A GRANULAR FILTER FOR THE REHABILITATION OF THE FLOOD DEFENCE AT GAMEREN

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ABSTRACT

Backward erosion piping is a failure mechanism at dams and levees that is normally accounted for in design. However, effects from climate change, land subsidence and socio-economic developments may lead to increased design loads, requiring strengthening of existing structures. A recent development applicable in existing flood defences is the coarse sand barrier: a granular filter constructed near the downstream side of the flood defence, but without the explicit drainage facility usually installed in the case that granular filters are applied at embankment dams. This drainage will instead be created by backward erosion piping during the first significant flood situation occurring after installation of the filter. This is illustrated for a pilot application behind the levee at Gameren, along the Waal River in the Netherlands.

1. INTRODUCTION

1.1 Significance of backward erosion piping

Backward erosion piping (BEP) is a type of internal erosion that poses a threat to both embankment dams and levees founded on a granular aquifer below a cohesive blanket layer. The groundwater flow through the aquifer, driven by the hydraulic head over the flood defence, may lead to erosion of grains at the downstream side after cracking of the blanket layer due to heave (ICOLD, 2017). An increase of the head results in a sand boil, the formation of an erosion lens below the blanket, and one or more pipes that grow upstream until a new equilibrium has been reached and the erosion process stops. However, beyond a certain pipe length, corresponding to the so-called critical head, on-going erosion including pipe growth to the upstream side and enlargement of the pipes is inevitable and failure will occur (Van Beek et al., 2011).

The effects of climate change and land subsidence lead to increased hydraulic loads on flood defences over the coming decades (Hallegatte et al., 2013; Galloway et al., 2016). Meanwhile, flood protection standards generally contain a certain return period or similar requirement, which varies from country to country, forcing improvements to existing flood defences to meet these flood protection standards (Winsemius et al., 2016). Moreover, socio-economic developments may lead to raising these standards, as for instance happened in the Netherlands in 2017 (Klijn et al., 2016; Schweckendiek et al., 2015). In many cases, this urges to improvement measures applicable to existing structures.

1.2 Available solutions

Generally, four groups of solutions are available: an increase of the horizontal seepage length, e.g. by a berm, a vertical screen, e.g. a sheet pile wall, a drainage, e.g. by relief wells, or a filter. This paper presents a novel application of a granular filter: the so-called coarse sand barrier.

In the state of practice as described in ICOLD Bulletin 95 on granular filters, all applications include a constructed drainage measure towards an exit point downstream (ICOLD, 1994). Recently, the use of a vertically inserted sand-retaining geotextile as a filter in the seepage and erosion path was proposed as a remedial measure for existing levees with emerging backward erosion piping issues (Förster et al., 2015). Here, a specific drainage measure is missing, reasoning that drainage will be provided by the pipes forming downstream of the geotextile. This geotextile blocks erosion and subsequent pipe growth further upstream. This same line of reasoning is followed with the coarse sand barrier, leading to significant savings on reconstruction costs.

2. THE COARSE SAND BARRIER

The effectiveness of the coarse sand barrier relies on both a lower hydraulic load on the barrier particles, as a result from its higher permeability and a higher resistance against particle detachment compared to the untreated natural background sand in the aquifer.

The barrier is constructed by excavating a shallow trench in the aquifer near the landside toe of the existing levee, filling this trench with appropriate filter sand to a level slightly above the interface between the aquifer and the blanket layer and covering the trench with a cohesive material. The resulting situation is schematically indicated in Figure 1. After cracking of the cover layer and in the crack at the weakest point (often a ditch), pipe progression is governed by a combination of loosening of grains at the tip of the pipe (primary erosion) and transport of grains on the bottom of the pipe (secondary erosion). Primary erosion is considered to be driven by the local hydraulic gradient at the tip of the pipe, fluidizing a group of grains at the pipe tip (Hanses, 1985; Van Beek et al., 2015; Robbins et al., 2018; Vandenboer, 2019). Secondary erosion can be modelled by limit equilibrium of forces on grains on the bottom of the pipe (Sellmeijer, 1988; Van Beek et al., 2015).

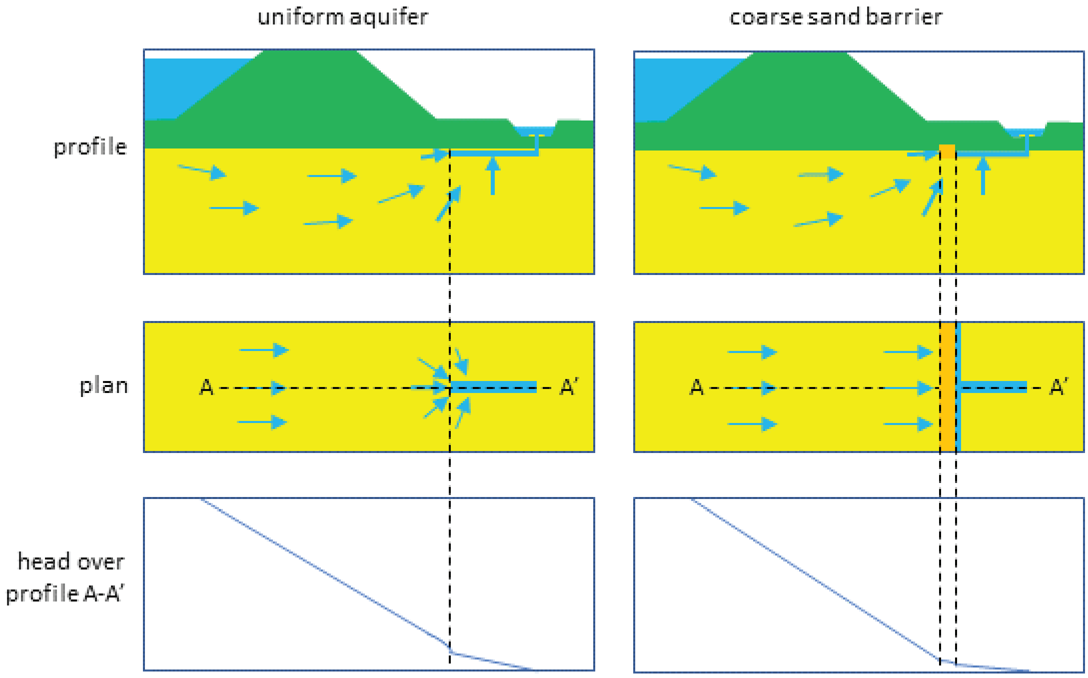

Figure 1 : Concept of the coarse sand barrier: situations without and with a barrier (Rosenbrand et al., t.b.p.).

As illustrated in Figure 1, the hydraulic load on the barrier is reduced in two ways. Firstly, the overall head drop will dissipate predominantly in the aquifer upstream of the barrier, due to the higher hydraulic conductivity of the barrier. Secondly, the pipe will progress parallel to the barrier at the downstream side of it, prior to damaging the barrier as found in experiments at various scales (Negrinelli et al., 2016; Rosenbrand et al., 2018, 2019; Förster et al., 2019), resulting in a more or less 2-D flow pattern with less concentration of flow to possible pipe tips and consequently a lower loading. The requirements of the barrier material are similar to those stated in Bulletin 95 (ICOLD, 1994): internally stable, able to retain the base material, with a higher permeability than the permeability of the background sand and non-cohesive. Moreover, segregation of the barrier material or mixing it with the base material during construction should be avoided.

3. PILOT APPLICATION

3.1 Site description

As the application of a granular filter underneath a levee as a measure against piping is novel, a pilot location has been carefully selected by the responsible water authority. This has been found close to the village of Gameren, along the Waal River (see Figure 2). After the flood of 1995, a new levee was built in front of a six centuries old levee which could not easily be adapted to meet the safety standards at that time. However, this new dike does not meet the current safety standards implemented in 2017, hence an improvement is necessary. For the 1.0 km long part between locations 134 and 144, a coarse sand barrier is preferred.

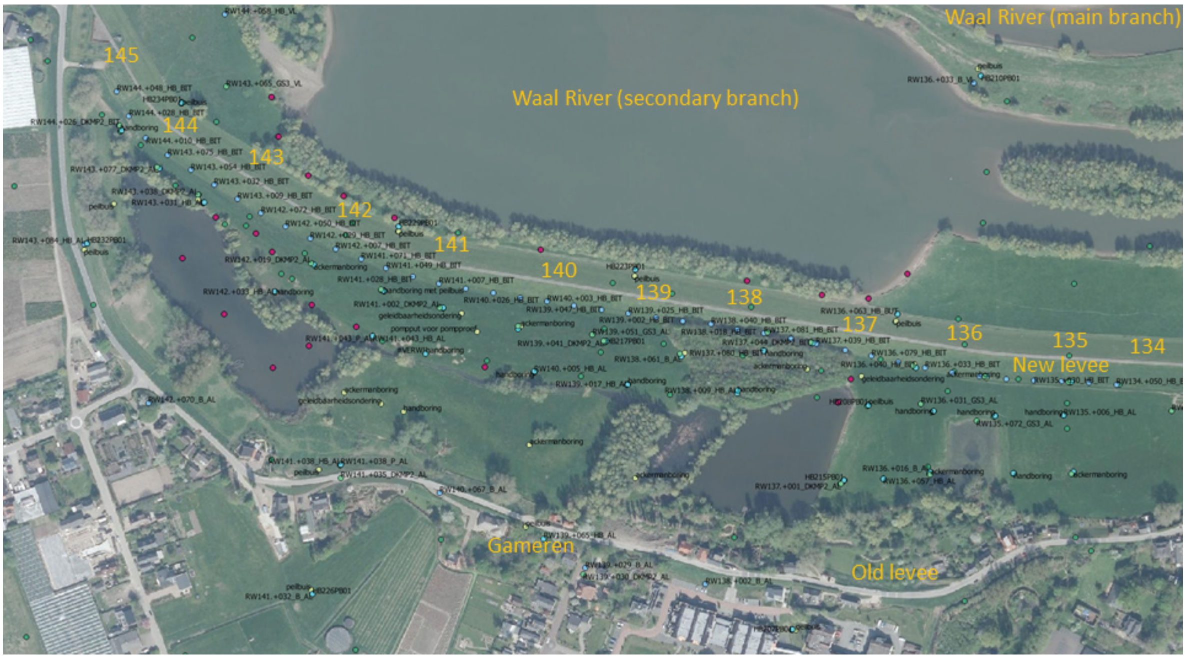

Figure 2 : Pilot site along the Waal River at the village of Gameren.

The village of Gameren and the old levee were built on a river bank with a 5 to 8 metres thick clay layer and a thick sand layer of at least 30 metres underneath. The new levee was built mainly on sand, with a 0.5 to 2 m thick clay layer at the surface and a thin peaty layer with a very low permeability at a depth of around 6 m below the surface underneath most of the area, except at the most eastern part at location 135 and at a sand-filled channel between locations 140 and 141. As visible in Figure 2, the clay layer at the top has been removed at several locations, leaving shallow ponds between the old and the new levee. The wide area in front of the new levee between locations 137 and 143 is a former sand pit, mainly filled with various dredged materials.

As a result of the geology and the complicated recent history of the area, the geohydrological situation is rather complex, while a proper safety assessment regarding backward erosion piping, especially with a coarse sand barrier, requires a reasonable estimate of the geohydrology. Therefore, a large number of borings (indicated in Figure 2) and several cone penetration tests were carried out and a long-term pore pressure monitoring system was installed. Most of this system was already active during a moderate flood (approx. 10 year return period) in early 2018, facilitating the calibration of the geohydrological model used for the calculations.

3.2 Safety assessment of current situation

The levee at Gameren is part of a larger levee system, for which a safety against flooding of 1:30.000 per year is stated by the Dutch law (Dutch Government, 2020). To translate this to an acceptable probability of failure for a specific failure mechanism for a specific part of the levee, both the subdivision over different (weakly dependent) failure modes and the subdivision over mutually independent failure locations (designated as the length effect) need to be taken into account (Schweckendiek et al., 2015). From a nation-wide calibration of safety factors (Huber et al., 2015), this results for the pilot site in a safety factor γ_{mp} of 1.61 to be applied to the results of calculations with the modified rule of Sellmeijer (Sellmeijer et al., 2011). In addition, another partial safety factor needs to be taken into account for the possible error due to the modelling of the subsoil and the geohydrological situation. In accordance with current practice, this factor γ_b has been estimated at 1.1 for the pilot site.

Table 1 shows the results of a safety analysis for backward erosion piping for the current situation for all ten locations along the pilot site. The resulting shortage means that if the actual seepage length would be increased by this distance, the situation would be marginally safe, but this does not imply that no other measures to comply with the required safety against flooding can be taken.

Table 1 : Shortages of seepage length according to the modified Sellmeijer rule along the pilot site at Gameren.

Location	Deepage length (m)	Aquifer thickness (m)	Grain size d_{70} (mm)	Design head (m)	Critical head H_c head (m)	Critical head with safety factors Hc/ $(\gamma_{mp}*\gamma_b)$ (m)	Required seepage length (m)	Shortage (m)
134	120	40.5	0.219	5.87	6.68	3.77	171	51
135	140	3.9	0.219	7.17	13.28	7.50	134	-
136	143	8.0	0.155	7.17	9.92	5.60	183	40
137	82	8.3	0.155	7.20	5.94	3.36	176	94
138	123	6.0	0.155	7.20	9.27	5.24	169	46
139	112	5.7	0.218	7.20	9.88	5.58	144	32
140	127	41.2	0.218	7.20	6.99	3.95	232	105
141	129	8.3	0.218	7.20	10.27	5.80	160	31
142	122	7.3	0.247	7.20	10.58	5.98	147	25
143	129	6.3	0.261	7.20	11.79	6.66	140	11

The aquifer thickness varies mainly with the depth of the basal peat layer. At the two locations where this peat layer is absent, the thickness of the aquifer is much larger. At location 134, the blanket layer is not cut by a ditch, resulting in a higher exit level.

During the moderate floods which occurred in 2011 and 2019 (each with a recurrence period of about once every ten years), a large well was observed near location 143. This well did not seem to carry any sediments. Another observation was that the water level in the area between the old and the new levee was raised by almost half a metre above the inland water level used for the design, because of the inflow of groundwater and the poor drainage facilities towards the hinterland. Yet, the inland level still needs to be taken into account in the safety assessments, as the drainage situation may be improved in the future.

3.3 Choice of barrier material

The choice of the barrier material depends on the materials found in the vicinity of the barrier, as the filter rules should be obeyed. Figure 3 shows all grain size distributions from sieve tests on the sands close to the proposed location of the barrier, as well as the grain size distributions of the materials used in the laboratory tests (GZB1, GZB2, GZB3 and GZB5). GZB1 and GZB2 are mixtures of commercially available sands, while GZB3 is a commercially available fine filter sand. The materials GZB4 and GZB5 are proportionally upscaled variants of GZB1. Both GZB3 and GZB4 can be applied. Because of the better availability, there is a preference for GZB3.

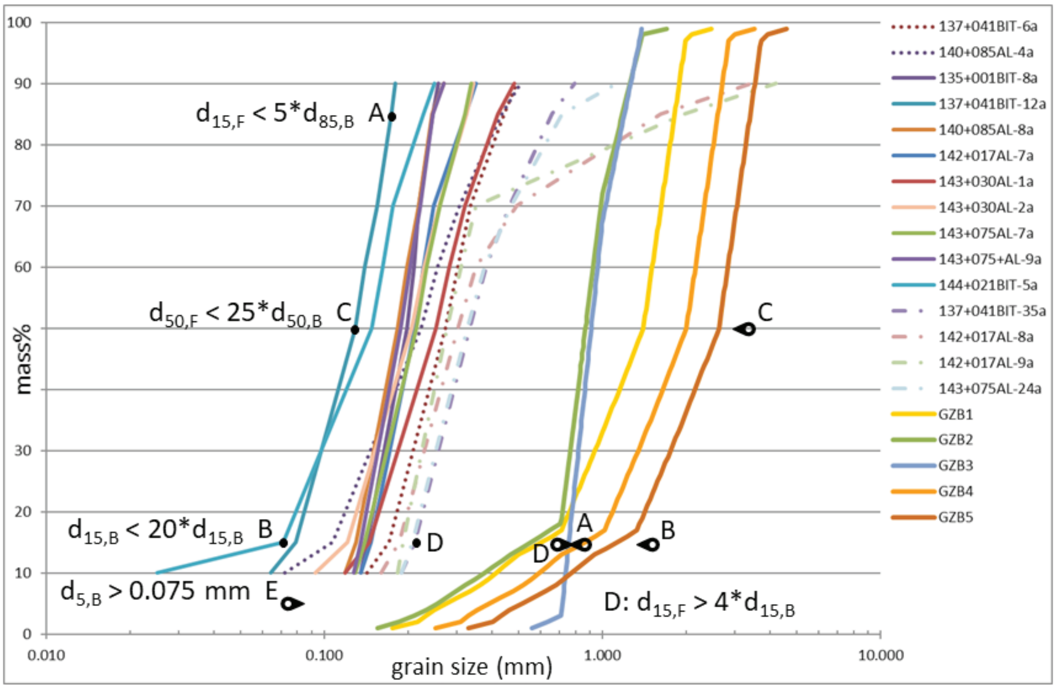

Figure 3 : Grain size distributions as found in the aquifer at the pilot site and for various coarse sand barrier materials, indicating filter rules applied to the normative distributions (subscript 'F' refers to the filter or barrier material, subscript 'B' to the base or background material).

3.4 Safety assessment of the situation with a coarse sand barrier

The geohydrological situation including a coarse sand barrier has been analysed for all ten locations with the DG Flow software package (Van Esch et al., 2013). It has been assumed that the strength of the coarse sand barrier ultimately depends on heave at the upstream side of the barrier, considering erosion inside the barrier leaving a slope as described by Van Rhee & Bezuijen (1992) of at least ten degrees. This is very likely to be a conservative estimate. For the GZB3 material the maximum gradient resisting heave would be 1.04. Based on experiments related to heave at rigid structures (Calle, 1998), a partial safety factor γ_h of 1.7 is applied. Because at a granular filter in case of only limited sideways progression the 3D flow pattern is possibly even more unfavourable than for a more homogeneous situation (cf. Van Beek et al., 2015), an additional partial safety factor γ_{3D} of 3 is applied. Further investigations into this aspect may lead to a reduction of this factor. Finally, the partial safety factor γ_b as explained above is applied. This results in a criterion of $1.04/(\gamma_h*\gamma_{3D}*\gamma_b) = 1.04/(1.7*3*1.1) = 0.19$ as a maximum permissible gradient. Table 2 shows the calculated values at the pilot site, which are all lower. Therefore, this granular filter provides a safe solution against backward erosion piping.

Table 2 : Hydraulic gradient in a coarse sand barrier at the pilot site.

Location	Design head (m)	Minimum pipe length (m)	Calculated hydraulic gradient (-)
134	5.87	15	0.16
135	7.17	28	0.10
136	7.17	22	0.17
137	7.20	22	0.13
138	7.20	64	0.17
139	7.20	59	0.09
140	7.20	69	0.16
141	7.20	54	0.10
142	7.20	56	0.07
143	7.20	25	0.10

The minimum pipe length is the distance from the exit point to the coarse sand barrier. This has been taken into account by a slight reduction of the head difference, considering the flow resistance in a well-developed pipe (Van Beek, 2019).

An extensive failure tree analysis has been performed, considering causes from design, construction and management (Koelewijn, 2019). This indicated that all other possible causes of failure can be either excluded or minimized to such an extent that these are negligible.

4. CONCLUSIONS

For the pilot site at Gameren, the application of a coarse sand barrier promises to solve the significant flood safety gap related to backward erosion piping there. The insufficient safety of this existing flood defence primarily derives from increased safety requirements and climate change resulting in a higher flood level to be accounted for than at the time of construction. The coarse sand barrier is a granular filter constructed near the downstream side of the flood defence, but without the explicit drainage facility usually installed in the case that granular filters are applied at embankment dams. This drainage will instead be created by backward erosion piping during the first significant flood situation occurring after installation of the filter.

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