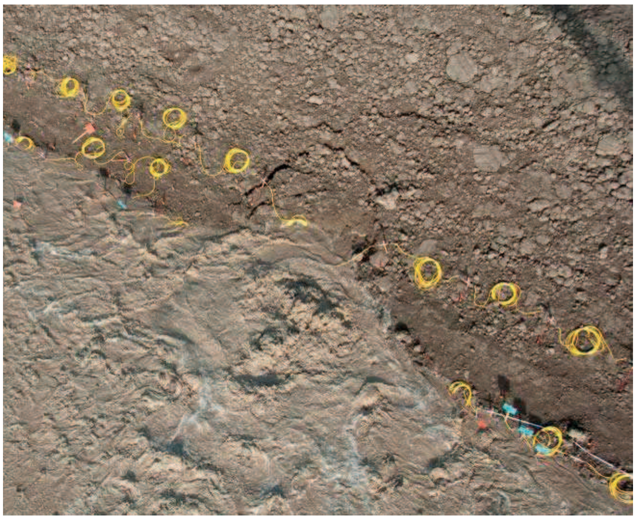

Figure 20 Increase of sand and water transport in experiment 2 (mud fountain)

In practice this process has not been observed, as based on visual observations, the amount of flow and the amount of sand transport, it cannot be judged, whether the process is in the backward or widening phase. The case of Zalk shows remarkable agreement to this finding, as in this case the transition from a small sand boil to failure appeared to be very sudden.

### *Phase 4: failure and breakthrough*

The final process of failure and breakthrough is only observed in the full-scale experiments and in some cases from the past, as the experiments in the laboratory do not allow for failure due to their limited dimensions. An important finding in this phase, is the behaviour of the clay levee. Failure can take place shortly after the first increase of sand transport (widening phase completed), but can also be delayed due to settlement of the levee, which causes the pipes to close. The connection between the upstream and downstream side must be re-established for sand transport and flow to increase again. Several phases of reconnection and deformation can take place before the levee fails. The period from increase of sand transport to failure may therefore be as short as 20 minutes, but it could take also a few days, if the widening process needs to be restarted due to settlement. In the full-scale experiments failure and breakthrough are accompanied by a violent flow of sand and water, mud fountains, cracks in the levee and subsidence of the levee. In the cases Zalk, Nieuwkuijk and Tholen a similar behavior is observed. The transition from sand boils to failure can be sudden and complicates the determination of the seriousness of piping.

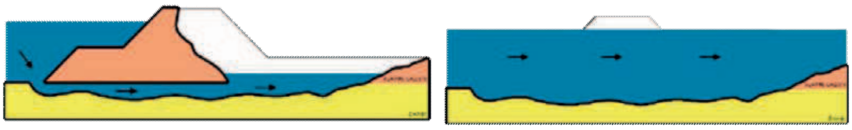

Figure 21 Failure and breakthrough

Figure 22 Breakthrough of the levee in experiment 1

**Lessons learnt on the piping process**

As a result of the laboratory experiments, the full-scale experiments and knowledge from theory and practice, the mechanism of piping is understood better. Under laboratory conditions, in homogeneous sand, piping can be predicted very well. To predict piping in the heterogeneous nature, involving different sand layers or (micro)heterogeneity within layers, is still more uncertain and needs to be studied in ongoing research.

With respect to the prediction in homogeneous sand layers, it appears that the model of Sellmeijer does not overestimate the risks of piping and that the failure probabilities as calculated in safety studies are likely to represent reality. The high water period of January 2011 reflects this idea; even though the water level was still far below design level, a dozen sand craters of significant size (>1 m in diameter) emerged.

Since Bligh's rule was considered unsafe for Dutch dikes, especially for levees with longer seepage lengths, and there have been amendments with respect to the Sellmeijer model, too, new safety assessment rules needed to be defined. Lately, a thorough probabilistic analysis of the model and parameter uncertainties of the revised model as well as their impact on the safety of the dikes has led to a new proposal for safety factors to be used in assessment of existing dikes and design of reinforcements. This approach follows the overall strategy in Dutch flood risk management to achieve a safety level in terms of economically optimal and socially acceptable probabilities of failure. The keyword here is explicit treatment of uncertainties, an addition to the improved insights in the physical processes involved.

## From empiricism towards reliability-based design

The historical development of the engineering view on piping excellently reflects the changing attitude of not only engineers but also the whole society towards safety and the built environment in time. The beginning of the 20th century was the genesis of disciplines such as geotechnical engineering. First steps were taken towards more scientifically sound approaches, based on observations. Since the fundamental knowledge was limited at the time, empirical approaches were very characteristic in that period. Keep it simple, base your actions on what you see in reality. The second half of the 20th century was characterized by much more fundamental approaches. Increasing understanding of soil mechanical behavior, flow and transport etc. lead to assessment and design methods like Sellmeijer's rule. And more generally spoken, that was the time of practically unlimited confidence in science and technology; everything was possible, everything was makeable. Towards the present we see a growing consciousness of what we do not know – uncertainties. There is a strong movement from deterministic approaches with implicit (but not quantifiable) conservatism towards explicit treatment of uncertainties. The safety assessment rules based on the re-calibrated piping model in the Netherlands are an excellent example of that.

## Notations

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|---|---|
| $H_c$ | $H_c$critical head over the levee [m] |
| $\gamma'_p$ | Volumetric underwater weight of particles [kN/m$^3$] $\gamma'_p = \gamma_p - \gamma_w$ |
| $\gamma_w$ | Volumetric weight of water [kN/m$^3$] |
| $\theta$ | Bedding angle [°] |
| $\eta$ | White's coefficient ( = 0,25) [-] |
| $\kappa$ | Intrinsic permeability of the sand layer [m$^2$] $\kappa = \nu{*}k/g = 1{,}35{*}10^{-7}{*}k$ |
| $k$ | Darcy permeability [m/s] |
| $\nu$ | Kinematic viscosity [m$^2$/s] |
| $g$ | Gravity acceleration ($g = 9{,}81$) [m/s$^2$] |
| $d_{70}$ | Grain size at 70-percent cumulative weight [m] |
| $d_{70m}$ | Mean $d_{70}$ of small-scale tests ($d_{70m} = 2{,}08{*}10^{-4}$) [m] |
| $D$ | Thickness of the sand bed [m] |
| $L$ | Seepage length [m] |

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