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Vertically inserted geotextile used for strengthening levees against internal erosion

Géotextile inséré verticalement utilisé pour la consolidation des digues face à l'érosion interne

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ABSTRACT: The effectiveness of a vertical inserted geotextile against internal erosion, in particular backward erosion, has been investigated. Some small- and medium-scale tests were performed as well as a field-scale test and compared with test series without any erosion mitigating measure. All tests demonstrated that the geotextile shield was very effective to prevent backward erosion. Numerical analysis showed that it was more effective than an impermeable sheet pile of the same length. The paper describes the technique in more detail as well as the results of numerical calculations. Furthermore, the test facilities are described.

RÉSUMÉ: L'efficacité d'un géotextile inséré verticalement face à l'érosion interne, en particulier l'érosion régressive, a été étudiée. Des essais à petite et moyenne échelles ont été réalisés ainsi qu'un essai grandeur nature et comparés aux séries d'essais sans aucune mesure prise pour atténuer l'érosion. Tous les tests ont montré que le géotextile est très efficace pour empêcher l'érosion régressive. Des analyses numériques ont montré qu'il était plus efficace qu'un mur de palplanches imperméable de même longueur. L'article décrit la technique plus en détails, ainsi que les résultats des calculs numériques. Par ailleurs, les conditions d'essais sont décrites.

1 INTRODUCTION

Internal erosion due to backward erosion (in Dutch also called 'piping') is one of the most important failure modes in the Netherlands, concerning the stability of cohesive water-retaining structures founded on a sandy aquifer. Though backward erosion had not yet led to levee-failure in the Netherlands since 1926, this cannot be excluded at design water levels.

The prevailing assessment and design rules underestimate this failure mechanism. Recent Dutch research work led to an improvement of the assessment rules (Sellmeijer et al. 2011). A consequence of these tightened rules is an increase of the required seepage length to ensure enough safety against failure. It is expected that fulfilling these prospective assessment rules will have a large impact on the costs for strengthening levees, in particular, in densely populated areas where little space is available for traditional strengthening measures against backward erosion. Thus, alternative cost-efficient techniques are required. Other piping prevention methods, as sheet piles, filters and dewatering pipes, have already been used, but the use of a geotextile to prevent backward erosion piping is new.

2 BACKWARD EROSION MECHANISM

For a better comprehension of the issue and deducing this practical alternative approach for strengthening, the backward erosion process is described firstly.

2.1 *Description of the backward erosion process*

When the seepage of groundwater in the aquifer concentrates at an open exit point due to e.g. cracks in the blanket layer of the hinterland, the high flow velocity near the exit can cause an emission of sand grains at that location. This results in an erosion process in the sand layer just below the cohesive layer. Consequently, shallow pipes are formed which do not collapse because of the arching action of the cohesive material. The pipes grow from downstream to upstream, finally forming a direct connection. This leads to a facilitated water transport and consequently to accelerated erosion. The pipe dimensions increase fast until the limit state of the arching action of the cohesive soil is reached, resulting in a (partial) collapse of the water-retaining structure (Beek et al. 2010).

For pipes beneath an almost horizontal clay layer the hydraulic head fall can be predicted by Sellmeijer's model (Sellmeijer 1988). In 2009 four full-scale piping tests were carried out, which were preceded by a series of small- and medium-scale tests. Based on these test series Sellmeijers's rule has been adjusted (Sellmeijer et al. 2011). This revised rule will be part of the prospective Dutch flood defence assessment rules.

2.2 *Principle of the vertically inserted geotextile*

A possible approach for preventing the development of a continuous pipe underneath the water-retaining structure is the interference with the sand transport.

This can be tackled by applying a vertically inserted geotextile shield in the upper part of the aquifer, fixed in the upper clay cover layer.

The main principle of operation of a vertically inserted geotextile as a measure to prevent backward erosion is that the transport of sand grains at the interface with the overlying clay layer will be blocked, while the groundwater flow is not affected by the geotextile, because of its high permeability (Figure 1).

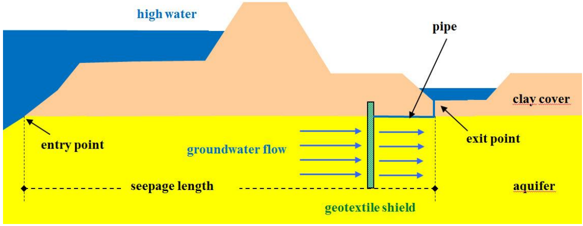

Figure 1. Principle of operation vertically inserted geotextile.

In principle, this technique does not require a minimum seepage length what is required, according to Sellmeijer's theorie, for ensuring a stable equilibrium of forces round the sand grains, so that no further sand transport will occur. It is thereby a space-saving strengthening technique.

Terzaghi & Peck (1967) describe a different internal erosion mechanism: heave that occurs in the vicinity of an impermeable vertical shield in sand as a result of fluidization of sand downstream the shield.

For applying geotextile as an inhibiting measure against backward erosion both erosion mechanisms, the forming of a horizontal pipe due to backward erosion and the heave, need to be checked. The latter becomes important when vertical gradients occur.

3 EXPERIMENTS

In order to get a better insight in the principle mode of action of the geotextile shield, two small-scale experiments were carried out. The critical gradient where piping starts depends on the scale (Beek et al. 2010; Bezuijen & Steedman 2010). Thus, to receive an impression of the scale effect of this measure and to limit boundary effects, two medium-scale experiments have also been performed. While tests that merely investigate the backward erosion mechanism with and without geotextile can be performed at small-scale, it is only possible to get quantitative information on the influence of this prevention measure on the dike stability in field-scale testing.

A test on field-scale has been performed on the IJkdijk facility to check the erosion mitigating performance under real circumstances. The IJkdijk (Dutch for 'calibration dike') is a Dutch test site at Booneschans, in the North-East of the Netherlands, where tests on geotechnical failure modes of levees on large scale can be carried out. The four piping tests performed in 2009 (Beek, Knoeff & Sellmeijer 2011) served as a benchmark for the effectiveness of the geotextile.

3.1 *Setup lab experiments*

First, two small-scale experiments were carried out in a PVC box (inner dimensions l*w*h = 0.50*0.30*0.10 m) with transparent acrylate (Perspex®) cover, imitating the behaviour of a cohesive layer while permitting observation of the pipe development from above. The length of the seepage path in this setup is ca. 0.34 m. A detailed description the general small-scale setup (without geotextile) is given by Beek et al. (2011). The sand has been prepared using the "wet method", in which dry sand is 'rained' into water with the box in vertical direction. Densification takes place by continuous tamping during the raining of sand. These methods ensure a homogeneous and well saturated sample. In the small-scale tests fine-grained sand (d_{50} = 220 µm, relative density 90 %) is used.

In the geotextile setup the inserted depth of the geotextile shield was 2 cm in the first and 5 cm in the second test to get an impression of the maximum head difference which can be retained without the pipe passing the shield to the upstream side. The influence of the developing pipe on the pressure head is monitored (Figure 2).

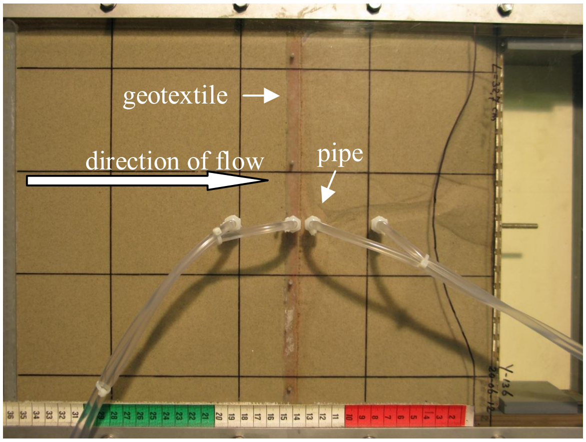

Figure 2. Small-scale test with measurement of piezometric head in the pipe by piezometric tubes in front of and behind the shield.

The setup of the medium-scale experiments is very similar to the setup of the small-scale experiments. The dimensions of the sand container are four times bigger in length and depth (inner dimensions 2.00* 0.88*0.40 m).

The sand is prepared in a similar way as in the small-scale experiments, by placing the container in vertical direction. After sand preparation the setup is put in horizontal position for the execution of the test.

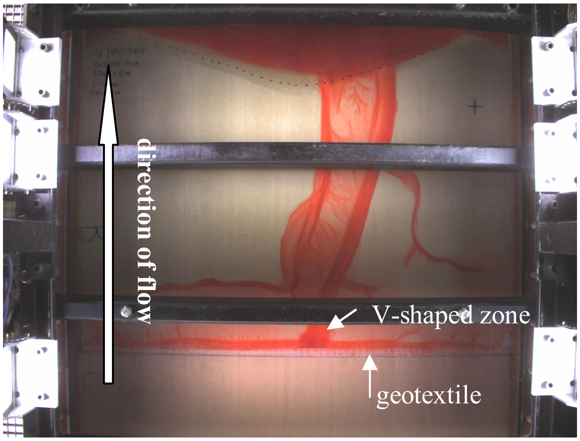

Figure 3. Medium-scale test with top view on interface aquifer / Perspex blanket. For a better contrast a red tracer marking is added. Notice the V-shaped zone adjacent to the geotextile with an increased erosion activity.

In the medium-scale tests (Figure 3) fine-grained sand (d_{70} = 270 µm, relative density 76%) is used. A geotextile strip of 0.02 and 0.08 m respectively was fixed at the acrylate cover and at the lateral edge of the container. In all tests a non-woven geotextile (Ten Cate GeoDetect® S-BR, O_{90} = 95 µm) was used. The geotextile shield is located at a distance of 2/5 of the total seepage length, counted from the exit point of the pipe.

3.1.1 *Course of the experiments*

During the tests the piezometric head is raised in steps of 1 cm per 5 minutes until erosion takes place. When erosion takes place, the head is maintained until the sand transport in the pipe has ceased for several minutes.

The piezometric head was raised until the pipe had immersed underneath the geotextile and grown further to the upstream side.

The critical head difference, necessary to start up the development of a continuous pipe, is roughly the same for both setups, with or without geotextile. The pipe growths to the geotextile, where the further upstream development of the pipe is blocked and proceeds both-way along the downstream side of the shield. At the split point increasing erosion activity is observed.

Without geotextile the pipe would grow to the upstream side. The geotextile is blocking the development of a continuous pipe. The average vertical gradient downstream the shield is bigger than 1 at the moment of collapse. This means that heave has occurred. Compared with de medium-scale tests from 2009, the hydraulic head differences at the moment of collapse are three times higher than without the inserted geotextile.

3.2 Setup IJkdijk test

A geotextile was placed 0.25 m into the aquifer. Its opening size fitted to the grain size distribution according to the recommendations by Giroud (2010). Based on the results of the small- and medium-scale model tests, 0.25 m depth seemed to be enough to achieve an increase of the critical head by a factor of 1.6 which would suffice to have a stable dike when the water level reaches the crest of the field test dike. However, for practical reasons an embedment depth of 0.5 m was applied. It was demonstrated by filter tests that the permeability of the applied geotextile was complementary to the adjacent sand so that the horizontal groundwater flow was hardly influenced by the geotextile. The geotextile was anchored in the toe of the clay dike with a vertical bond length of 1.0 m, 4 m from the toe of the dike, to ensure a firm connection between the upper part of the aquifer and the clay cover, see Figure 4.

The test was carried out with the same setup and under the same conditions as the four full-scale piping tests in 2009. When the maximum possible difference in piezometric head was reached, a head considerably above the critical head of the 2009 tests has been retained for 138 hours by the geotextile shield, while only a limited amount of sand had been eroded downstream of the shield up to that time.

Taking into account a certain infiltration resistance, caused by the sedimentation of suspended solids, the effectively retained head difference was at least 20% higher than the critical head difference from the 2009 tests. Furthermore, the levees from the 2009 tests collapsed within five days after reaching the critical head difference. This was not the case in the strengthened setup.

Excavation of the levee revealed downstream the geotextile a subsidence of the bottom of clay layer of about 0.1 m. This subsidence may be caused by repeated collapses of the V-shaped zone of the piping canal adjacent to the geotextile.

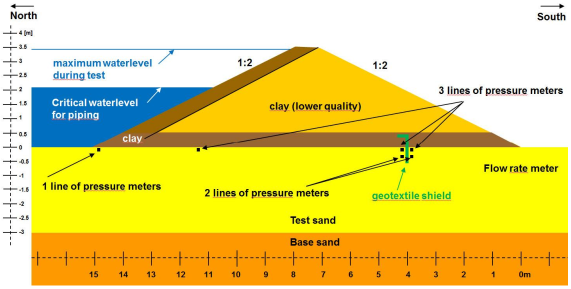

Figure 4. Design of the clay IJkdijk test dike including geotextile and monitoring instruments.

Figure 5. Installation of the geotextile before construction of the clay test dike.

Figure 6. Total view at the end of the IJkdijk test with a completely filled upstream basin and minor sand deposits as a result of piping activity at the downstream side.

4 NUMERICAL ANALYSIS

Two possible piping mechanisms are of importance: backward erosion piping (Van Beek et al., 2010) and piping by heave as described by Terzaghi and Peck (1967). Both mechanisms may occur around the geotextile. Therefore the flow pattern in the sand and around the geotextile is simulated with the 2-D groundwater flow program MSeep (GeoDelft, 2002). The situation with and without a pipe in front of the geotextile and with a permeable or impermeable geotextile is calculated, which results in 4 calculations. The geometry of the dike is modelled together with the sand layer underneath the dike. The clay layer has a low permeability of 2.10^{-7} m/s. The sand layer has been simulated with a constant permeability of 2.10^{-4} m/s, the permeable geotextile as a thin layer with a ten times lower permeability: 2.10^{-5} m/s. This lower permeability is chosen because it is reasonable to assume some blocking of the pores in the geotextile by the sand. In the calculations with a pipe, a high permeable pipe of 1 cm depth is used in the simulations. The permeability of this pipe was 1000 m/s in the simulations, a very high value, just to prevent any pressure drop in the pipe (worst case situation with respect to stability). Results of the calculations are shown in Figure 7 and Figure 8.

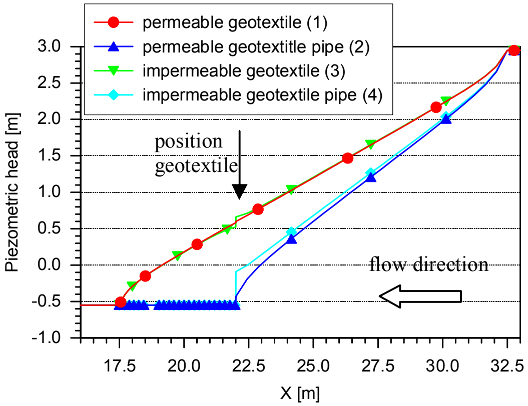

Figure 7. Calculated piezometric head directly underneath the clay layer for different situations.

Looking at the piezometric head underneath the clay layer (Figure 7), it can be seen that for the situation without a pipe the difference in piezometric head is small comparing the situation with a permeable and an impermeable geotextile. When a pipe has formed the difference is larger and in case of in impermeable geotextile there is a significant horizontal loading on the geotextile, which is not present in case of a permeable geotextile. For a permeable geotextile the loading is more distributed in the sand.

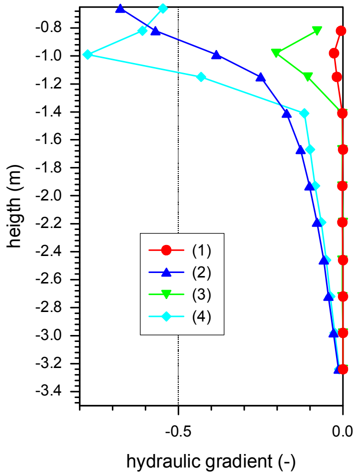

Figure 8. Calculated vertical hydraulic gradient. A gradient pointing to the top is negative. The numbers refer to the calculations described in Figure 7.

From the vertical gradient calculation (Figure 8) it appeared that with a pipe the vertical gradient is in both situations close to 1. This means that piping by heave to the pipe may occur. The average vertical gradient in the upper part of the sand (between -0.6 and -1.2 m) is higher for the situation with an impermeable geotextile.

From the calculations it can be concluded that in case of an impermeable geotextile there will be:

- a higher horizontal loading;
- a higher average vertical gradient.

It is therefore likely that a permeable geotextile is more stable than an impermeable geotextile or sheet pile of the same length.

5 SUMMARY AND CONCLUSIONS

The mode of action of the geotextile shield is proven by small-, medium-scale tests in the lab and a field-scale tests and numerical analysis. The vertically inserted geotextile seemed to work as an effective structure to inhibit backward erosion, because an essential step in the failure process was blocked. On the basis of one field-test a certain strengthening factor is obtained in relation to the critical head without any mitigating measure.

On the basis of the laboratory scale test the failure mode has become apparent: as a result of the ever wider growing pipe, the head in the whole pipe will reach the same, constant, value as on the adjacent downstream side of the shield. This results in an upward gradient to the pipe just downstream the geotextile. When this gradient becomes too high, the affected aquifer zone collapses together with the embedded geotextile shield. Laboratory tests showed that an increase of the critical head by a factor of three may easily be reached. But, because of the existing scaling effects, we cannot be sure of it. The possibility of liquefaction of the aquifer as a result of vertical flow (heave) round the shield is influenced by the permeability of the geotextile. From numerical sensitivity analysis it is concluded that the vertical gradient on the downstream side of the shield remains low enough at an adequate installation depth and permeability of the geotextile, so that heave cannot occur.

Besides, the laboratory tests differ from reality due to the unflexible Perspex cover: particularly nearby the geotextile, where erosion occurs intensively, the interaction with a natural clay cover can differ. The observed subsidence of the clay-layer in the IJkdijktest raises question concerning the long-term behaviour during longer load periods and consecutive flood events. Hence, unambiguous conclusions with respect to the durability of this piping impeding technique – also in relation to the impact of clogging - cannot be drawn from these tests only.

The feasibility and applicability of this concept will be tested on a longer dike section along the upper river basin of the Rhine by the Dutch Water Board of Rivierenland. Five pilot locations with different blanket thicknesses (between 2 en 6 m) will be strengthened by using different installation techniques. For this purpose the Dutch building industry is developing two different installation techniques: one is a milling-machine digging a small ditch in de blanket and the upper aquifer and placing the geotextile shield from an unwind-unit; the other technique makes use of sheet-pile-like frame construction with an integrated geotextile.

As it doesn't take up any extra space and may be relatively easy to install, the use of geotextile shields could be a good alternative to conventional prevention measures. To improve our knowledge about the long-term behaviour of this piping impeding technique, the permeability of the geotextile and the deformation of the adjacent ground will be monitored using fiber optics. A change in cooling rate of heated fibers is related to a change in groundwater flow-velocity which can be caused by a declining permeability of the adjacent geotextile. The strain behavior of fibers gives information about occurring deformations of the clay layer downstream the shield.

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