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The effect of a suspended cut-off wall on backward erosion piping - laboratory tests and calculations

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Abstract

The effect of a suspended cut-off wall on susceptibility of a water retaining structure to backward erosion piping (BEP) was investigated in a small-scale model test. The critical head was tested without and with a cut-off wall. The piezometric head in the model was measured at different locations in the with standpipes. One was located in the lower end of the cut-off wall to measure the vertical gradient on the downstream side of the cut-off wall. The maximum difference in piezometric head that could be resisted by the model was 4.9 times higher in the presence of a suspended cut-off wall over half the depth of the permeable sand layer compared to the test without a cut-off wall.

The measured distribution of piezometric head agrees with the results of 2 D numerical calculations with D-Geo Flow and with the results of analytical calculations following the exit gradient method.

The stability against BEP is significant. A vertical gradient downstream of the suspended cut-off wall of 1.7 was necessary to reach failure while normally a gradient of 1 is assumed. Possible causes for this high stability are discussed.

Keywords

Backward erosion piping, Suspended cut-off wall, Model test, Calculations

1 Introduction

Backward erosion piping (BEP) can be a serious threat for low permeable dikes and levees founded on permeable soil. BEP is a process in which the hydraulic head difference across a water-retaining structure causes the erosion of particles, resulting in the formation of shallow hollow spaces underneath the levee, eventually leading to failure. In various countries it is marked as a significant risk factor for levee failure (Danka & Zhang, 2015; Liu et al., 2023). In cases where the safety requirements for BEP are not met, elongating the seepage paths horizontally, often with a berm, is a common mitigation measure. In cases where widening the dike is not possible, the installation of a suspended cut-off wall (SCOW) is a possible, but more expensive, alternative. A SCOW is a vertical construction, commonly a steel sheet pile wall or screen in an aquifer underneath a dike that lengthens the seepage path in the aquifer, see Figure 1a. In addition to steel, concrete, plastic and mixed-in-place (soil mixing) materials are applied as material for SCOWs.

Expected sea level rise has led to stricter safety requirements for the dikes along the Dutch rivers and estuaries. In the Netherlands, over 1300 km of the levees must be reinforced by 2050 as part of the Flood Protection Program (Kamerbrief, 2025). Installation of a SCOW will be the solution for several stretches of river levees. This task justifies the revisiting of the design rules for these structures.

Lane (1935) describes how a SCOW increases stability against erosion. The design of such a SCOW is relatively straight forward. Assuming a stable sheet pile, the average pore pressure at the bottom of a rectangular sand body downstream of the sheet pile, with width of 0.5D (with D the depth of the SCOW) and embedment depth of D must be less than the average vertical effective stress exerted by the soil within the rectangular sand body, indicated in orange in Figure 1b (Terzaghi and Peck, 1948).

Although this calculation procedure is well described, still some questions remain. The flow pattern in the aquifer under a levee with a SCOW is somewhat different from the flow pattern assumed by Terzaghi and Peck, due to the presence of a blanket instead of an open outflow and the formation of pipes towards the SCOW. The influence of this difference on the occurrence of heave is yet to be investigated. Experiments have been conducted by other researchers, but when comparing the critical heads to numerical simulations, the spread in results is large (Van Beek et al., 2013). These experiments were conducted as a black box, providing only the total head difference with only the total head and offering no insight into local heads and give little information about the pipe development, whereas the local heads and pipe pattern can provide relevant information on the flow pattern in the situation with a SCOW. Also, measurements to obtain the vertical gradients along the SCOW would allow direct comparison with possible existing models regarding the heave criterion. This study aims to address the following questions: How does the presence of a SCOW alter the pore pressure distribution and failure mechanism of backward erosion piping compared to the classical Terzaghi & Peck configuration? To what extent do existing analytical stability criteria remain valid when significant downstream erosion occurs prior to failure?

The results of small-scale model tests are described, next to erosion patterns and piezometric heads. The resulting piezometric heads are simulated with numerical and analytical calculations. The stability criterion of Terzaghi and Peck (1948) will be described as well as the difference with the measurements. The research described in this paper is a first preliminary step investigating the mechanisms that lead to failure of a levee with a suspended SCOW and the accuracy of the existing design rules. The results of these tests will be used in a more comprehensive research program to the resistance of SCOW against piping in the Netherlands

2 Small-scale model tests

2.1 Setup

Tests were performed in a PVC box with the dimensions of 0.4*0.1*0.1m. The original 0.3 m with was reduced to 0.1 m using two PVC plates to 0.1 m to prevent erosion pipes from forming far from the standpipes, see Figure 3. The low-permeability levee is simulated using an acrylate plate. The diameter of the exit was 5 mm and the exit was located 0.3 m from the inlet filter (Vandenboer, 2019). A circular exit was chosen to obtain a reproducible exit formation. The hole-type exit measures 10 mm in height (equal to the local acrylate plate thickness). One test was done without a SCOW and one with a SCOW of 5 cm embedment over the entire width of the container. The setup is shown in Figure 2.

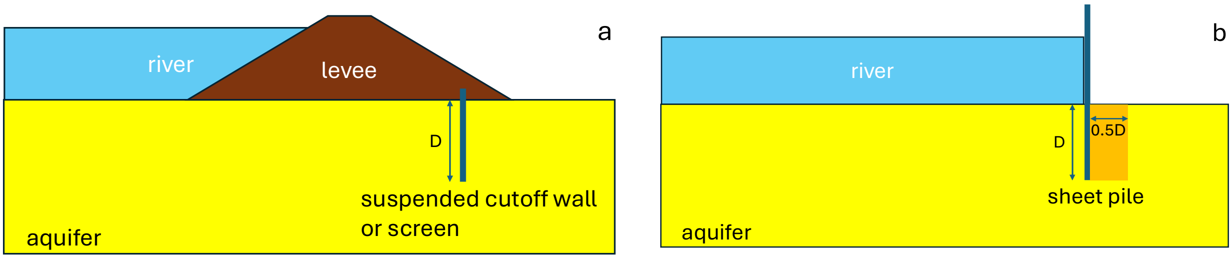


Figure 1. Principle sketch of suspended cutoff wall (a) (SCOW) and sheet pile as studied by Terzaghi and Peck (1948), see also text.

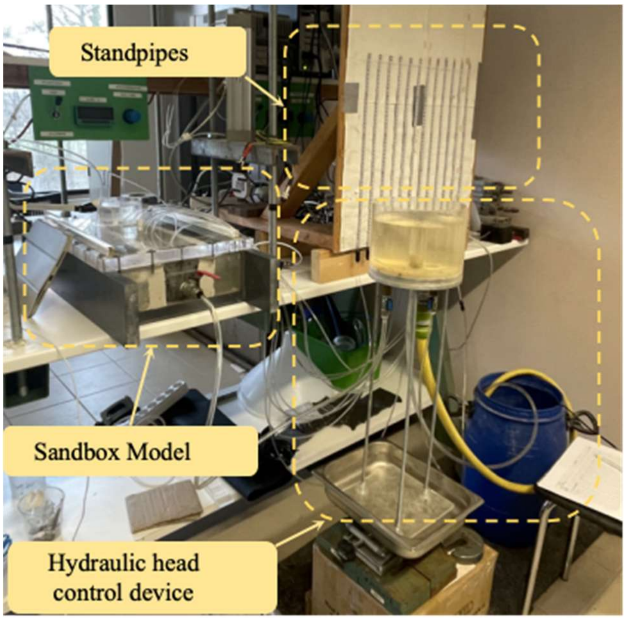


Figure 2. The various parts of the setup

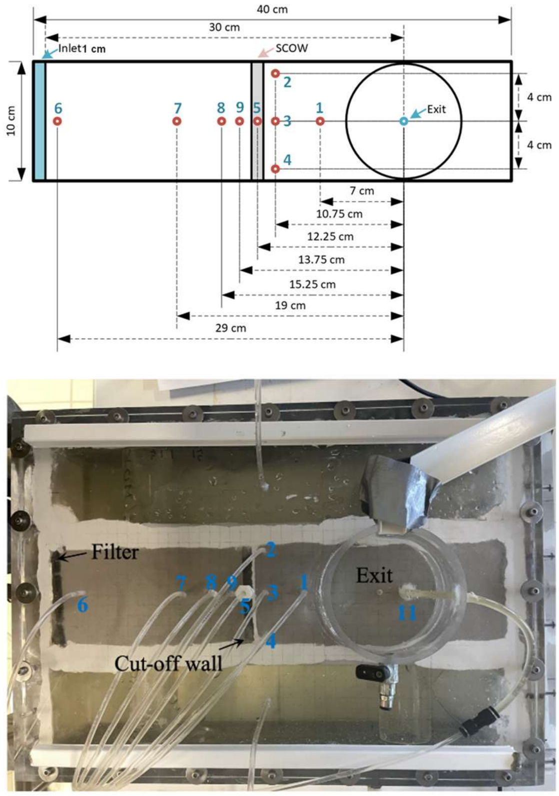


Figure 3. Top view showing the reduced inner dimensions of the sand box, with location of the cut-off wall and the instruments. The depth of the sand model is 10 cm, the depth of the cut-off wall 5 cm.

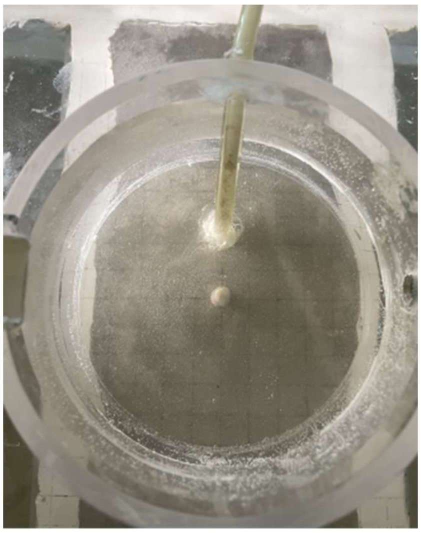
The locations of the standpipes (P), all mounted in the top plate, are shown in Figure 3 (bottom). All standpipes measure the head at the top of the sand bed, except for transducer 5, which leads to the bottom of the SCOW. Tubes to the standpipes are transparent to detect and remove possible air bubbles The container was filled with fine sand (MOL sand M34) with a d50 of 155 μm and a uniformity coefficient (d60 /d10) of 1.30. Dry sand was rained in the water from the side of the box to obtain a fully saturated soil sample and densified by tamping under water until a porosity of 40%, corresponding to a relative density of 80%. This procedure resulted in a saturated sand bed with hydraulic conductivity of approximately 10^{-4} m/s. The water flow was recorded with an electronic scale with an accuracy of 0.1 gr. The SCOW was made of 1 cm thick acrylic glass. The filter was a permeable geotextile filter, approximately 1 cm thick. The seepage length is 30 cm.

A test started with a piezometric head that was equal at the inlet (the filter left in Figure 3) and exit. During the test the difference in piezometric head across the sand body with seepage of length of 30 cm between inlet and exit (ΔH) was stepwise increased, by increasing the height of the water reservoir at the inlet. When erosion was visible, the difference in head was kept constant until the erosion stopped before a new step was applied. The test ended when the pipe reached the upstream filter.

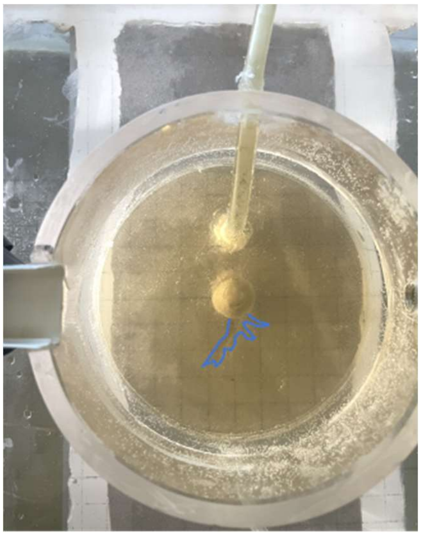
3 Results

3.1 Experimental results without cut-off wall

In the test without SCOW, sand boiling occurred at the outlet when the difference in hydraulic head reached ΔH = 1.2 cm (Figure 4(a)). Subsequently, the outlet hole became filled with sand. At ΔH = 2.1cm, sand particles were ejected from the outlet and accumulated around it, forming a small pit on the top plate. The erosion area, the area where sand grains are removed indicated with the blue line in Figure 4, extended approximately 0.5 cm from the center of the outlet. When ΔH increased to 5.2 cm, the erosion area becomes a pipe and started growing in the preferential upstream direction, with a length of L = 2.5 cm (Figure 4(b)). As hydraulic head increased to ΔH = 6.1 cm, the pipe extended to L = 5 cm (Fig. Figure 4(d)). Upon reaching a hydraulic head ΔH = 7.4 cm, the pipe length reached L = 9 cm (Figure 4(e)). From that point on, the channel continued to grow slowly even without further increases in hydraulic head. After approximately 110 min, the pipe connected to the upstream filter (Figure 4(i)), at which point the test was terminated.

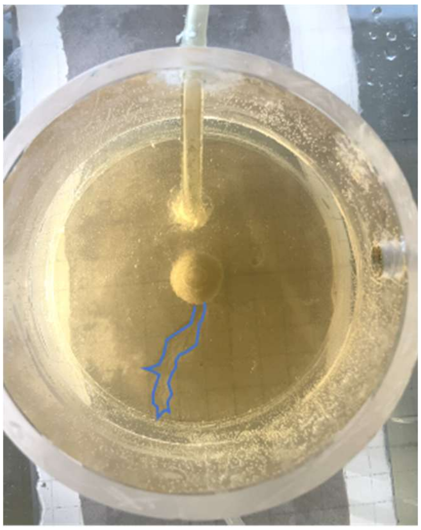


(a) Boiling sand phenomenon at the outlet, ΔH = 1.2 cm

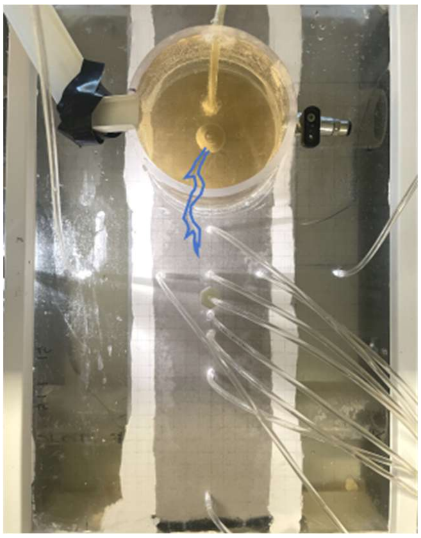


(b) L=2.5cm, ΔH = 5.2 cm

(c) L=3.4cm, ΔH not recorded

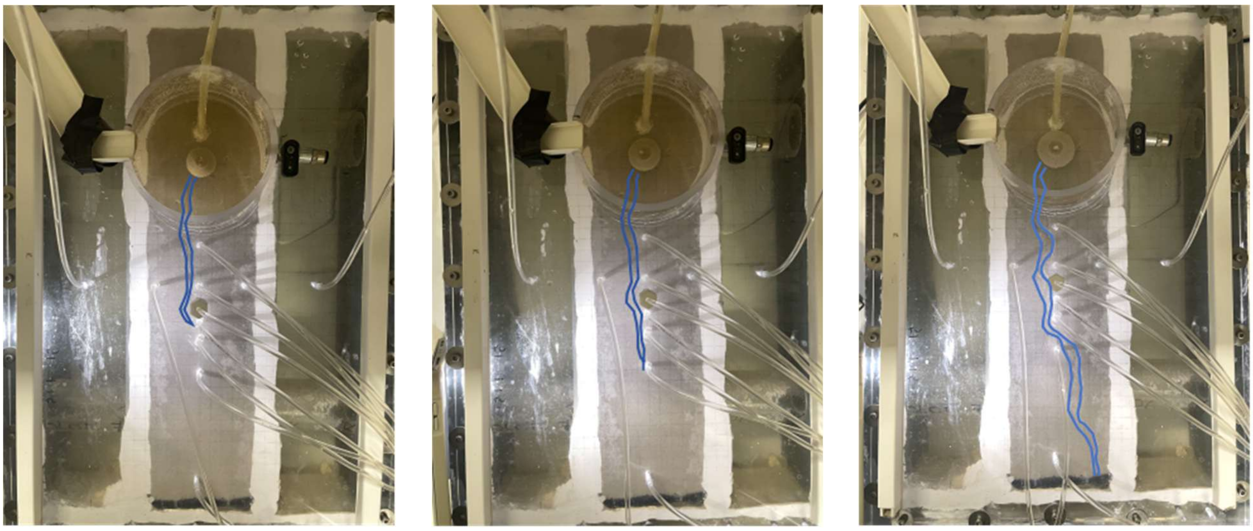


(d) L=5 cm, ΔH = 6.1 cm



(e) L=9 cm, ΔH = 7.4 cm

(f) L=10 cm, ΔH = 7.4 cm (constant)



(g) L=14cm, ΔH = 7.4 cm (constant) (h) L=18cm, ΔH = 7.4 cm (constant) (i) L=29cm, ΔH = 7.4 cm (constant)

Figure 4. Development process of backward erosion piping (model test without SCOW)

It should be noted that this head loss ΔH is a summation of the head difference in the sand, the head loss at the exit and the head loss in the filter at the inlet. The piezometric heads at the top plate as measured with the standpipes are shown in Figure 5. The head loss over the filter can be determined from the head difference between the standpipe upstream of the filter, and the one at 0.29 m (P6). Since the total head loss is rather small, the head loss in the exit cannot be neglected. The head loss in the exit is caused by the contraction of flow lines near the exit in the sand and by the sand water mixture in the exit and in the 'volcano' on top of the exit. The contribution of the first mechanism decreases when the erosion pipe becomes longer. The contribution of the second mechanism first increases because the volcano increases in size. For larger values of the applied hydraulic head over the model this contribution decreases again because the increased flow leads to a low concentration sand-water mixture in the 'crater' of the volcano, a process also described by Robbins et al. (2020). The change in exit loss at different time steps can be seen in Figure 5.

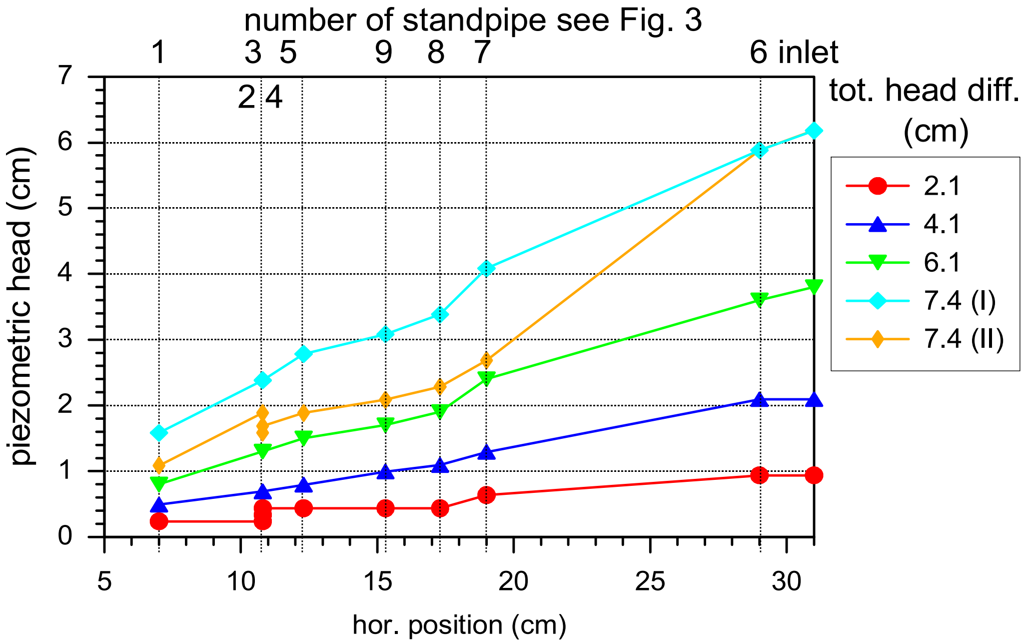


Figure 5. Piezometric head measured at the top of the soil sample for different total heads (ΔH) applied versus the horizontal position (x=0 at the exit). Standpipes 2, 3 and 4 are at the same distance from the exit.

At a constant head drop of 7.4 cm there is ongoing erosion and therefore the pressure distribution changes from line (I) to line (II). During the stage corresponding to line (I), there is already an erosion pipe of several centimeters, increasing the outflow area. This means that the contraction of flow lines to the exit is reduced compared to the initial situation, such that head losses at the exit are dominated by the sand water mixture. However, during the measurement of line II, the discharge is larger than in stage 1. The larger discharge results in a lower concentration of the sand-water mixture in the volcano and thus a lower pressure close to the exit, as measured with standpipe 1, located 7 cm from the exit.

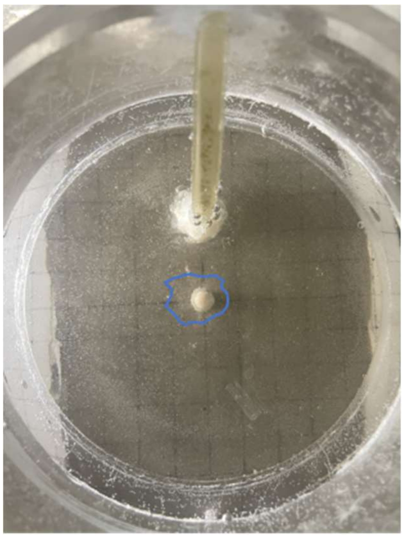
These observations confirm that, in the absence of a cut-off wall, backward erosion piping rapidly evolves into a continuous pipe once the critical head is exceeded, consistent with classical BEP behavior (van Beek, 2015 and Vandenboer et al., 2017).

3.2 Results with suspended cut-off wall (SCOW)

In this experiment, sand boiling was observed at the outlet when the hydraulic head reached ΔH = 1.1 cm (Figure 6(a)). Subsequently, the outlet hole was filled with sand. At ΔH = 2.9 cm, sand particles were ejected from the outlet and accumulated around it, forming a small pit on the top plate. The erosion zone extended approximately 0.5 cm from the outlet center (Figure 6(b)). When ΔH increased to 4.9 cm, the pipe started growing in the preferential upstream direction, with a pipe length of L = 2 cm (Figure 6(c)). As the hydraulic head continued to increase, the channel gradually extended upstream. At ΔH = 7.9 cm, the pipe reached a length of L = 6.5 cm (Figure 6(d)). At ΔH = 8.4 cm, the pipe extended toward standpipe 1, with a length of L = 9.2 cm (Figure 6(e)). This erosion process was similar to that observed in the test without the SCOW. When ΔH = 10.9 cm, the pipe continued to erode, and after 30 min, it reached the SCOW (Figure 6(f)). From this point onward, the presence of the SCOW began to influence the development of the pipe. Unlike the test without a SCOW, the pipe progressed parallel to the wall and gradually extended across its entire width creating a 2-D situation in this small model (Figure 6(g)), forming a T-shaped pipe. Sand particles continuously migrated toward the outlet through this T-shaped pipe. Meanwhile, multiple branching pipes formed during this stage (Figure 6(h)). With time and a further increase in hydraulic head, the downstream area of the SCOW experienced overall erosion. When ΔH = 33.9 cm, the pipe began to erode beneath the wall. From that moment on, even without any further increase in the hydraulic head, the pipe propagated upstream across the SCOW and formed a depression near the upstream side of the wall (Figure 6(j)). As the depression gradually expanded, a pipe appeared near the upstream filter after approximately 201 min. Thereafter, the erosion process no longer progressed in the upstream direction but instead extended along the seepage path (Figure 6(m)).

These results demonstrate that, although backward erosion piping initiates in a manner similar to the case without a SCOW, the presence of the SCOW wall fundamentally alters the failure mechanism by delaying upstream pipe progression and requiring substantially higher hydraulic heads for instability to occur.

(a) Boiling sand phenomenon at the outlet, ΔH = 1.1 cm

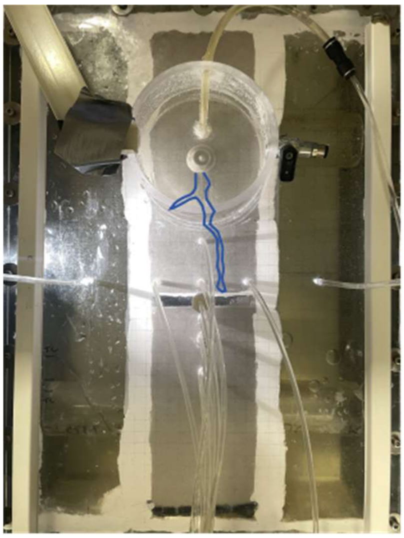


(b) Sand particles ejected from the outlet, ΔH = 2.9 cm

(c) L=2 cm, ΔH = 4.9 cm

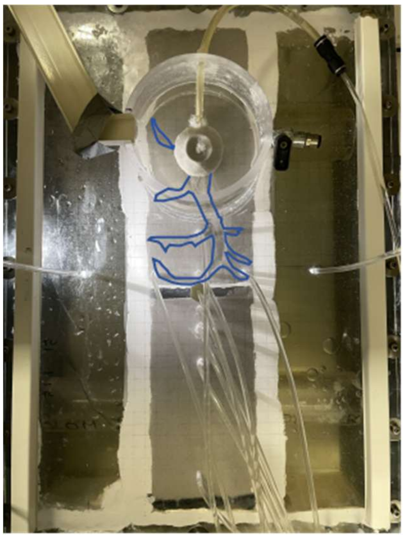
(d) L=6.5cm, ΔH = 7.9 cm

(e) L=9.2cm, ΔH = 8.4 cm

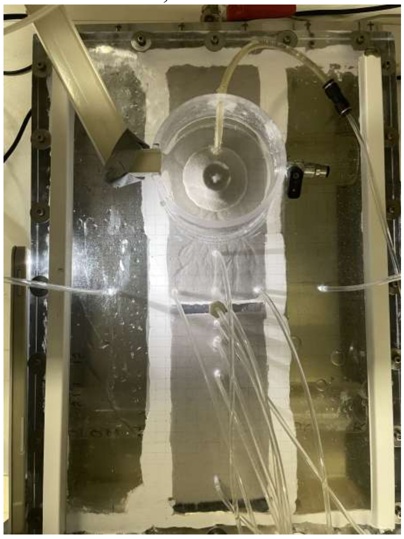


(f) The pipe extended to the SCOW, ΔH = 10.9 cm

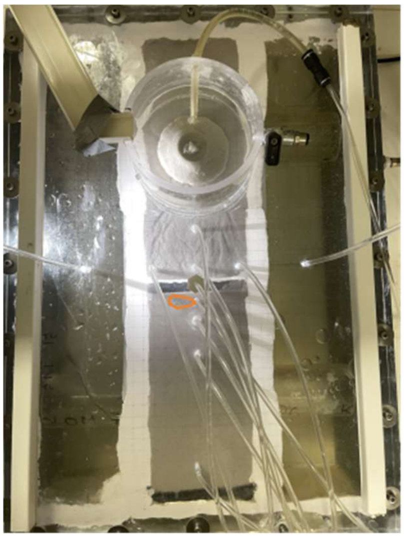
(g) Formation of a T-shaped pipe
ΔH =13.9 cm



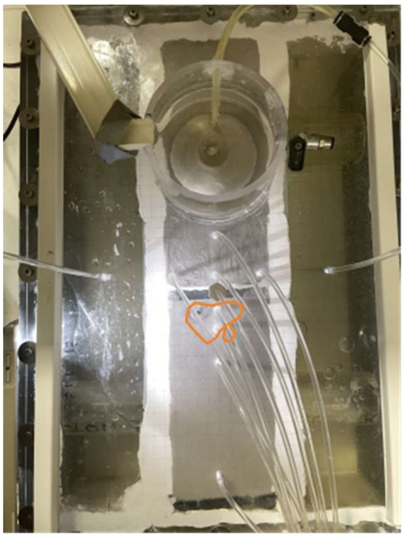
(h) Formation of multiple branched pipes
ΔH = not recorded



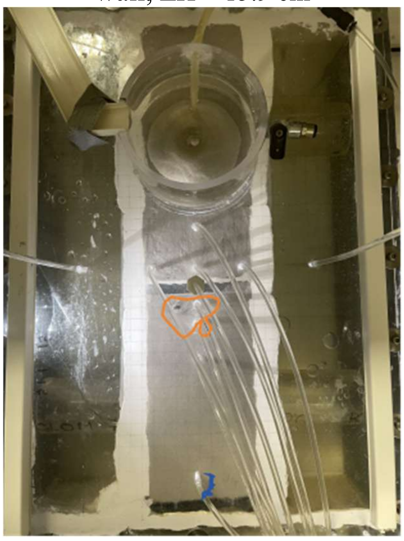
(i) Overall erosion in the downstream area of the cut-off wall, ΔH = 15.9 cm



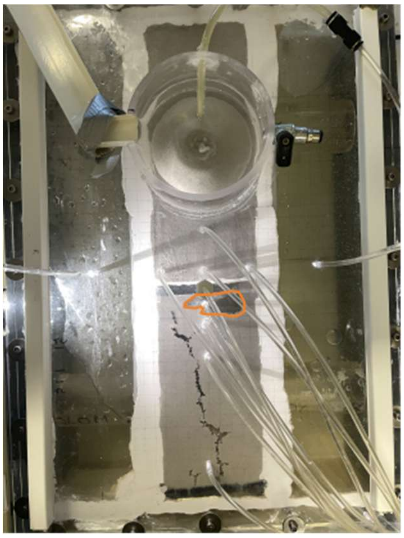
(j) Formation of a depression on the upstream side of the SCOW, ΔH = 33.9 cm



(k) Depression expansion, ΔH = 33.9 cm (constant)



(l) Erosion failure occurred at the filter layer, ΔH = 33.9 cm (constant)



(m) Progressive erosion failure along the seepage direction, ΔH = 33.9 cm (constant)

Figure 6. Development process of backward erosion piping (with SCOW).

The critical head at failure was 33.9 cm, more than a factor 4 higher than the 7.4 cm in the test without SCOW. The vertical gradient downstream of the cut-off wall was 1.74.

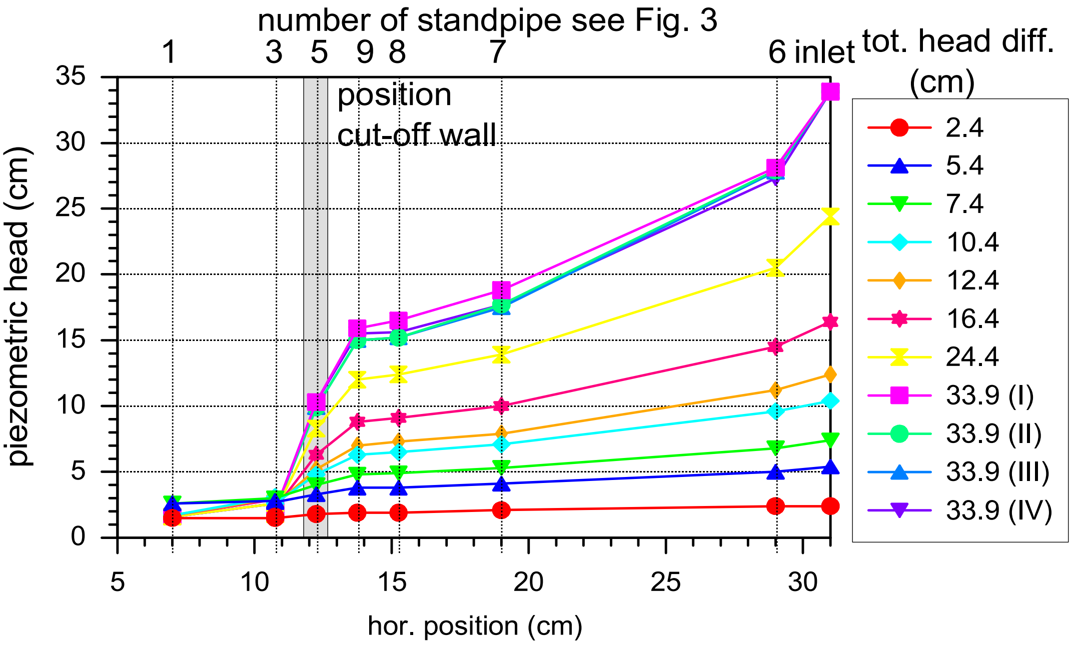


Figure 7. Piezometric head measured at the top of the soil sample for different heads applied in the test with SCOW, plotted against the x-coordinate (x=0 at exit center). The total head difference applied is mentioned in the legend.

The measured piezometric heads at various positions and different total head differences are shown in Figure 7. For higher heads, there is a clear head drop over the SCOW. Downstream, the head is low because of the erosion of the sand just below the top plate. Upstream of the SCOW, the hydraulic gradient decreases close to the SCOW, because the SCOW causes the flow to bend underneath it. The head measured at the tip of the SCOW (P5) can be compared to the average head measured in the standpipes at x=0.1075 m (P3) and x=0.1375 m (P9). In the 'classical case' as studied by Terzaghi and Peck there is a horizontal sand bed with a sheet pile perpendicular to the sand bed and a water difference over the sheet pile. For that situation, the piezometric head at the tip of the sheet pile is the average pressure measured in the 2 standpipes left and right of the sheet pile. In this case we have a different situation since the inflow and outflow are different from the configuration of Terzaghi and Peck (Figure 3). Although, initially, before erosion takes place, the head drop over the SCOW is equal on both sides of the SCOW (standpipes at 0.1075 and 0.1375 cm), as is the case in the Terzaghi and Peck configuration.

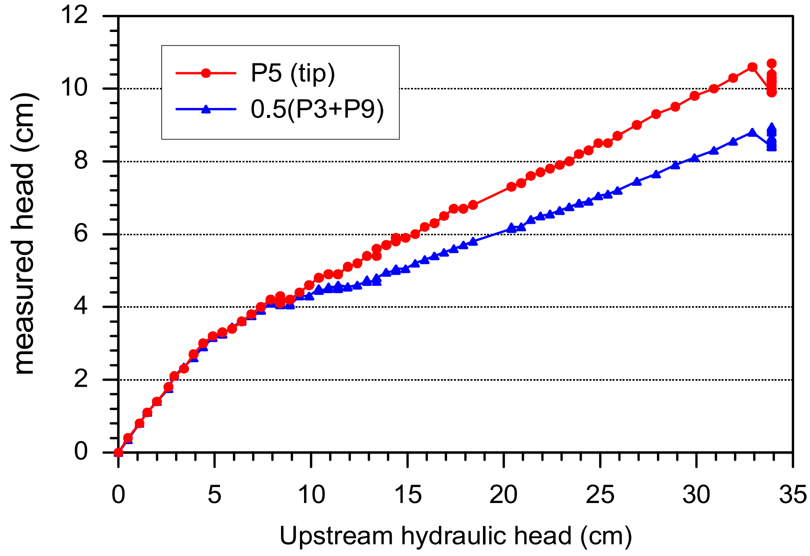


Figure 8. Head measured at tip (P5) compared with average head of standpipes just upstream (P9) and downstream (P3) the SCOW. For the locations corresponding to the numbers of the standpipes, see Figure 3.

Figure 8 shows the influence of the downstream erosion. With low average heads there is sand on both sides of the SCOW and the head measured at the tip is the average head. However, as shown in Figure 6, there is quite some erosion of the downstream sand when the head difference increases. This results in less outflow resistance and a relatively higher head at the tip. At an applied total head difference of 15 cm or more around the SCOW the downstream area is completely eroded.

4 Flow and stability calculations

4.1 Introduction calculations

To calculate whether a retaining structure with a suspended SCOW is stable against piping due to heave, it is necessary to calculate the groundwater flow in the permeable layer and to select a heave criterion. For the situation of a sheet pile wall, or SCOW, in a horizontal aquifer with a water difference on both sides this is commonly evaluated using the method of Terzaghi & Peck (1948). This 2-D method compares the vertical seepage force on the sand rectangle with the embedment depth D and a width 0.5D just downstream of the sheet pile wall with the effective weight of that same rectangle. Failure occurs when the seepage force exceeds the effective weight of the rectangle. Harza (1935) proposed an alternative method, in which the heave criterion states that the vertical hydraulic gradient at the downstream sand surface of the SCOW must remain below the submerged unit weight of the sand. In the Netherlands a third method is used (Rijkswaterstaat, 2025), which is described in the literature by Davidenkoff (1970). In this method the critical heave gradient is evaluated over a soil rectangle with height of the wall, but with an infinitely small width.

All these methods assume an open outflow downstream of the SCOW. However, in situations with a blanket, such as simulated with the experiment presented in this paper, the outflow is controlled by pipes. Therefore, it is first checked whether the assumption of open outflow is valid by comparing the measured heads in the experiment with the calculated heads using analytical and numerical methods.

Consequently, the stability is evaluated using the three methods. Tanaka and Verruijt (1999) have previously examined the methods of Harza and Terzaghi & Peck for their experiments with open outflow and provided analytical equations for determining the average gradient over the rectangle and for the exit gradient. Their results serve as a reference for the situation with blanket evaluated in this paper.

4.2 Analytical method

The analytical method to determine the flow pattern around a SCOW is proposed by Pavlovsky (1956) and further developed by Sellmeijer (1995). The method is based on analytical equations for groundwater flow in the aquifer below a levee or water retaining structure with one or several SCOWs. Assuming a constant piezometric head underneath each wall, the flow resistance of each section of the aquifer between the SCOWs can be calculated. For each section analytical solutions are presented in Sellmeijer (1995) assuming an aquifer with homogeneous thickness and constant permeability. For a given value of the average upward vertical gradient along the SCOW (φ_2/L), downstream of the SCOW, the upstream head φ_1 can be calculated. It is then assumed that the piezometric head is zero at the downstream sand surface.

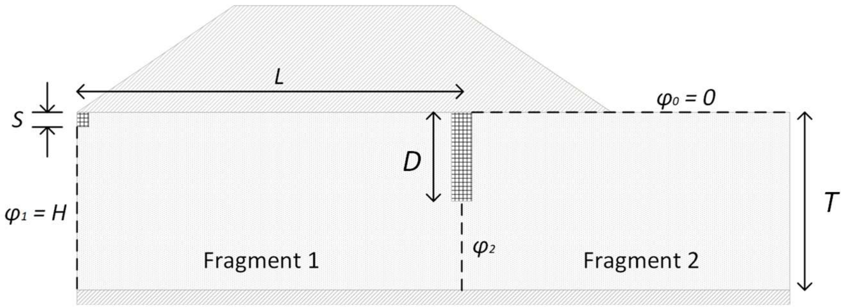


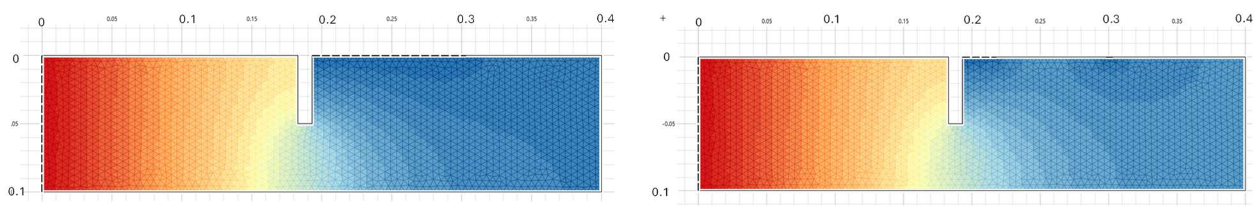
Figure 9. Exit gradient method for 2 fragments. In the calculations is s=0, D=0.05 m, L=0.1675 m and T=0.1 m

The situation is sketched in Figure 9. The caption presents the input parameters of the simulation of the model test with the SCOW. The length of the fragment 1 is chosen to be 16.75 cm, the length of the model from the SCOW to P6. The filter layer at the inlet of the experiment is not modelled in this calculation.

The experimental average vertical gradient downstream of the SCOW just before failure, 1.74, is based on the measured heads just before failure: at the bottom of the SCOW, P5, minus P1 to correct for exit losses that are also not present in the numerical model. The calculated difference in piezometric head over the model to reach a downstream hydraulic gradient of 1.74 is 25.2 cm, which is a bit lower than the measured head difference between P6 and P1, which is 26.5 cm. At failure, the hydraulic head at P 6 is 28.1 cm and the hydraulic head in P1 is 1.6 cm due to the exit pressure loss caused by the sand volcano. Since the calculated head for φ_1 is similar to the experimental head, the assumption of an open outflow area in the different methods seems acceptable.

4.3 Numerical calculations

Two-dimensional numerical calculations were performed with the FEM program D-Geo Flow (Deltares, 2024). The geometry of the model test setup was modelled in the program. The outflow area was modelled in two different ways. (1) assuming that all sand between the SCOW and the exit has been eroded and (2) the situation that it was eroded over 0.5D=2.5cm, see Figure 10.



1 2

Figure 10. Results of FEM calculations for situation (1) and (2) mentioned in text. The SCOW of 5cm is in the middle of the mesh. The drawn lines around the mesh indicate a boundary condition q=0 (no discharge), the dotted lines left (vertical) and right of the SCOW (horizontal) have a constant piezometric head as boundary condition.

A total head difference of 28.1 cm was applied between P6 and the outlet just before failure. The inlet filter was not modelled. The head drop over the exit was 1.6 cm (this head difference is not included in the simulations), thus the head difference over the sand model is 26.5 cm. The calculated average vertical gradient at a head difference of 26.5 cm, calculated from the downstream edge of the SCOW, was 1.53 for scenario (1) and 1.72 for scenario (2). Situation (2) resulted in the largest vertical gradients and was more in agreement with the measurements. This outcome will depend on the amount of erosion of the top layer of the sand before failure of the structure. The calculated average gradients over the height of the SCOW are in good agreement with the measured gradients, for the head difference just before failure. The distribution in piezometric head measured on the top of the physical model is in reasonable agreement with the calculated head distribution, for both scenarios, see Figure 11. The piezometric head distribution upstream is quite comparable for both scenarios. The effect of the length of the outflow area is clearly visible downstream. Also, here it can be concluded the assumption of an open outflow area is acceptable.

It should be noted that the piezometric head changes considerably around the tip of the SCOW. The comparison with the measurements is therefore highly dependent on the exact position of P5.

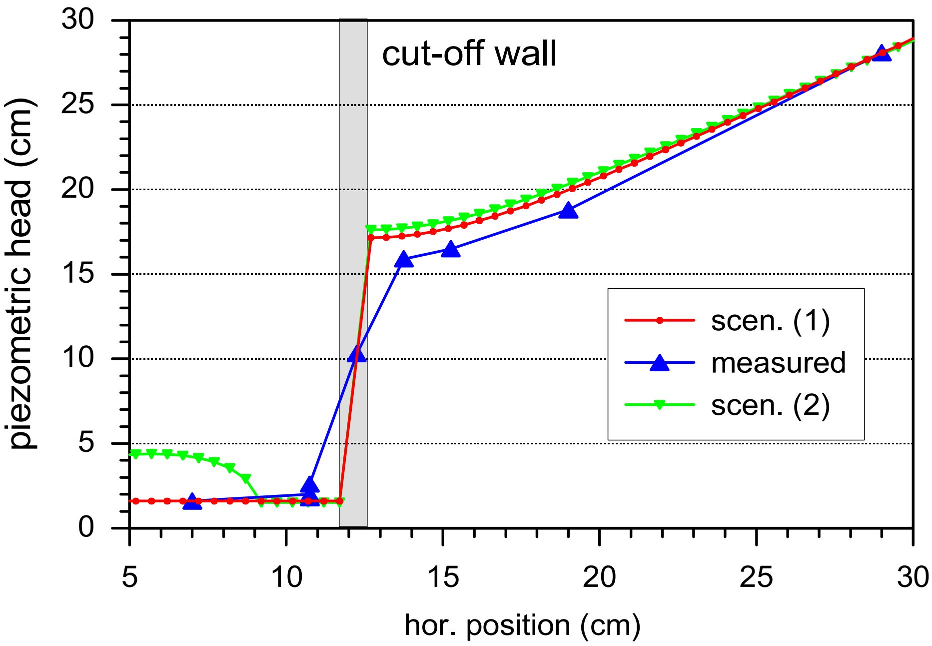


Figure 11. Measured heads compared with calculations for scenarios (1) and (2) with different modelling of the erosion area downstream. The measurement points are at the top of the sand model except the point at 12.25 cm that is in the tip of the SCOW. Calculated points are all at the top of the model.

4.4 Stability calculations

Now that it is confirmed that the assumption of open outflow is valid, the methods of Harza (1935) and Terzaghi & Peck (1948) are used to calculate the stability of the sand downstream of the SCOW. Tanaka & Verruijt (1999) have shown that the calculated critical vertical gradients in these methods are in agreement with the critical vertical gradients in their experiments: Harza's method overpredicts the critical head somewhat, while Terzaghi and Peck underpredicts. The experiments by Tanaka and Verruijt were done for the situation as investigated by Terzaghi and Peck, a sheet pile in a horizontal sand bed with a difference in water level of H, a sheet pile depth of D and a thickness T of the sand layer. The flow pattern is symmetrical for this situation and the head at the tip of the sheet pile is 0.5 H.

Harza's method requires that the vertical gradient at the downstream soil surface is less than corresponding to the underwater weight of the soil.

With h=0.5H, the head at the tip, the experimental results of Tanaka and Verruijt (1999) have been replotted in a dimensionless graph that gives the ratio of the average vertical gradient downstream along the SCOW at critical conditions (h/D) and (γ'/γ_w)for different ratios of cut off wall depth and total sand bed thickness (D/T), see Figure 13. The red dots are their measurement points at which failure occurred. The light blue diamond corresponds to the highest average vertical gradient measured along the SCOW in the experiment described in this paper. The experimental values can be compared to the different design methods. In the Netherlands, the average gradient along the wall is compared to the critical heave gradient for uniform vertical flow (γ'/γ_w). The predicted ratio of h/D. γ_w/γ' in that method would thus be equal to 1, the orange line in Figure 13.

The blue line, Harza's method, indicates the average value of the gradient downstream of the SCOW that corresponds to an exit gradient equal to γ'/γ_w at the downstream surface. This exit gradient is lower than the average vertical gradient along the SCOW, which explains the higher values of h/D. γ_w/γ'

The green line is the h/D. γ_w/γ' along the SCOW based on Terzaghi and Peck's solution, which is also higher than 1.

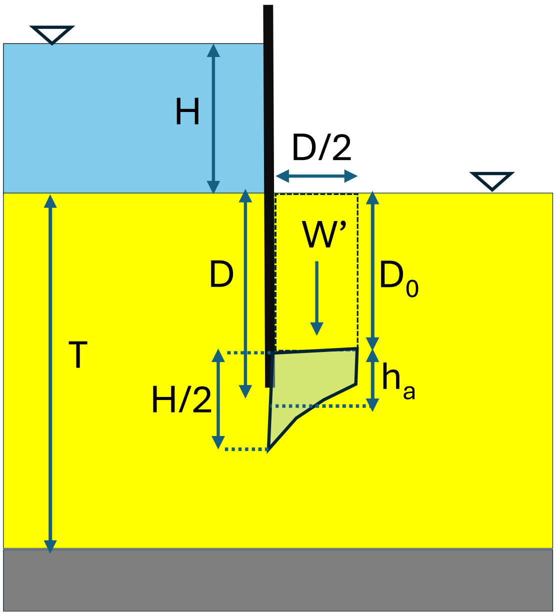


Figure 12. Terzaghi's method. In this paper it is assumed that D_0=D.

The results show that the design methods of Harza and Terzaghi & Peck yield higher critical heads than the method often used in the Netherlands (by a factor of 1.6-2 and 1.3-1.8 respectively). The graph also shows that the experimental results align more closely with the design methods of Harza and Terzaghi & and Peck than with the Dutch method. The Dutch criterion appears conservative. The Terzaghi &Peck solution is on the safe side with respect to failure. Tanaka & Verruijt reported deformation in the sand when the Terzaghi & Peck solution was reached. Since in our experiment it is difficult to distinguish the first deformation, here the failure points are compared. Therefore the head that leads to failure in the situation with blanket investigated in this paper is a bit higher than in the traditional Terzaghi & Peck sheet pile setup, possibly because in the measurement the piezometric head in the middle of the sheet pile is measured and not at the corner downstream or the surface of the downstream area is not fully eroded before failure.

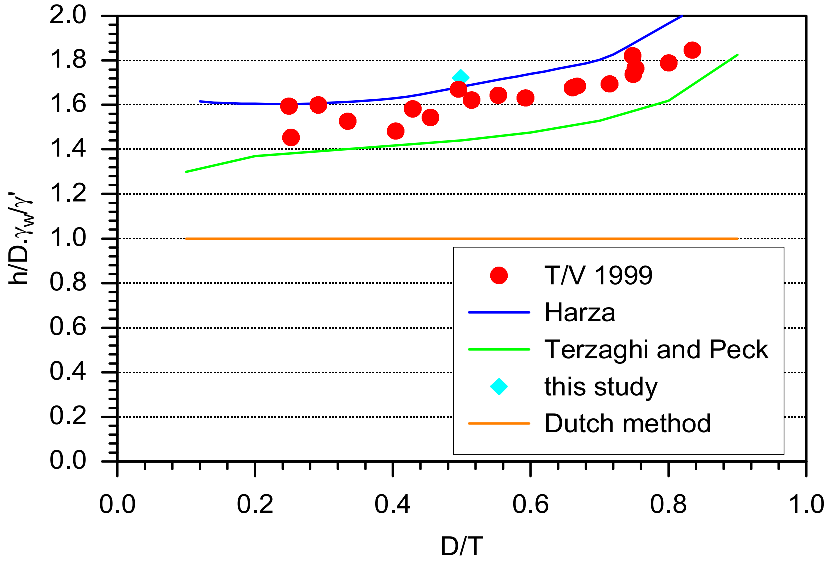


Figure 13. Failure according to theory and measurements. Data from Tanaka and Verruijt (1999), (replotted) except for the point marked "this study".

5 Conclusions

Backward erosion piping experiments with and without suspended cut off wall were conducted for the situation with a blanket layer. A small-scale setup is presented that allows to measure the vertical gradient downstream of a SCOW by using a standpipe that measures the head at the bottom of the SCOW. These head measurements allowed for validation of the typical groundwater flow pattern assumed in common design methods. The experiments showed that:

- A suspended SCOW leads to a significant increase in stability against piping. In the experiment described in this paper this was more than a factor 4.
- Before the pipe reached the SCOW, the erosion with and without SCOW is comparable. In the presence of a SCOW only a slightly higher head is needed to reach the same pipe length, see Figure 4 and Figure 6. This means that with a SCOW there will be sand boils. However, they will not lead to failure of the water retaining structure, until a much higher hydraulic head is applied.
- In presence of a SCOW there can be significant downstream erosion before piping through heave occurs. This makes the boundary conditions close to the exit comparable to the boundary conditions for a sheet pile with two different water levels. In practice embankment settlement may lead to (partial) closure of the pipes formed.
- Experiments with different widths of the model container will be necessary to see up to what width the process can be described as 2 dimensional. Furthermore, tests at a larger scale are planned to investigate possible scale effects.
- The average gradient measured along the SCOW at failure was in this experiment equal to 1.74.

Local gradients downstream of the SCOW in the experiment were compared to gradients based on various prediction methods, with experiments by Tanaka and Verruijt (1999) serving as reference for experiments with open outflow:

- The method by Harza, based on exit gradient, yields larger critical heads than the method by Terzaghi & Peck (evaluation over rectangle of soil) (Tanaka and Verruijt,1999)). The critical heads according to both methods are higher than according to a method used in the Netherlands (after Davidenkoff, 1970), based on the average gradient along the SCOW, see Figure 13.

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Author contributions (CRediT)

TW: Set-up, Investigation, Writing – review & editing.

AB: Supervision, Validation, Visualization, Writing – original draft.

YT: Calculation, Writing – review & editing

VB: Methodology, Writing – review & editing.

Data access statement

The data acquired in the study and used/analyzed/reported in this paper will be made available when requested.

Declaration of interests

The authors report no conflict of interest.

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