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A coarse sand barrier as an alternative preventive measure against backward erosion piping

Une barrière de sable grossière comme mesure préventive alternative contre le renard hydraulique

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ABSTRACT: Backward erosion piping is an important failure mode concerning the stability of levees along the main rivers of the Netherlands. The threat has strongly increased because of the expected effects of climate change and tightened assessment rules including higher safety demands and adapted calculation models. In order to prevent the development of a continuous pipe in a sand layer underneath an impervious levee, a barrier made of much coarser sand can be placed in the course of the growing path. Due to the larger grain size of the barrier particles, increasing erosion resistance, and the relatively high permeability in comparison with the surrounding material reducing the load on the barrier, the levee can withstand a larger head drop, resulting in a much higher safety level for the levee. As it does not take up any extra space and may be relatively easy to install, the use of a coarse sand barrier could be a good alternative to conventional prevention measures. To determine the strength of different barrier materials and to get a better insight in the principal mode of action and the scale effects, experiments at different scales have been performed. The research shows that a coarse sand barrier is a highly effective piping inhibiting measurel. This paper presents two large-scale experiments that have been carried out in the Delta Flume facility of Deltares.

RÉSUMÉ: Le renard hydraulique est un mode important de défaillance en ce qui concerne la stabilité des digues le long des rivières principales des Pays-Bas. Cette menace a fortement augmenté en raison de règles d'évaluation strictes et sévères, y compris des exigences de sécurité plus élevées. Afin d'empêcher le développement d'un conduit continu dans une couche de sable sous une digue imperméable, une barrière constituée de sable beaucoup plus grossier peut être placée le long du chemin en formation. En raison de la granulométrie plus grande des particules de la barrière et du contraste relativement élevé de la perméabilité par rapport au matériau environnant, la résistance à l'érosion du matériau de la barrière est élevée, ce qui augmente considérablement le niveau de sécurité de la digue. Comme elle ne prend pas beaucoup de place et peut être relativement facile à installer, l'utilisation d'une barrière de sable grossière pourrait constituer une bonne alternative aux mesures de prévention conventionnelles. Afin de déterminer la résistance de différents matériaux de barrière et de mieux comprendre le mode d'action principal et les effets d'échelle, des expériences à différentes échelles ont été réalisées. Il a été prouvé qu'une barrière de sable grossière est une mesure très efficace pour empêcher l'érosion. Cet article présente les deux expériences à grande échelle réalisées dans l'usine Delta Flume de Deltares.

Keywords: Backward erosion piping; coarse sand barrier; large-scale test; mitigating measures

1 INTRODUCTION

Internal erosion due to backward erosion piping (BEP) can lead to failure of water-retaining structures that are founded on an aquifer which is overlain by a cohesive blanket layer of moderate thickness. Backward erosion piping is one of the most important failure modes for dikes in the Netherlands. The process starts with a break in the blanket layer, such as a crack or a ditch. With a high outside water level, groundwater seepage through the aquifer concentrates towards the open exit point, resulting in locally elevated hydraulic gradients that can cause erosion of sand particles, recognized by the formation of sand boils. One or several shallow pipes are formed which do not collapse because of arching by the cohesive blanket layer material above. If the hydraulic gradient remains sufficiently high, the eroded pipe progresses in the upstream direction. When the pipe contacts the outside water body, erosion in the pipe increases significantly, this can lead to collapse of the levee (Van Beek et al. 2011). For pipes underneath an almost horizontal blanket layer the critical hydraulic gradient across the structure, at which continuous pipe growth occurs, can be predicted by Sellmeijer's model (Sellmeijer 1988).

Recent research work led to an improvement of the Dutch assessment rules (Sellmeijer et al. 2011, Van Beek 2015). This and the more stringent safety standards lead to an increase of the required seepage length to ensure enough safety against failure.

Fulfilling the new assessment rule has a large impact on the costs for strengthening levees, in particular, in densely populated areas of historic interest in combination with a high scenic value of the landscape where little space is available for traditional strengthening measures against backward erosion piping. Traditional measures like landside berms are too costly in terms of land use, and vertical measures like cut-off walls are costly, because of the long stretches that have to be reinforced. Thus, alternative cost-efficient piping mitigating techniques are getting more attractive.

An example for such an innovative measure is the vertically inserted sand-retaining geotextile (Bezuijen et al. 2014, Förster et al. 2015), which is inserted into a trench nearby the dike toe. The top of the trench is then refilled with clay in order to eliminate upward seepage.

The coarse sand barrier (CSB) is a similar alternative to this innovative measure to prevent the pipe from growing further upstream. The geotextile is substituted by a barrier consisting of a narrow and shallow coarse-grained filter that is placed in the top of the aquifer underneath the blanket layer. Negrinelli et al. (2016), Bezuijen et al. (2018), and Rosenbrand et al. (2019) showed by laboratory experiments that a CSB provides significant strength against backward erosion piping.

2 PRINCIPLE OF THE COARSE SAND BARRIER

The effectiveness of the coarse sand barrier relies on the fact that coarse sand provides more resistance to pipe formation than fine sand. A trench is filled with coarse sand and covered with clay to prevent discharge of groundwater by upward seepage.

Failure of the barrier will occur when the hydraulic head across the water-retaining structure is high enough for pipe growth through the barrier. The progression of the pipe in upstream direction as a result of primary erosion (Van Beek 2015) requires exceeding a local critical gradient in the sand directly upstream of the pipe tip (Robbins et al. 2018). This critical gradient will be larger in coarser sand and more graded sand. Furthermore, the actual local gradient in the barrier will be relatively low, because of the higher permeability of the barrier material in comparison to the surrounding material. When the pipe encounters the barrier, it will continue to develop parallel to the barrier in the direction perpendicular to the flow (Negrinelli et al. 2016, Rosenbrand et al.

2018), thereby further decreasing the load in the barrier. The combined effect of the higher resistance, the lower gradients due to permeability contrast and the distribution of flow due to lateral pipe growth cause a significant increase of strength. An additional decrease of the loads in the barrier due to further distribution of flow occurs when the pipe has grown into a (sufficiently thick) barrier, before ultimate failure.

3 FEASIBILITY STUDY

Since scaling effects are associated with piping (Bezuijen and Steedman 2010) a three-stage experimental programme supported by groundwater flow modelling has been carried out to investigate the feasibility and attendant scale effects of this measure. In Koelewijn et al. (2017) the outline of the study is described to quantify the increase in safety achieved by a CSB and to arrive at the validation of the proposed design methods for the application of a CSB in the field as a cost-effective piping mitigating measure.

Several technical requirements apply to the appropriate use of a CSB: the required filter criteria and internal stability criteria, providing sufficient resistance to pipe formation and imperviousness for fine sand are specified by Koelewijn et al. (2017).

Small-scale experiments with a CSB and numerical modelling support the hypothesis that the critical gradient is a material property of the barrier, independent of scale or background sand (Rosenbrand et al. 2018, 2019a). This implies that scaling issues can only occur because ambient gradients differ at different scales.

The experiences with the smaller scale physical experiments in combination with analytical and numerical groundwater flow simulations (Rosenbrand et al. 2019a) were used to estimate the outcome of the large-scale experiments in the Delta Flume and to build confidence in the reliability of the method of analysis (Bezuijen et al. 2019). Finally, these simulations will be used to extrapolate to field-scale under design conditions.

4 LARGE-SCALE EXPERIMENTS

Two large-scale tests were run in the Delta Flume of Deltares. These tests were meant to validate the models on the largest possible scale that allowed for failure at affordable costs. In both tests the same background material is tested in combination with a barrier material, contributing appropriate additional strength against piping but also suitable to reach failure under the attainable load conditions.

The Delta Flume is a hydraulic research facility with an internal width of 5 m, a depth of 9.5 m and a bottom length of 300 m. The model was built inside the flume. The total thickness of the aquifer was 3.0 m, as measured prior to the tests at 21 points. The length of the sand bed was 34.1 m at the top side and 18.0 m at the bottom side of the aquifer. For this aquifer the Delta Flume allows for a maximum head difference of 6.5 m. On top of this sand layer, a continuous clay layer has been placed over a seepage length of 15.5 m in Test 1 and 15.0 m in Test 2, ending at a small ditch (0.5 m bottom width) along the centreline of the flume with a clay cover on both sides over the full length of the outflow section. The inflow section is not covered. Figure 1 shows the general set-up of the Delta Flume tests.

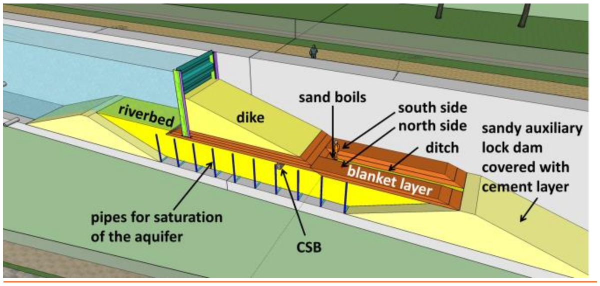

Figure 1 General set-up of the coarse sand barrier model in the Delta Flume

In Test 1 the CSB was situated at a distance of 6.00 m to 6.30 m from the exit point at the face of the ditch, and in Test 2 at a distance of 11.00 m to11.30 m from the exit point (i.e. 3.7 m to 4.0 m from the upstream edge of the clay cover), and extended 0.5 m deep into the background sand. In Test 1 the CSB also extended 0.2 to 0.25 m into the clayey blanket layer, in order to investigate the influence of the positioning of the top of the CSB with respect to the top of the aquifer, given the variability in the field. In Test 2 the top of the CSB was level with the top of the aquifer. The CSB was not applied over the full width of the Delta Flume: near the concrete walls pockets of swelling clay (Mikolit) had been installed over a distance of approximately 0.2 m on both sides over the full width and depth of the CSB.

In both tests the same combination of CSB material and background sand was applied: For the barrier the compound CSB material "GZB2" (d_{50} = 0.870 mm, d_{60}/d_{10} = 2.5) was used, for the aquifer a batch of sand from the Western Scheldt Estuary (d_{50} = 0.23 mm, d_{60}/d_{10} = 1.7). The relative density of the barrier material and the background material was 0.74 resp. 0.35 to 0.65, determined prior to Test 1.

This barrier material was used earlier in the small- and medium-scale tests where it turned out to be less resistant against backward erosion piping than other CSB variants which would have been more optimal barrier materials due to a higher conductivity contrast and a higher strength. The aim of the Delta Flume tests was eventually to achieve failure of the CSB, and therefore a relatively weak material was selected.

In order to reach the maximum achievable head drop a steel bulkhead, situated between 12.17 m and 12.50 m upstream from the ditch, was connected with the flume walls and inserted in the upper part of the blanket layer, as indicated in Figure 1. The sand body of the aquifer was constructed in layers of ca. 30 cm thickness, compacted by a vibratory plate compactor and had been fully saturated after applying vacuum by means of a system of drainage pipes and vacuum tubes in order to avoid any entrapped air.

4.1 Monitoring

Beside the gauges (level meters), belonging to the standard equipment of the Delta Flume, 28 pore pressure transducers (PPTs) were installed (2 at a depth of 2.0 m with respect to the sand-clay-interface and the others directly at the sand-clay interface, which also concerns the PPTs in the coarse sand barrier), as illustrated in Figure 2 and Figure 3.

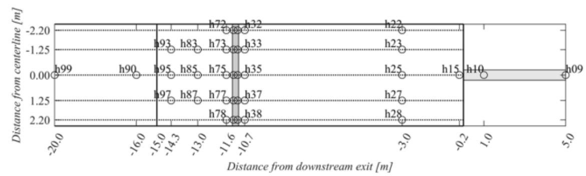

Figure 2 Position of all PPTs along the aquifer in Test 2. The aquifer itself runs on the top from -24.0 m to +10.1 m.

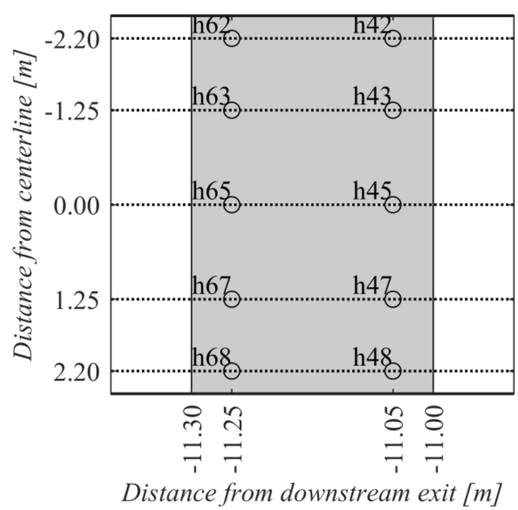

Figure 3 Detailed view of the positions of the PPTs in the CSB in Test 2

In addition, 5 rows of tiny Polystyrene foam balls In Gelatine (PIGs) were built in. These PIGs were expected to flow to the exit point soon after they had been reached by the pipe(s). These PIGs had different colours depending on their position in the set-up, to give an indication of the progress of pipe development, for instance green (at PPTs

42-48) and blue (at PPTs 62-68) at the top of the barrier.

The monitoring in Test 2 also involved water temperature measurements in the top of the sand layer by using actively heated fibre optics, discharge measurements and visual inspections. The area downstream of the bulkhead (cf. Figure 1) was inspected every hour by two trained inspectors. This included searching for any exited PIGs, removal and measuring of the sand in the ditch as produced by the sand boils (to maintain the effective head over the experimental set-up) and detecting any unforeseen and unusual events, like leakage at the bulkhead. During these inspections the flow rate at the downstream end of the ditch was also measured, by collecting the discharge over a given time span in a bucket and weighing the effluent. Upstream inspections were performed at least every six hours.

The head was basically increased every hour, unless one or more of the PPTs had not yet levelled (more than 0.2 kPa variation in the past 30 minutes), the produced amount of sand had increased by more than 20% or the discharge had changed by more than 10% over the past hour. At the beginning of each test, the head was typically increased in steps of 0.50 m, with an expected break at a total head drop of 1 m to enable a precise measurement of the bulk permeability. Once the first sand boils had occurred, the head was increased in steps of 0.10 m only, to ensure that the point of failure would be reached within a reasonable accuracy. At the first test, a head of 4 m, i.e. a head higher than achievable when constructing a dike of soil only, was to be maintained for 24 hours according to the planned load scheme, for demonstration purposes.

4.2 Observations on the piping process

The observed process of pipe formation until reaching the barrier was similar in both tests.

During Test 1 four sand boils had developed, but only two of them continued with boiling. These two started in both corners at the face of the ditch, the other two sand boils started later approximately 30 cm downstream from the others and ran dry later. Approximately 0.5 m³ sand was discharged by the active sand boils. 76 white polystyrene foam balls originating from the area 5 cm downstream from the CSB had been detected, but only one green polystyrene foam ball, originating from the tracer line situated 5 cm upstream of the downstream edge of the barrier, exited and floated on the surface of the ditch water at a maximum head drop of 5.50 m, depicted by Figure 4. This was also the maximum head drop that could be reached before abandoning Test 1 because of serious leakage problems reappearing at the bulkhead connection.

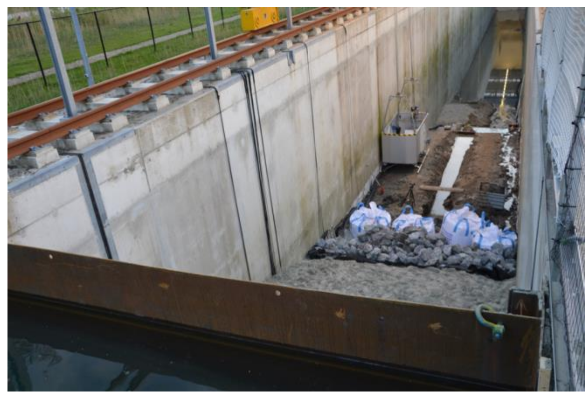

Figure 4 View in downstream direction on Test 1 at maximum head drop of 5.50 m

No clear collapse of the barrier was observed, even at that extremely high head difference despite a slightly, in upstream direction, shifted position of the barrier compared to the projected position of the CSB under field conditions. However, it cannot be ruled out that a pipe did progress in the barrier as discussed in Rosenbrand et al. (2019b). Test 1 had to be abandoned ahead of schedule because of other symptoms of damage. Leakage occurred along the bulkhead connection with the flume wall as a result of an insufficient sealing of the connection and an insufficient embedding of the steel wall into the blanket. This provided the opportunity to excavate the clay blanket layer between the ditch and the levee in order to examine how the pipes had formed underneath the clay layer. Two sand boils were formed beginning from the upstream end of the ditch: one at the southern edge, one at the northern edge (Figure 5). Starting from the sand boil at the southern side a meandering path of deposited sand (partially coarse sand from the barrier) has formed, which has been conserved as positive relief in the blanket layer (Figure 6). This pipe is approximately 5 cm high and 5 cm wide and continues in an angle of approximately 45° in the direction of the flume wall. Nearby the exit point in the ditch the sand path in the blanket layer is cut into the blanket layer.

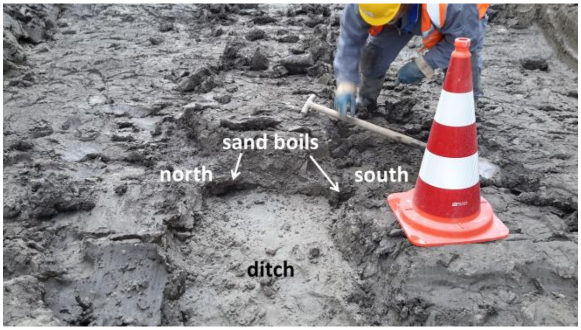

Figure 5 View on the upstream edge of the ditch with sand originating from two sand boils

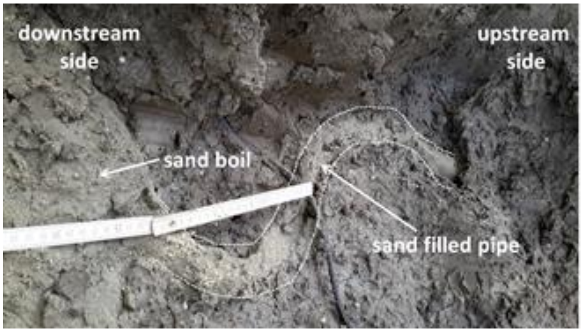

Figure 6 Pipe underneath (and in) the blanket layer, filled up with sand, partially coarse

The pipe on the southern side was followed until half a metre away from the wall of the Delta Flume, where the pipe was turning upstream, parallel to the flume wall. The same pipe was traced again by excavating the southern side of CSB. The sand-filled pipe was 8 cm wide and 5 cm high and at this location it was also situated in the bottom of the blanket layer. Around this location the blanket layer was approximately 5 cm lower in an area of 40 cm wide adjacent to the barrier. It seemed that the sand underneath the blanket layer was eroded so that the blanket layer above subsided. The CSB was partially eroded over a length of half a meter at the location where the southern pipe was leading to (Figure 7). The blue PIGs, lying on this part of the coarse sand barrier, were shifted and there was some fine sand deposited on top of the CSB. As discussed in Rosenbrand et al. (2019b) this sand might be indicative of a pipe progressing through the barrier, however, this did not result in a clear failure or complete erosion of the barrier. The other parts of the CSB were still in their original position, the coarse sand and the green and blue PIGs had not shifted.

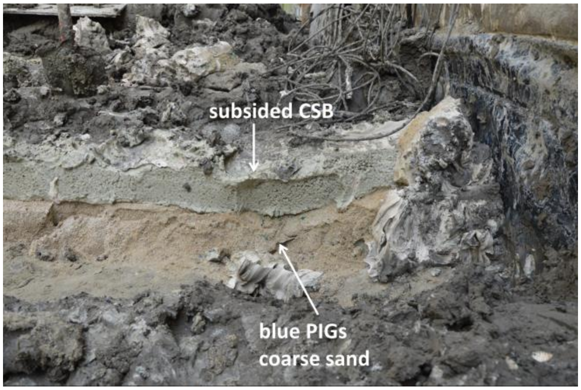

Figure 7 Subsided top of the CSB (view in upstream direction)

In Test 2 the position of the barrier had been changed considerably, it was placed further upstream in order to make failure of the CSB definitely possible. The sealing of the bulkhead connections with the flume walls had been improved.

During Test 2 sand boils emerged not before removing the muddy top of the ditch bed, but then lingered active during the whole test. High amounts of sand were eroded which had to be removed frequently in order to measure the eroded amount and to keep the downstream water level constant.

Due to all these measures the CSB in Test 2 did fail at a head drop (upstream head to h09) of 3.38 m due to backward erosion piping. Analysis of the PPT measurements has to confirm the head drop at which the pipe passed the barrier. At the entry point on the upstream side of the outer dike a huge erosion hole over the whole width of the Delta Flume appeared just before failure (Figure 8).

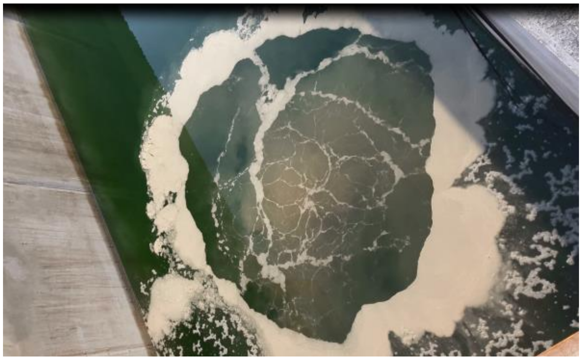

Figure 8 Upstream eddy above the open sand bed as a result of hydraulic short-circuit in Test 2

Figure 9 shows the erosion on the upstream side of the dike after the drawdown.

Figure 9 Erosion along the whole width of the Delta Flume on the upstream side after drawdown

Subsequently, some parts of the CSB were excavated for examination of the failure mode. The CSB was largely eroded, but at some locations parts of the CSB were still intact (Figure 10).

At the location where the upstream eddy stopped (nearby the northern flume wall) the CSB was completely eroded. Pipes could not be found in the downstream background sand after excavation, since all evidence was destroyed after failure.

Figure 10 Irregularly eroded CSB with subsided blanket layer after failing in Test 2 (view in upstream direction). Length of the excavated CSB is approximately 2.5 m.

5 DISCUSSION

In case of more realistic design conditions, concerning the position of the CSB in relation to the exit point and the use of an optimally adapted barrier material, a significantly higher head difference could have been required for failing which will particularly induce another failure mechanism viz. overflow.

6 CONCLUSIONS

Two large-scale experiments for backward erosion piping were conducted in the Delta Flume of Deltares in a set-up containing fine sand and a CSB. In both tests piping initiated in the fine sand and after the pipe had reached the barrier a significant increase in head drop was required for breaching the CSB. Water pressure measurements in several rows along the aquifer were used to follow the progress of the pipe development.

The two tests indicate that a barrier material which is not optimally designed is capable enough to strengthen a levee against backward erosion piping. However, results of the research still require extrapolation to field conditions.

Analysis of pore pressure transducer measurements in combination with observations during excavations are yet to be completed and will be published at a later stage in Rosenbrand et al. (2019b). Numerical analyses of the Delta Flume tests will be published at a later stage.

7 ACKNOWLEDGEMENTS

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