The development of a coarse sand barrier as an effective measure against piping underneath dikes

Le développement d'une barrière de sable gros comme mesure efficace contre le renard

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ABSTRACT: Backward erosion piping is a serious threat to dikes founded on sand. Along the main rivers of the Netherlands, it is one of the major issues. For several reasons, including a higher safety demand, this threat has strongly increased recently. Therefore the traditional measure consisting of a landside berm becomes too costly in terms of materials and land use with a length of tens of meters. Moreover, behind many dikes people live at a rather close distance to the dike. Vertical measures like sheet pile walls are even more costly, because of the long stretches of dikes that are potentially to be reinforced. With a thin but continuous barrier of coarse sand, covered by clay, installed underneath an existing dike, a cheap and yet effective measure against piping is achieved, with the ability to withstand a hydraulic head that is considerably higher than the head that can be withstood without this measure for dikes of sizes common along the rivers in the Netherlands. This paper describes the research to be performed to quantify the increase in safety achieved with this measure, before field application at a large scale in the Netherlands can start. Tests at various scales are planned, varying from small-scale tests with seepage length of 0.35 m to large-scale tests using the full 9.5 m depth of the Delta Flume.

RÉSUMÉ : Le renard est une menace sérieuse pour les digues fondées sur le sable. C'est un des périls plus sérieux le long des grands fleuves des Pays-Bas. Récemment, cette menace a fortement augmenté par augmenter le niveau de sécurité, le changement climatique et l'adaptation du modèle de Sellmeijer. La mesure traditionnelle consistant en une berme devient trop coûteuse avec une longueur de quelques dizaines de mètres. Aussi, souvent des maisons doivent être démolies. Des mesures verticales sont encore plus coûteuses en raison de la longueur des améliorations. Avec une petite barrière de sable gros installé sous une digue existante, couverte par l'argile, une mesure pas cher et pourtant efficace contre le renard est atteint, avec la capacité de résister à une pente qui est considérablement plus élevée que sans cette mesure. La recherche pour arriver valider cette mesure est décrite. Des tests à différentes échelles seraient réalisés, variant des essais à petite échelle avec une longueur d'infiltration de 0,35 m à des tests à grande échelle avec une pente maximale de plus de 6 mètres.

KEYWORDS: dike safety, backward erosion, piping, coarse sand barrier, filter, scale test, Delta Flume.

1 INTRODUCTION

Backward erosion piping is an internal erosion mechanism for water-retaining structures founded on granular layers. Shallow pipes are formed at the interface of a cohesive layer and a sandy layer, due to the removal of sand particles under the action of water flow, starting at the downstream side and progressively moving towards the upstream side. This phenomenon is recognized by the formation of sand boils downstream of the structure, where the sand particles are being deposited in a ring around the boil. Ongoing pipe development can lead to severe erosion and finally failure of the water-retaining structure. The foundation that is susceptible to this mechanism, a combination of a uniform sandy layer covered by a cohesive layer, is often encountered below river dikes in deltaic areas. Numerous sand boils have been observed in the past, but failure due to backward erosion piping is quite rare. Nevertheless, several dike failures in the Netherlands, Italy, China and the U.S. are attributed to this mechanism (Vrijling et al. 2010, Cirio et al. 2004, Calabresi et al. 2013, Camici et al. 2015, Yao et al. 2009, USACE 1956).

In the Netherlands, safety assessment for backward erosion piping is conducted with the Sellmeijer model (Sellmeijer 1988, Sellmeijer et al. 2011, TAW 1999). The Sellmeijer model predicts the head difference across the structure that once exceeded will lead to ongoing pipe formation. The progression of the pipe is considered the critical stage in the entire process. In other words, once the pipe has progressed along a critical length under the water-retaining structure, it will lead to breaching when hydraulic loads sustain. This model predicts the critical head on the basis of the groundwater flow towards the pipe, the viscous flow through the pipe and the limit-state equilibrium of particles at the pipe bottom. The model has been validated using experiments, but application in the field proves to be complex, as required parameters like particle size and permeability are difficult to determine and show large fluctuations in the field. The uncertainty with respect to input parameters leads to the selection of safe estimates, such that considerable dike reinforcements are due. The more stringent safety standards, due to a recent validation of the model (Sellmeijer et al. 2011), the inclusion of the length-effect (Kanning 2012) and the risk approach, recently embraced in the Netherlands (Kind 2014, Van der Most et al. 2014), lead to a further increase of the dike length to be reinforced.

In the Netherlands, reinforcements for backward erosion piping are traditionally conducted using berms or cut-off walls. Berms are becoming less attractive with increasing required seepage lengths and when houses are situated closely behind the dikes. Sheet pile walls are an alternative, but are economically unfeasible when it comes to application for long dike stretches. Innovative or alternative piping measures are therefore becoming more attractive. An example of an innovative measure is the vertical sand-retaining geotextile (Bezuijen et al. 2014, Förster et al. 2015). Using this method, nearby the toe of the dike a vertical geotextile is inserted into a trench. Above the sand layer the trench is refilled with clay, such that upward seepage is not possible. An optimization of this innovative solution is proposed: a coarse sand barrier. In this solution the pipe formation is resisted by coarse sand instead of a geotextile.

This paper describes a few relevant tests and the feasibility study required for safe design and application in practice.

2 PRINCIPLE OF THE COARSE SAND BARRIER

The coarse sand barrier relies on the concept that coarse sand provides more resistance to pipe formation than fine sand: once a pipe develops and encounters a barrier of coarser sand, the progression of the pipe will stop (Figure 1). After trenching and simultaneous filling with coarse sand, the trench is covered with clay, to prevent upward seepage. Due to the clay filling above the barrier, the method is different from a more common filter, which aims for controlled discharge of water.

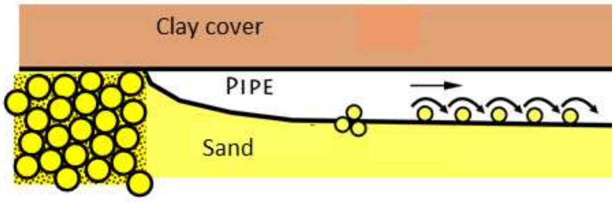

Figure 1. Principle of the coarse sand barrier

Failure of the barrier will occur when the hydraulic head across the water-retaining structure is high enough for the pipe to progress through the barrier. The permeable barrier will deflect excessive vertical seepage below the pipe tip, such that fluidisation of the sand bed below the pipe is less likely than for an impermeable structure like a sheet pile wall.

The effectiveness of the barrier can be attributed to various factors. The progression of the pipe requires a local critical gradient in the sand directly upstream of the pipe as illustrated in Robbins et al. (t.b.p.). For a coarser sand this critical gradient will be larger, thereby forming a barrier for pipe formation. In addition, the actual local gradient in the barrier will be relatively low, since the barrier material is more permeable than the material surrounding it. Several studies (Van Beek et al. 2008, Ding et al. 2008, Dolphen 2014, Förster et al. 2015) indicate that once a pipe encounters a barrier of any kind, it will continue to develop parallel to the barrier (i.e. in the direction perpendicular to the flow). As a result, the local gradient upstream of the pipe will decrease further due to the distribution of flow, as was illustrated by Negrinelli et al. (2016). These three effects combined – larger grain size, lower existing gradients due to permeability contrast and distribution of flow due to lateral pipe migration – cause a significant increase of strength.

3 PROOF OF CONCEPT

Laboratory and field experiments conducted in the past years illustrate the effectiveness of the coarse sand barrier. Small-scale laboratory experiments were conducted by Van Beek et al. (2008) and Negrinelli et al. (2016). Two configurations were used, one with an open exit representing a 2D exit with unconstrained flow towards the surface and one with a circular exit in the cover, representing a 3D exit with concentrated flow towards a single point. In both configurations the box was filled with fine sand (total seepage length of approximately 0.35 m) with a band of (medium) coarse sand. The acrylate cover of the box represented the blanket layer and dike. A head difference, resulting in horizontal water flow, was applied to the sand bed until full pipe formation occurred (critical head). The experiments illustrated the resistance of the barrier to backward erosion and the consequent lateral migration of the pipe along the barrier.

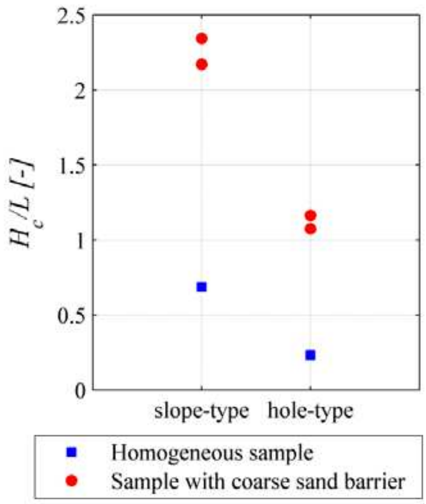

Figure 2. Critical gradients obtained in the experiments

A comparison with reference experiments, without barrier, illustrates the effectiveness of the barrier in terms of critical gradients (Figure 2).

In 2009 and 2012 large-scale experiments were performed at the location of the IJkdijk, a test site in the North-East of the Netherlands. In these tests an actual dike was built on top of a sand bed placed in a basin. The test dike was 3.5 m high, 15 m long and 15 m wide at its base. It was constructed of compacted clay. The base consisted of a 3 m thick sand layer which extended 15 m beyond the test dike both at the upstream side and at the downstream side. Homogeneous tests without coarse sand barrier were conducted in 2009 (Van Beek et al. 2011). In 2012 piping measures were tested, one of which was a coarse sand barrier (Koelewijn et al. 2014). This coarse sand barrier was applied as an obstructing bar underneath the dike, 0.5 m wide and 0.5 m deep, at about one quarter of the seepage length from the downstream toe. The water level in the experiment with the barrier was raised to the maximum level of 3.49 m, at which it did not fail due to piping. In 2009, the dike failed at a hydraulic head difference of 2.1-2.3 m. These experiments indicate that at this scale the dike with the coarse sand barrier can withstand a head that is at least 1.6 times of the critical head of a dike without the barrier.

4 PROPOSED DESIGN METHODS

Before application in the field is possible a design method should be available, which has been validated at different scales. The validation at different scales is required because of the scaling effects associated with piping (Bezuijen and Steedman 2010). Practical aspects related to installation of the barrier, e.g. employing a trench cutter, are not considered here.

4.1 *Filter criteria*

The barrier faces several technical requirements: it should provide sufficient resistance to pipe formation, it should be internally stable and the upstream sand should not move through the barrier. This complies with the general criteria for filters (ICOLD 2015), except for the 'sufficient drainage' criterion mentioned there. For application in rather uniform soils, as encountered in the Netherlands, compliance with the basic filter rules (Lambe and Whitman 1969) is basically sufficient, i.e. $D_{15,\,filter}/D_{85,\,soil} < 5$ and $D_{50,\,filter}/D_{50,\,soil} < 25$. In addition, the barrier material should not be cohesive, to avoid crack formation. USACE (2000) gives as a rule $D_{5,\,filter} > 0.075$ mm. According to that same reference, if gravel is present, the particle distribution should be determined for the fraction smaller than 4.75 mm. For sandy sediments containing both clay and gravel $D_{15,\ filter}$ should be larger than 0.7 mm. Following USACE (2000), no specific criterion is applied to ensure the permeability. Yet, additional criteria are formulated to ensure the resistance to pipe formation.

4.2 *Criteria for resistance to pipe formation*

It is expected that pipe formation in the coarse sand barrier will take place once the local critical gradient upstream of the pipe exceeds the critical local gradient. The local gradient in the barrier just upstream of the pipe can be predicted using numerical groundwater flow calculations. The local gradient will depend on the size of the aquifer, the permeability contrast of the aquifer and the barrier, and the depth of the barrier. Theoretically, the local gradient will also depend on the head drop in the pipe, but it is expected that this can be neglected, since the head drop in the pipe will decrease rapidly as a result of pipe depth increase due to ongoing erosion in the pipe. The local critical gradient is yet unknown for the barrier material and will be subject of investigation.

5 POTENTIAL FIELD APPLICATION

Based upon the results found so far, the coarse sand barrier is expected to add a considerable resistance against backward erosion piping. The associated costs are likely to be very modest, even compared to a berm: preliminary calculations indicate that the break-even point is at a deficit in seepage length of around 5 metres, while the barrier is always cheaper than a vertical geotextile. Considering the required dike improvement works related to piping in the next decade, application of this solution in the Netherlands alone is likely for at least 100 kilometres of dike. This justifies a significant investment in an extended feasibility study, to be followed by field trials aiming at the reliable application of this solution (Senhorst 2016, Tonneijck 2016).

6 FEASIBILITY STUDY

A feasibility study is proposed to validate the proposed design methods. Since the local gradient upstream of the pipe depends on the size of the aquifer, and scale effects are thus expected, the feasibility study consists of laboratory experiments at three different scales: small, medium and large scale. The laboratory experiments will be accompanied by numerical simulations. The proposed research programme is preliminary and may be adjusted based on experimental and numerical findings.

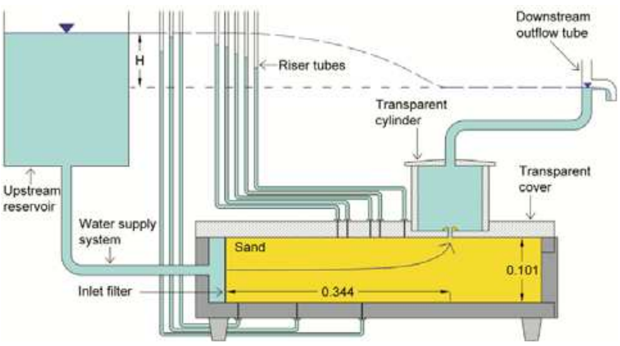

Figure 3. Schematic cross-section of the small-scale experimental set-up (all dimensions are in metres) (Negrinelli et al. 2016)

6.1 *Small-scale experiments*

The objective of the small-scale experiments is to validate the approach of comparing the existing local gradient in the coarse sand barrier, upstream of the pipe, to the local critical gradient, and to quantify the local critical gradient. The small-scale experiments will be conducted in the set-up described by Negrinelli et al. (2016), with a circular exit, a configuration commonly observed in the field. A sketch of the laboratory set-up is shown in Figure 3.

In the experimental programme several variations will be introduced to quantify the local critical gradient for different soil types. At this point three different barrier materials are proposed for testing. Essentially, the background material (simulating the aquifer) does not affect the local critical gradient, as this is assumed to be a property of the barrier material. However, the contrast in permeability of background material and barrier material does affect the local gradient in the sand barrier upstream of the pipe, and will therefore affect the overall critical gradient. Conducting tests with different background materials is therefore useful to test the proposed design concept. Three types of background materials will therefore be tested in combination with one of the coarse sands. The penetration depth of the barrier also affects the local gradient in the coarse sand barrier directly upstream of the pipe. One experiment will be conducted to investigate the influence of penetration depth. Reference experiments without barrier will be conducted for the three background materials as well. Based on the experiments one preferential barrier material will be chosen. Finally, experiments are foreseen which aim to eliminate the possibility of other failure mechanisms of the barrier, such as vertical fluidization.

6.2 *Medium-scale experiments*

The size of the aquifer has different effects on the formation of the pipe. Firstly, the pipe that will develop downstream of the barrier will increase in length with increase of scale. Secondly, a larger aquifer depth will result in increased flow towards the barrier, and thus in increased local gradients upstream of the pipe. It is therefore that the average critical gradient across the structure will be lower for larger scale (Bezuijen and Steedman 2010, Van Beek 2015). The objectives of the medium-scale experiments are therefore threefold: 1. to validate the proposed design method at larger scale, 2. to validate the local critical gradients and 3. to investigate the pipe behaviour at larger scale. The variations proposed are three background materials in combination with the preferential barrier material, as well as reference tests of the three background materials and one test with limited barrier depth.

6.3 *Large-scale experiments*

The large-scale experiments basically validate the scale effects at the largest possible scale at which the test can be carried out until and including failure, without prohibitive costs. Only one background material is tested, in combination with the preferential barrier material. Two duplicate tests will be run using the Delta Flume facility.

The Delta Flume is a hydraulic research facility with an internal width of 5 m, a depth of 9.5 m and a (flat) bottom length of over 200 m. A configuration similar to the one at the IJkdijk tests will be made here, with an overall seepage length of 15 m and a total thickness of the sand of 3 m, see Figure 4. In contrast to the earlier test at the IJkdijk, the Delta Flume allows for a maximum head of 6.5 m. The coarse sand barrier is placed at one quarter of the total seepage length, from the downstream side. The preliminary thickness of the barrier is 0.3 m and it extends 0.5 m into the background sand and 0.2 m into the clay cover.

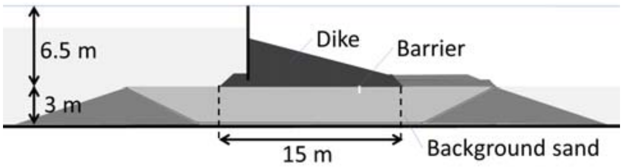

Figure 4. Cross-section of the large scale experiments in the Delta Flume

6.4 *Numerical simulations*

All tests are supported by numerical simulations, both for predictions of the tests and for analysis afterwards. The simulations will be done using finite element software for groundwater flow including applicable erosion laws: MSEEP (2D) (GeoDelft 2002, Sellmeijer 2006) and the recently developed DG-Flow (2D and 3D) (Van Esch et al. 2013ab).

The experiences with the smaller scale experiments, both with the physical experiments and with the numerical simulations, are used to estimate the outcome of the large scale experiments and to build confidence in the reliability of the method of analysis. Finally, the simulations are used to extrapolate to field conditions under design conditions.

7 CONCLUSIONS

The outline of a multi-stage experimental and numerical feasibility study is described to arrive at the validation of the coarse sand barrier as a cost-effective method to improve the safety of a dike against backward erosion piping.

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