Analysis report coarse sand barrier

Delta Flume tests (phase 2c)

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Deltares

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Client	Project	Attribute	Pages
Waterschap Rivierenland	11200952-012	11200952-012-GEO-0001	39

Trefwoorden
Piping, preventive measure, coarse sand barrier, innovation, large-scale, scale effects, Delta Flume

Samenvatting
Piping is one of the most important threats for the safety of Dutch levees, especially for the sections that are located along the main rivers. Based on research conducted in the past years several piping mitigating measures have been developed that prevent the pipe from progressing towards the river. One of these measures is the coarse sand barrier. The coarse sand barrier is a trench of coarse sand that prevents fine sand from upstream of the barrier from being eroded, and thereby hinders the pipe from progressing upstream below the dike.
The coarse sand barrier seems to be a promising measure based on preliminary and small-scale (phase 2a) and medium-scale (phase 2b) experiments, but additional research is required to assess the feasibility of this measure in practice.
The report at hand describes the research conducted in the third experimental phase (2c) of a larger research programme in which the feasibility of this method is assessed: the analysis of two large-scale experiments in the Delta Flume.

The current phase, similar to the previous phase, shows that the coarse sand barrier can provide a significant amount of resistance against piping. Two tests were conducted, using the same type of background- and barrier material. The first Delta Flume test had to be abandoned because of leakage problems attributed to imperfections in the sealing of the joints between flume wall and bulkhead and an insufficient embedding of the bulkhead in the blanket layer. During this test, the pipe did not progress through the barrier. Because of this, the distance of the coarse sand barrier with respect to the entry point was shortened in second test, in order to be certain that failure of the barrier will be reached at head differences attainable in the flume. Indeed, the barrier collapsed at the end of the second test.
The tracers which were used to indicate the progress of pipe growth did only reliably work in the first test. The progress of pipe growth, followed by the appearance of tracers at the sand boils, was in good agreement with the findings during the excavation of the pipes and the barrier afterwards. The pipe growth into the barrier stopped in the downstream part of the barrier. The other parts of the barrier were still intact.
During the second test almost no tracers were detected until the final loading phase. Only at the very end of the test a high amount of tracer particles originating from all marked positions along the longitudinal section of the set-up appeared in the ditch at once, namely on the brick of dike failure. Hence, the moment of reaching the barrier and of the breakthrough could only be deduced from the change in gradient of the pore pressure transducers.

Based on the models of the head profiles, it appears that the barrier in the Delta Flume tests had a comparable relative density (in the range of 0.7 to >1) to that of the barriers in the medium-scale tests (the test which led to the tentative strength criterion – a local critical gradient measured over 10 cm from the pipe tip). Therefore, a comparable local critical gradient can be expected, and the model indeed predicts a critical gradient upstream of the barrier that is comparable to the strength criterion when a 4 cm pipe is modelled with a barrier hydraulic conductivity in corresponding to 90%. This supports the hypothesis that a local

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critical gradient derived in 2D medium-scale models can be used to predict the progression of a pipe in a barrier at larger scale.

Versie	Datum	Auteur	Paraaf	Review	Paraaf	Goedkeuring	Paraaf
1.0	jan. 2019	Esther Rosenbrand		Vera van Beek		Leo Voogt	
		Ulrich Förster					

Status
final

Contents

1 Introduction

The current safety assessment method for piping, applied in the Netherlands, results in a large amount of sections to be reinforced. One of the sections that failed the safety assessment criteria is located at the river Waal nearby the village of Gameren. A dike stretch of 0.3 km failed the safety assessment criteria in the third safety assessment round, that was conducted in the period 2006-2011, and will need to be reinforced within short term. However, this is not the only dike section that will need to be reinforced. Indicative studies show that approximately half of the levees that are operated by Dutch Water Authority Rivierenland will not pass the current safety assessment criteria for piping.

Traditional reinforcement methods, like berms to increase seepage length, become less and less attractive due to the large required seepage length and the dense population and building development in this area. Several alternative (and innovative) methods are available that require less space. A new alternative method is the coarse sand barrier. This method entails the replacement of existing sand with coarse sand in a trench on the landside of the levee directly below the blanket layer. The blanket layer is restored after trenching.

The Dutch Water Authority Rivierenland intends to apply the coarse sand barrier at the pilot location Gameren as an innovative measure. Although experiments in the laboratory and at the IJkdijk (a former full-scale test facility in the North-Eastern part of the Netherlands) indicate the potential of the method, it is required to conduct a feasibility study to investigate whether the method offers sufficient resistance against piping in the field, both for the intended pilot location and for other, comparable locations. Based on the result of this feasibility study and the exploration of alternative measures, a preferential measure will be selected for the pilot location.

The purpose of the study is to assess the feasibility of the application of a coarse sand barrier as a piping measure for the location of Gameren, and for other locations along the Dutch main rivers in a more generic sense. To quantify the strength of the barrier, a criterion needs to be identified that predicts pipe formation into the barrier.

Based on analysis of small- and medium-scale experiments (Deltares, 2017d,e; Deltares, 2018a,b,c,d) the hypothesis is that the local horizontal gradient in the barrier near the tip of the pipe characterises the strength of a given barrier material at a given relative density, i.e. implying that different tests with the same material show the same local critical gradient in the barrier, regardless of the configuration or dimensions of the barrier. This hypothesis is validated at larger scale in this report, using the Delta Flume experiments described in (Deltares, 2019).

The approach to the feasibility study is described in (Deltares, 2017a) and consists of the following phases:

- Phase 1: Literature study filter requirements and selection of barrier material.
- Phase 2a: Small-scale experiments and numerical simulation.
- Phase 2b: Medium-scale experiments and numerical simulation.
- Phase 2c: Large-scale experiments and numerical simulation.

The feasibility study is oriented towards one pilot location, but much of the knowledge developed in this study will be applicable in a more generic sense (at other locations). The study focusses explicitly on the technical feasibility of the measure and will not address the practical aspects of installing the coarse sand barrier in the field. Phase 1 involved a literature study concerning applicable filter criteria for the design of a coarse sand barrier and was reported (Deltares, 2017b). This has led to the selection of barrier materials used for the small-scale experiments reported in (Deltares, 2017c). The report at hand presents the analysis of the experiments conducted in phase 2c of the feasibility study. The research questions for phase 2, which contains: the small-scale tests in phase 2a, and the medium-scale tests in phase 2b, and the Delta Flume tests in phase 2c (this report), are:

- How much additional resistance to erosion will the barrier material provide, given the characteristics of the original sand body at the pilot location?
- What is the local gradient upstream of the pipe, at which the pipe progresses into the barrier, in small-, medium- and large-scale experiments? How does this local gradient affect the average gradient for the pilot location?
- What is the influence of the hydraulic conductivity contrast and grain size contrast of the chosen barrier material and original material on the resistance to piping?
- What are the effects of trench thickness and penetration depth?
- How can we monitor pipe formation through the barrier (failure of the barrier)?

2 Experiments

The experimental set-up including the details concerning the installed monitoring system containing pore pressure transducers and coloured tracers, the experiments and the observations of the two Delta Flume tests are reported in de Factual Report Delta Flume Experiments Coarse Sand Barrier (Deltares, 2019). A general impression of the set-up is shown in Figure 2.1.

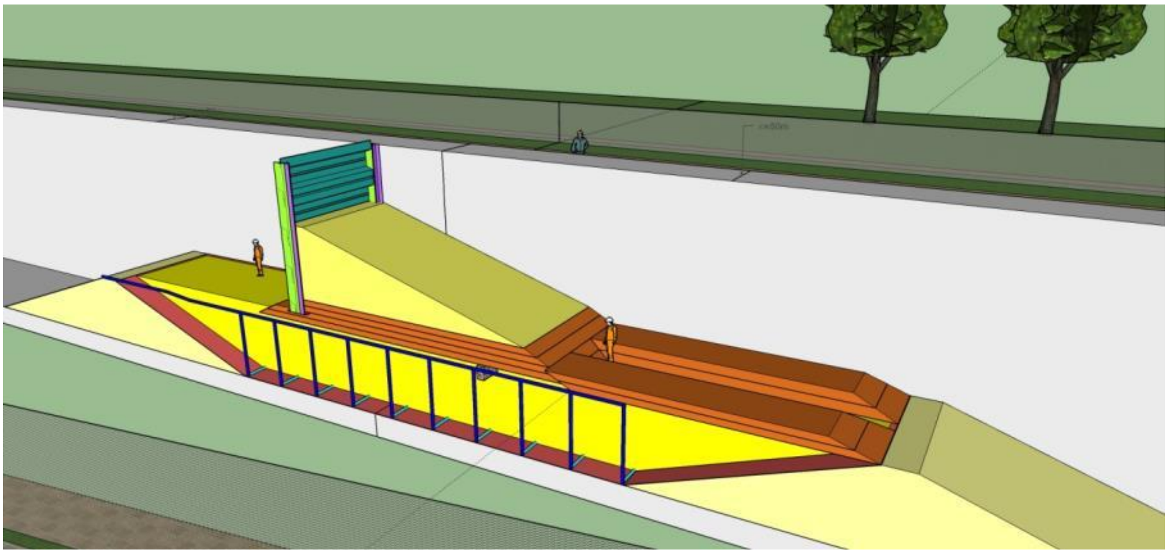

Figure 2.1 General set-up of the coarse sand barrier model in the Delta Flume (in this figure the CSB is situated at a distance 4 m upstream from the exit point (ditch), this has to be 6.0 m to 6.30 m in test 1 and 11.00 m to 11.30 m in test 2 respectively).

Figure 2.2 and Figure 2.3 present longitudinal sections and top views of the set-up of the two tests.

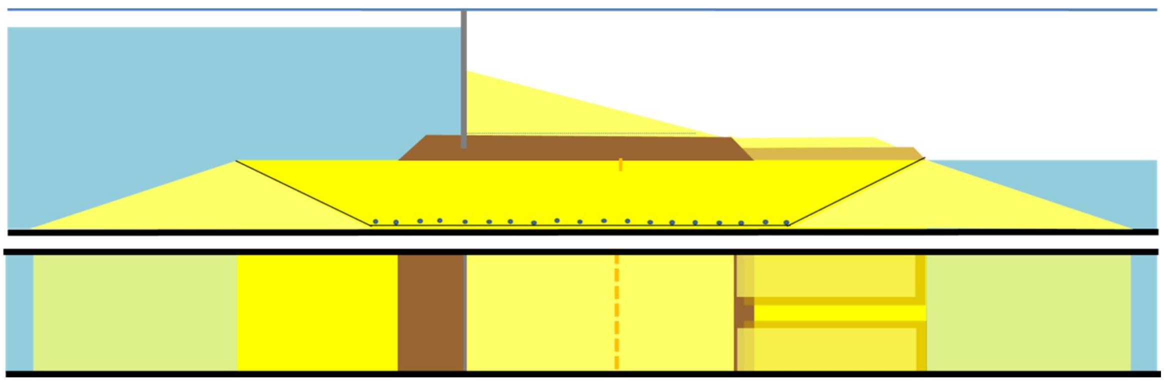

Figure 2.2 Longitudinal section and top view of first test (to scale): aquifer (bright yellow) is 3.0 m thick, clay top layer (dark brown) 1.0 m thick and 15.5 m long

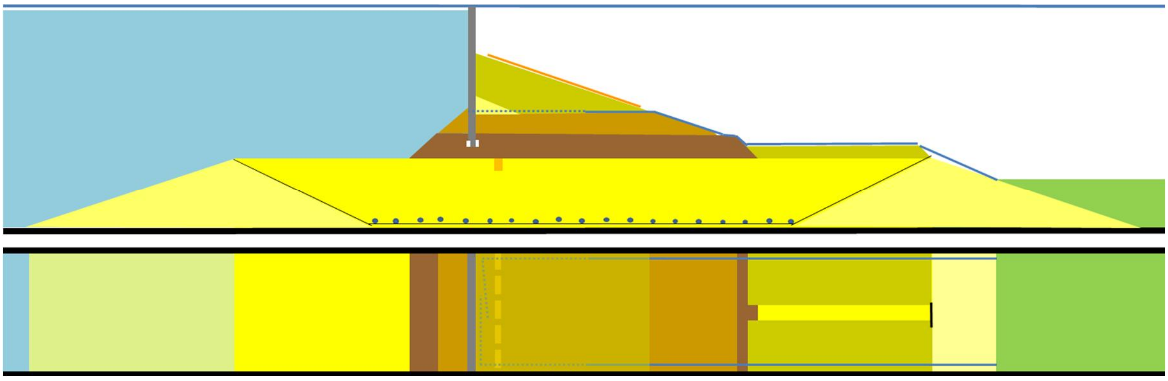

Figure 2.3 Longitudinal section and top view of second test (to scale)

The width of the Delta Flume is 5.00 m. The sand layer prone to piping is 3.0 m thick. The test sand is separated from the bottom of the flume and the supporting dikes by means of a foil. On top of the test sand layer, a continuous clay layer has been placed over a length of 15.5 m, ending at a small ditch (0.5 m bottom width) in the centreline of the flume with a clay cover on both sides over the full length of the outflow section. The thickness of the clay layer is 0.5 m. The inflow section is uncovered. Generally, a coordinate system is applied with its origin at middle of the head of the ditch, i.e. 2.5 m from each wall, at the top of the sand layer. The clay layer at the inflow area thus extends to x = 15.5 m in test 1.

The coarse sand barrier extends 0.50 m into the sand layer. In test 1, its top also extends 0.20 to 0.25 m into the clay cover. The thickness of the barrier is 0.30 m at the clay-sand-interface, on top of the barrier the thickness is 26 cm. It is not applied over the full width of the Delta Flume: near the concrete walls pockets of swelling clay (Mikolit) have been installed over a distance of approximately 20 cm on both sides over the full width and depth of the coarse sand barrier.

In modification to test 1, in test 2 a seepage length of 15.0 m is applied and the coarse sand barrier is placed at a distance of x = 11.00 to x = 11.30 m upstream from the exit point (i.e. 3.7 to 4.0 m from the upstream edge of the clay cover). It extends 0.5 m into the sand layer and its top is at the same level as the top of the sand layer.

In both tests the same combination of background sand and coarse sand barrier material is applied. For the barrier GZB2 is used, for the sand bed a batch of sand from the Western Scheldt Estuary.
The background sand was constructed in 10 layers of 30 cm. Each layer was compacted by vibrating compacting equipment. From all layers except for the eighth layer, three samples were taken to determine the relative density. The achieved relative density for the background material varied between 35 and 65%. Two samples were taken from the coarse sand barrier. For these samples a relative density of 73-74% was found.

In test 1 there are 28 pore pressure transducers (PPTs) placed in the sand bed. Two have been placed at a depth of 2.0 m with respect to the sand-clay-interface and the others were placed directly at the sand-clay interface, including those in the coarse sand barrier. The positions of the pore pressure transducers (PPTs) of Test 1 are depicted to scale in Figure 2.4 and Figure 2.5.

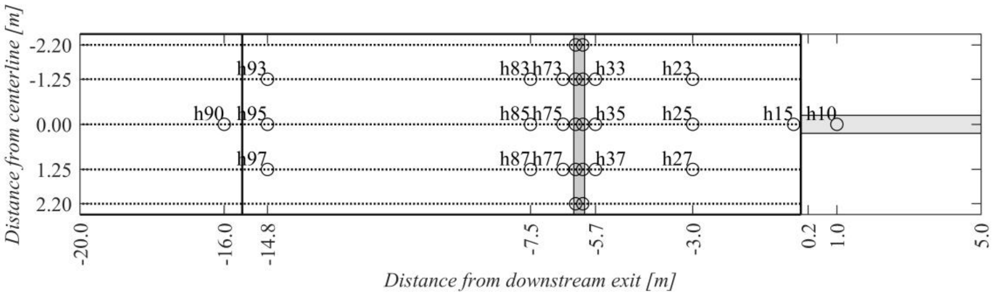

Figure 2.4 Positions of all PPTs along the aquifer in test 1with respect to the position of the downstream exit

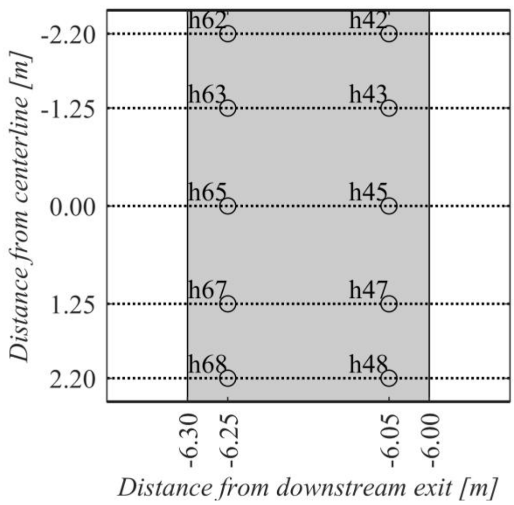

Figure 2.5 View on positions of PPTs in coarse sand barrier in test 1with respect to the position of the downstream exit

The location of the transducer pairs is denoted by the line in which they are located (i.e. 2 and 8 near the flume wall, 3 and 7 East and West of the centre and 5 in the centre.

In addition, 5 rows of tiny Polystyrene foam balls In Gelatine (PIGs) are built in. These PIGs are expected to flow to the exit point as soon as they are reached by the pipe(s). The PIGs have different colours depending on their position in the set-up, which means that they can give an indication of the progress of pipe development. The distance of the rows with PIGs with respect to the position of the downstream exit at the edge of the ditch is given in Table 2.1.

Table 2.1 Positions rows of coloured PIGs in test 1

Colour of PIGs	Distance x from ditch [m]
white	5.95
green	6.05
blue	6.25
black	6.40
red	8.00

The positions of the pore pressure transducers (PPTs) of Test 2 are depicted to scale in Figure 2.6 and Figure 2.7. In the second tests 37 instruments were available to employ. Based upon the experience of the first test, where much piping activity took place near the walls of the flume, most additional instruments have been installed close to the walls (numbers 22-28-32-38-72-78). Another additional instrument has been placed at a depth of approximately 35 cm inside the barrier, near the downstream side and close to the middle (number 246).
The PPTs 10 and 90 are installed at around 2.0 m depth below the sand surface. The instruments 09 and 99 are located near or at the surface. Furthermore, a pore pressure transducer is added in the upstream reservoir (number 99) to reliably measure the reservoir level once the basic instrumentation of the Delta Flume does not register properly anymore (at a level of approximately 5.9 m above the sand-clay interface, or at exactly 8.927 m above the bottom of the flume). At the downstream side, an additional pore pressure transducers is placed inside the ditch, near the top of the sand (number 09), to enable a precise calculation of the hydraulic head over the structure.

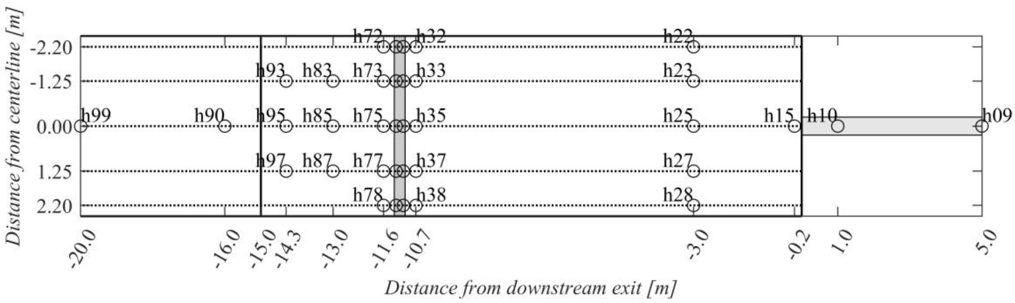

Figure 2.6 Positions of all PPTs along the aquifer in test 2 with respect to the position of the downstream exit

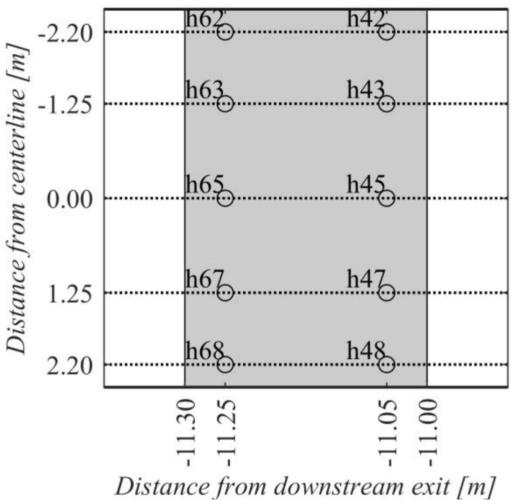

Figure 2.7 View on positions of PPTs in coarse sand barrier in test 2with respect to the position of the downstream exit

In addition to these instruments, also four rows of tiny PIGs and an additional line of red coloured Metselzand were built in as tracers. The distance of the rows with PIGs and the coloured sand with respect to the position of the downstream exit at the edge of the ditch is given in Table 2.2.

These particles may be transported rather quickly through the pipes towards the exit point, giving an indication that the barrier has nearly been reached (red and black PIGs), slightly damaged (green), severely damaged (white), or failed (purple). Moreover, excess production of red, black and white PIGs will indicate sideways enlarging of the pipe system. One thin row of red-coloured Metselzand (normally constituting 20% of the coarse sand barrier) was added 8 cm upstream of the downstream end of the coarse sand barrier in order to serve as an extra tracer and to test its suitability as a tracer in field situations

Table 2.2 Positions rows of coloured PIGs and coloured Metselzand in test 2

Tracer	Distance x from ditch [m]
black (southern side) / red (northern side) PIGs	10.95
green PIGs	11.05
red Metselzand	11.08
white PIGs	11.25
purple PIGs	11.40

During the tests the head drop across the dike is increased according to a certain load scheme, which is described in detail in Appendix E of de factual report (Deltares, 2019).

During the tests the following data is collected:

- Hydraulic head in the upstream reservoir. The actual water level is automatically measured by a gauge at the upstream side of the bulkhead. This system works accurately until a water level of approximately 8.927 m above flume floor level. Beyond this, the actual water level has to be controlled by hand, using a tape rule or a folding rule, based on the height of the edge of the flume wall of 9.50 m. The accuracy of the automatic measurements is 1 cm.
- The water level in the ditch is variable and measured throughout the test. In test 2 the effective head difference is derived from the measured heads with water pressure transducer 09 and 99 which are situated near or at the surface of the sand layer.
- Observations concerning sand boil forming in the ditch and the discharge of tracers (PIGs).
- Photographs are taken during every patrol of inspection.
- Flow is recorded manually regularly at the downstream side of the ditch by weighting the mass of water flowing through a pipe at the end of the ditch within a certain time, using a 5 l bucket or a measuring jug, a stopwatch and a balance with an estimated uncertainty of ca.1% during the tests (uncertainty arising from time taken to collect sample and uncertainty in weight of the sample).
- At the beginning of the tests also samples of sand originating from the sand boils were collected in frequent intervals. It was the intention to use these samples for tentative sieve analyses determining the percentage of coarse sand in case of inconsistencies concerning the erosion development of the barrier itself. Afterwards, it turned out that this was not necessary. It was possible to detect the output of coarse sand in the sand boils visually. Thus, it was decided to omit further sieve analyses. Additional, during test 2, a fibre optic cable for temperature measurement (Active Distributed Temperature Sensing, ADTS) combined with copper wire heating was installed to give an indication of the groundwater flow.

At the start of test 2 the temperature of the water in the sand bed was 15°C.

Concerning the recorded flow, there are several things to be aware of for test 2:

- A few hours after the start of the test a heavy rainfall occurred (approximately 30 to 70 mm in less than half an hour, not measured locally). A better approximation may be derived from the variation in the upstream level, considering seepage losses during this period of time.
- Long, steady rain for about 10 hours roughly from t=32 to t=42 hours, with a strong variation in total amount perpendicular to the wind direction within a few miles only, total amount at the Delta Flume again roughly between 30 and 70 mm.
- The discovery at some point that the ditch had not been dug deep enough; water flow and sand boils started at a higher head than should be expected, not until removing some 10-20 cm of clay.

The test characteristics of the two tests are presented in Table 2.3 and Table 2.4.

Table 2.3 Test characteristics Test 1

Delta Flume test 1		
Type of background sand and barrier	**Western Scheldt sand**	**GZB 2**
Relative density	35-65%	74%
d_{50}	0.227 [mm]	1.053 [mm]
d_{70}	0.271 [mm]	1.240 [mm]
d_{60}/d_{10}	1.7	3.0
Seepage length	15.5 [m]	
Gross head difference at first observation	0.8 [m]	
Gross head difference at intended type of failure	-	
Gross head difference at start of sand boiling	2.0 [m] (22-04-2018 around 0:00)	
Gross head difference at termination of the test	6 [m]	

Table 2.4 Test characteristics Test 2

Delta Flume test 2		
Type of background sand and barrier	**Western Scheldt sand**	**GZB 2**
Relative density	35-65%	-
d_{50}	0.227 [mm]	1.053 [mm]
d_{70}	0.271 [mm]	1.240 [mm]
d_{60}/d_{10}	1.7	3.0
Seepage length	15.0 [m]	
Gross head difference at first observation	-	
Gross head difference at intended type of failure	3.5 [m]	
Gross head difference at start of sand boiling	2.2 [m] (31-05-2018 around 23:00, delayed by a thin clay or mud layer	
Gross head difference at termination of the test	3.5 [m]	

During test 1, the bulkhead, embedded in the top of the blanket layer of the test dike for enabling a maximum hydraulic load, showed some leakage problems. For this reason test 1 had to be interrupted at a head drop of 4.0 m in order to take additional sealing measures. After this the test was restarted. Test 1 was abandoned at a head drop of 6.2 m, because of reoccurring leakage damages. The pipe did not progress through the barrier in this test.

Test 2 failed at a head drop of 3.5 m.

A detailed record of the observations at the different load steps and is given in Appendix E of the factual report (Deltares 2019).

3 Piping process during 2nd Delta Flume test

The first Delta Flume test had to be abandoned because of leakage problems attributed to imperfections in the sealing of the joints between flume wall and bulkhead and an insufficient embedding of the bulkhead in the blanket layer. During this test, the pipe did not progress through the barrier. Because of this, the distance of the coarse sand barrier with respect to the entry point was shortened in the second test, in order to be certain that failure of the barrier will be reached at the head differences attainable in the flume. Indeed, the barrier collapsed at the end of the second test.

Therefore the piping process is first analysed for the second Delta Flume test, and subsequently the first Delta flume test is discussed.

Due to the presence of a clay cover, the piping process in the Delta Flume experiments can only be described by interpretation of pressure transducer measurements. This interpretation is aided by experience gained in the medium-scale experiments. Contrary to the observations in test 1, the tracers (PIGs) which were intended to give an indication of the progress in pipe growth did only emerge in the final stage of the second test. Furthermore, the application of coloured coarse sand did not succeed, because no eroded coloured sand could be detected or distinguished in the ditch.

During the medium-scale experiments, the progression of the pipe could be observed through the Perspex plate, and monitored using the pore pressure transducers (PPTs). It was noted that several steps of the pipe progression were distinguished in the pore pressure profile, and that these can typically be most clearly observed when considering the gradient that is computed parallel to the flow direction between the transducers on the upstream side of the barrier and the transducers on the downstream side of the barrier.
Steps in the process that were clearly observed in the medium-scale experiments are:

- the pipe reaching the barrier, this causes a sharp increase in the gradient over the barrier;
- the long growth step, where the pipe progresses approximately past half way in the barrier but does not lead to failure. This causes the gradients in the barrier to fall sharply on the side of the barrier at which the pipe progresses. The effect is visible, but less pronounced in the transducer pairs that are further away from the location at which the pipe progresses.

The outline of the pipe at the different progression steps, and the computed gradient profile in the barrier, is shown for medium-scale test MSP 26 in Figure 3.1 and Figure 3.2. This can be compared to the gradient profile for the second Delta Flume test in Figure 3.3.

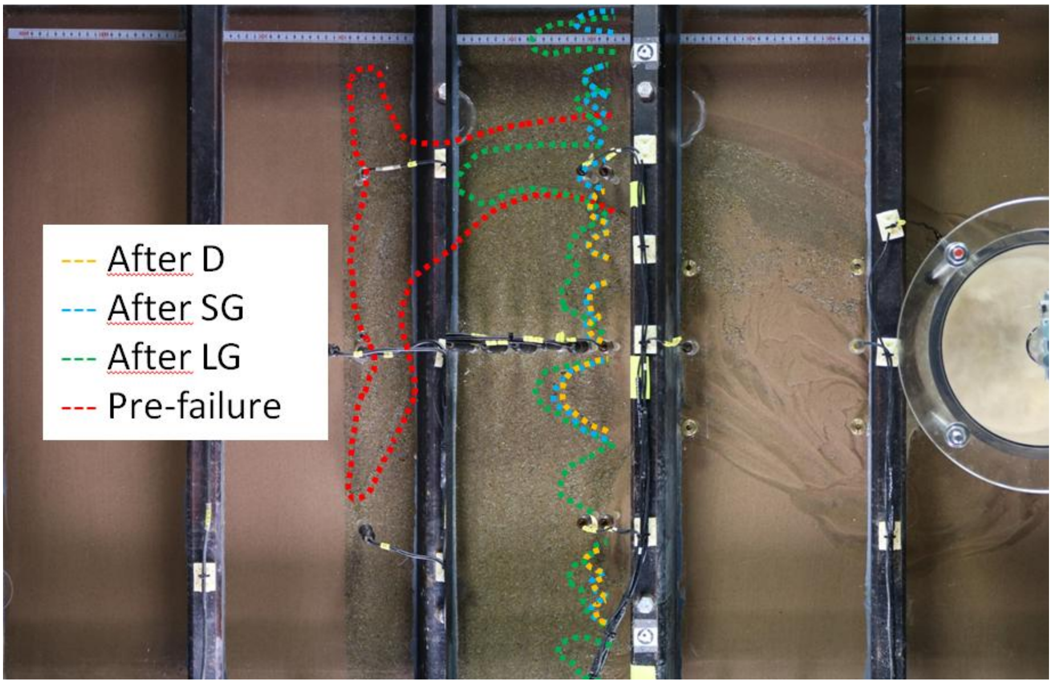

Figure 3.1 Indication of the extent of the pipe after characteristic growth steps and prior to failure based on visual inspection for medium-scale test MSP 26 (GZB 1 and Baskarp 25)

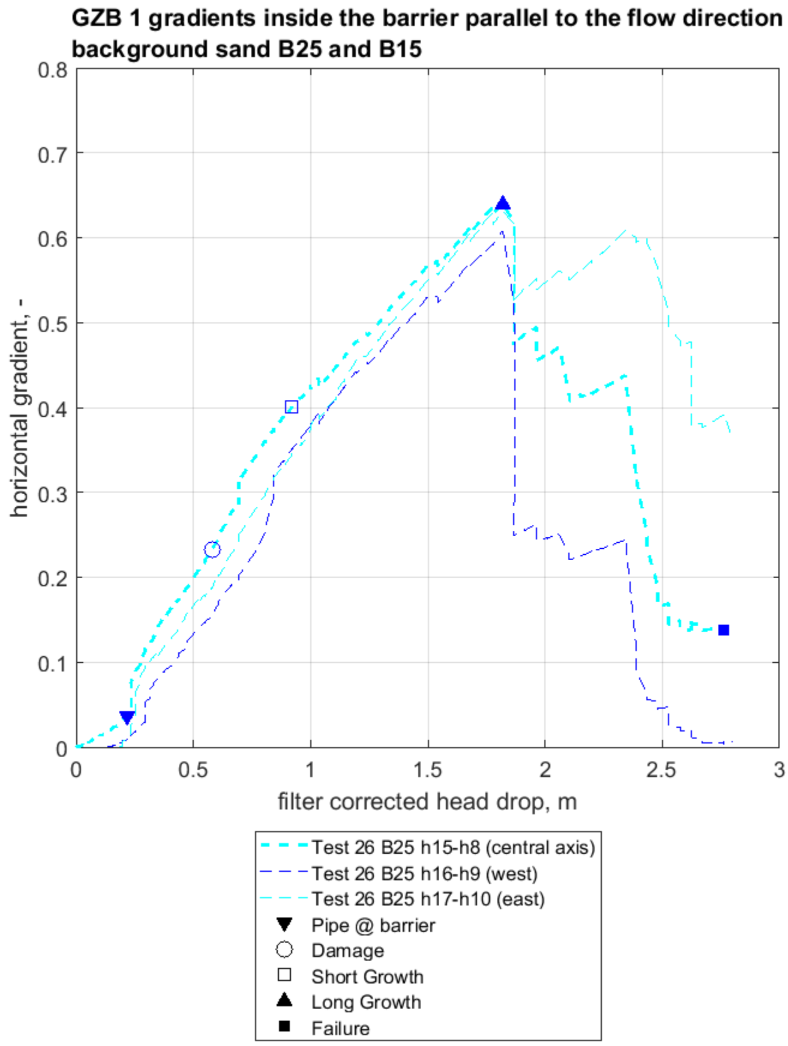

Figure 3.2 Gradients parallel to the flow direction inside the barrier (over distance 27 cm) for medium-scale test MSP 26 (GZB 1 and Baskarp 25)

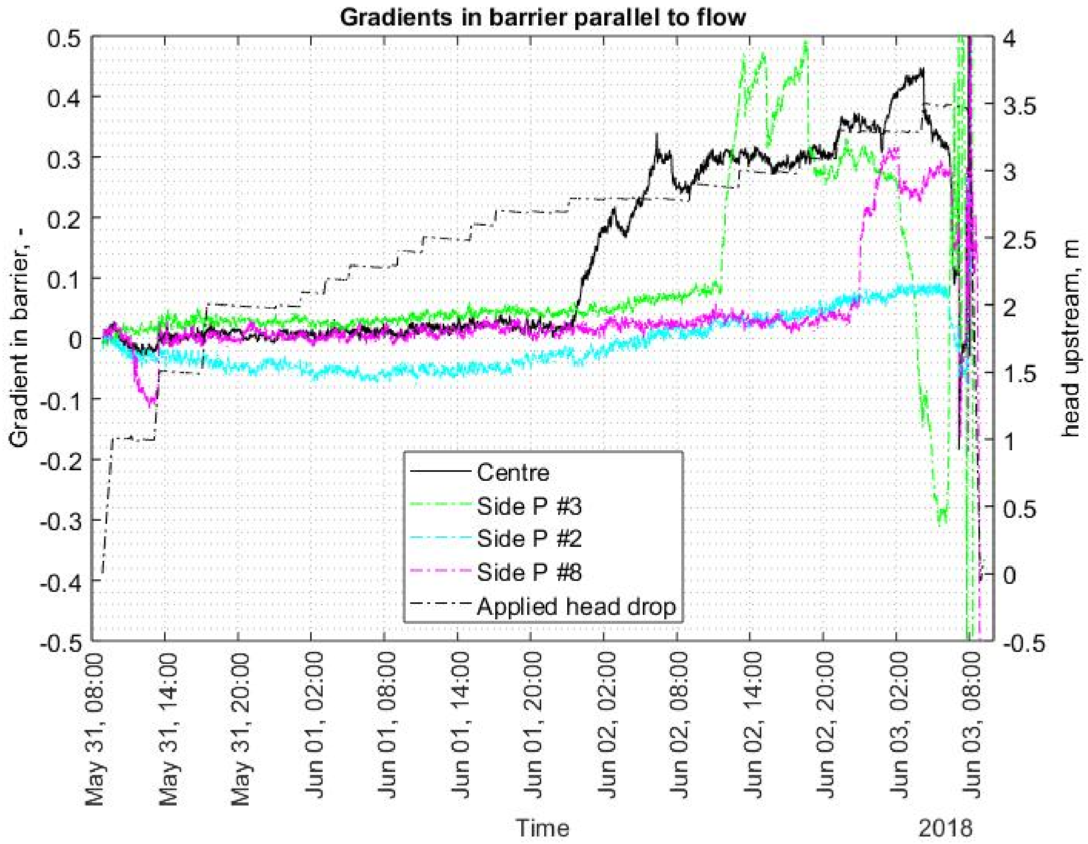

Figure 3.3 Gradient parallel to the flow direction inside the barrier (over 20 cm) during the second Delta Flume test (GZB 2, Delta Flume sand). Line 7 is not shown as the transducers P47 and P67 were both considered to be unreliable.

For medium-scale test 26, Figure 3.2 shows that the gradients all rise sharply when the pipe reaches the barrier. When the long growth step occurs, the gradient falls most strongly in the west side of the model, which is where the long growth step takes place. After the long growth, gradients stabilise again, and the test is continued by further increasing the head drop. In that test, the pipe progresses parallel to the upstream interface of the barrier, causing the gradients to fall sharply prior to failure. At failure the upstream tap was closed directly therefore no further fall of the gradients is observed.

In the Delta Flume tests the transducers were located at several locations at the interface of the sand bed and the clay cover, both in the coarse sand barrier and the surrounding sand. Figure 2.6 and Figure 2.7 show the locations of the transducers. The transducer pairs in the barrier (row 6 and row 4) have been used for the analysis of pipe progression.

Figure 1.3 shows the gradients measured over these transducer pairs during Delta Flume experiment 2. Considering the point of the pipe reaching the barrier for the Delta Flume test, there is a distinct lag between the increase in the gradient in the centre of the model and at the side of P#3, and a further lag before the side P#8 rises. Side P#2 does not rise strongly at all. If it is assumed that the rise in local gradients is due to the pipe in front of the barrier progressing parallel to the barrier to the location of the transducer pairs, this suggests that the pipe did not progress along the entire extent of the barrier prior to damaging the barrier. This contrasts with what was observed to happened during the medium-scale tests. Possibly the absence of equilibrium in the pipe affected the lateral progression of the pipe along the barrier.

The evolution of the gradients inside the barrier during the 2nd Delta Flume test is summarized in Table 3.1.

Table 3.1 Summary of evolution of gradients inside the barrier during the 2nd Delta Flume test.

Time (±20 min)	Observation	Interpretation
23:20 Jun 1	Increase gradient centre	Pipe reaches the barrier close to the centre.
11:15 Jun 2	Increase gradient side P#3	Pipe progresses along the barrier to vicinity of transducer pair at side P#3.
22:15 Jun 2	Increase gradient side P#8	Pipe progresses along the barrier to vicinity of transducer pair at side P#8.
18:30 Jun 2	Gradient at side P#3 falls to a plateau value	Progression of the pipe in the barrier in the vicinity of transducer pair at side P#3 (pipe remains somewhere in between P63 and P43).
02:00 Jun 3	Gradient at side P#3 falls to negative values	Progression of the pipe in the barrier in the vicinity of transducer pair at side P#3 (pipe progresses beyond P63, possible displacement of the transducer causing the gradient to become negative).

Since the transducer row on the upstream side of the barrier is still 5 cm short of the upstream interface of the barrier, it is not possible to assess whether the pipe has progressed through the upstream interface of the barrier at 02:00 on June 3rd. It is difficult to assess what exactly causes the different gradients at different locations in the barrier. The distance among parallel transducer pairs in the medium-scale tests was only 20 cm and there were already differences in gradient among these depending on the location of pipe progression in the barrier. In the Delta Flume test the distance between the centre and the line #3 transducers is 1.25 m, thus larger differences are to be expected.

Following the approach in the medium-scale tests to consider the first significant fall in gradient (which corresponded to the point at which the gradient in the barrier is maximum) as the critical (long growth) step, the point at 18:40 at June 02 is considered as the critical step and used for modelling the local critical gradients. As the pipe appears to progress into the barrier on the P#3 side, the measured head profile on that side can be considered to be most representative for the local heads upstream of the pipe tip.

3.1 Head profile at critical step

For modelling the heads that were measured just prior to the growth step are used. Thus, the heads at 18:20 on June 02 are shown in Figure 3.4, and a close-up of the barrier is shown in Figure 3.5. As transducer P35, P47 and P67 are considered unreliable, those are not shown.

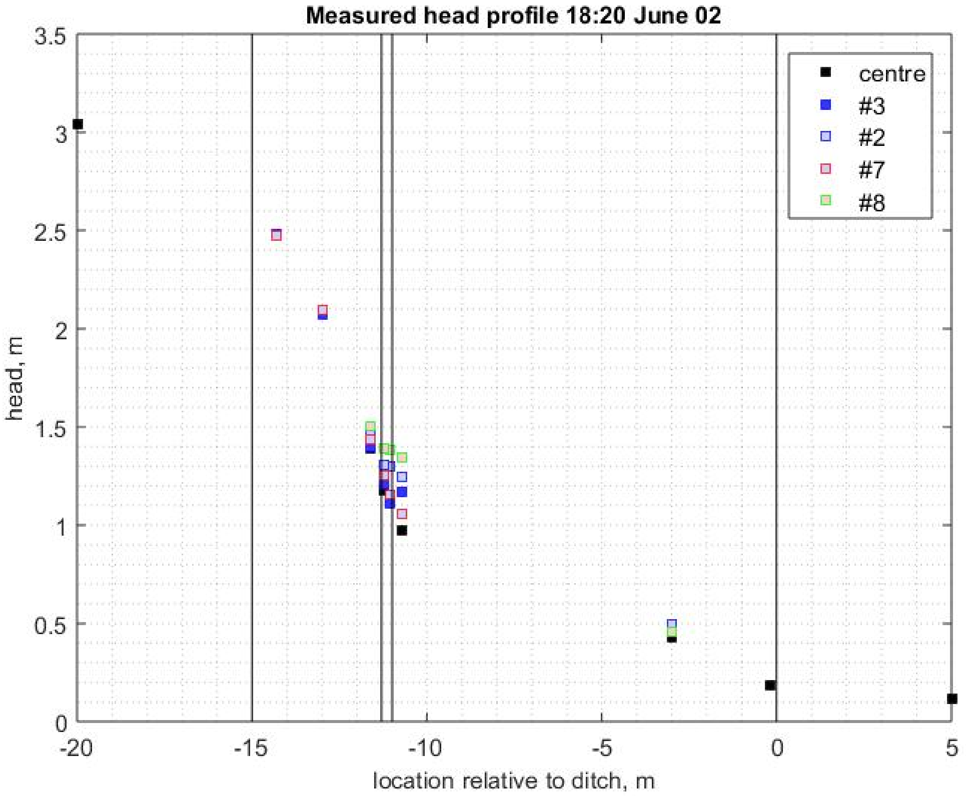

Figure 3.4 Measured head profile at 18:20 on June 02 in Delta Flume test 2

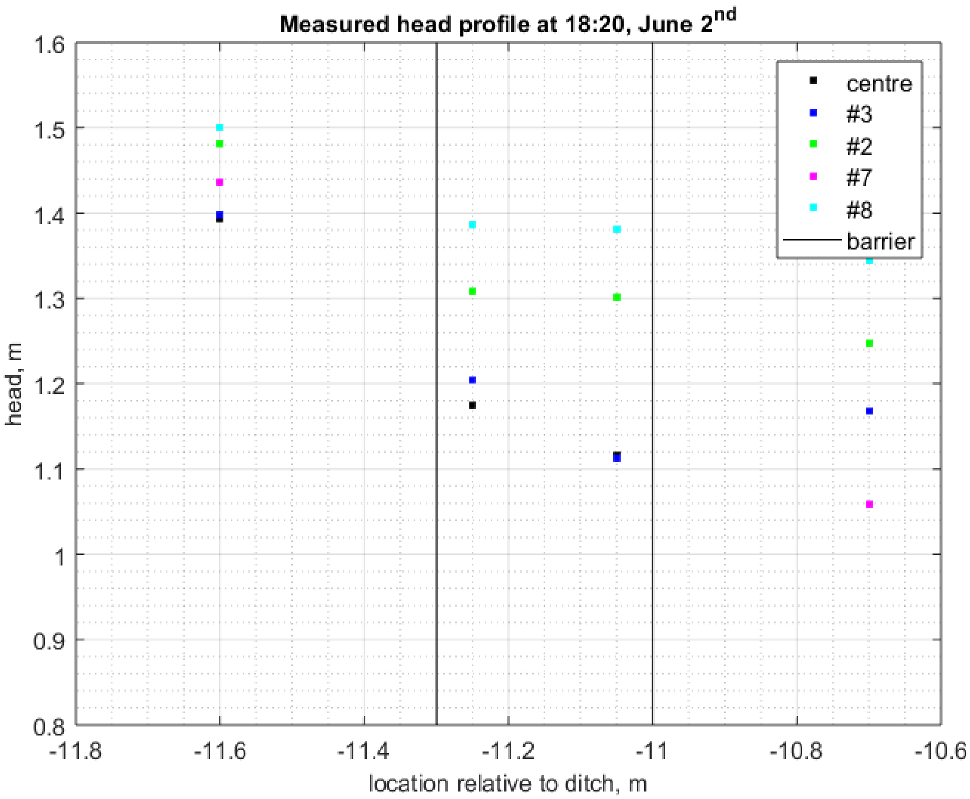

Figure 3.5 Measured head profile at 18:20 on June 02 in Delta Flume test 2, close up

Downstream of the barrier, at -10.7 m, the head is lower in P35 in the centre than in the transducers to the side of this, probably the pipe is present here. There is still a significant head loss between this location and the ditch, ca 1 m. **In the medium-scale tests, the head loss in the pipe was negligible, but that does not appear to be the case here. This could indicate that the limit equilibrium for grains on the bottom of the pipe was not fulfilled, and that grains were still eroded in the downstream pipe.**

On the downstream side inside the barrier, at -11.05 m, transducers P45 and P43 indicate a similar value. The value in P43 is lower than in P33 (Figure 3.5) suggesting that indeed there is some crumbling or damage of the barrier, resulting in a lower head in the barrier than downstream of the barrier where there is no pipe.
Inside the barrier, the heads measured by P48 and P42 are significantly higher, indicating that there is no pipe there. The head measured by P47 and P67 is considered unreliable, as it was consistently lower than the other heads in the early phase of the test prior to piping.

On the upstream side of the barrier, at -11.25 m, the head measured in the centre at P65 is lower than in P63. This results in the lower gradient in the centre of the barrier than on the P#3 side. A lower head in the centre upstream side might be expected if there has been more crumbling in the centre, or if there is a deeper erosion hole in front of the barrier there than on the P#3 side. Such phenomena were also observed in the medium-scale experiments.

A sketch of the possible pipe progression steps is shown in Figure 3.6.

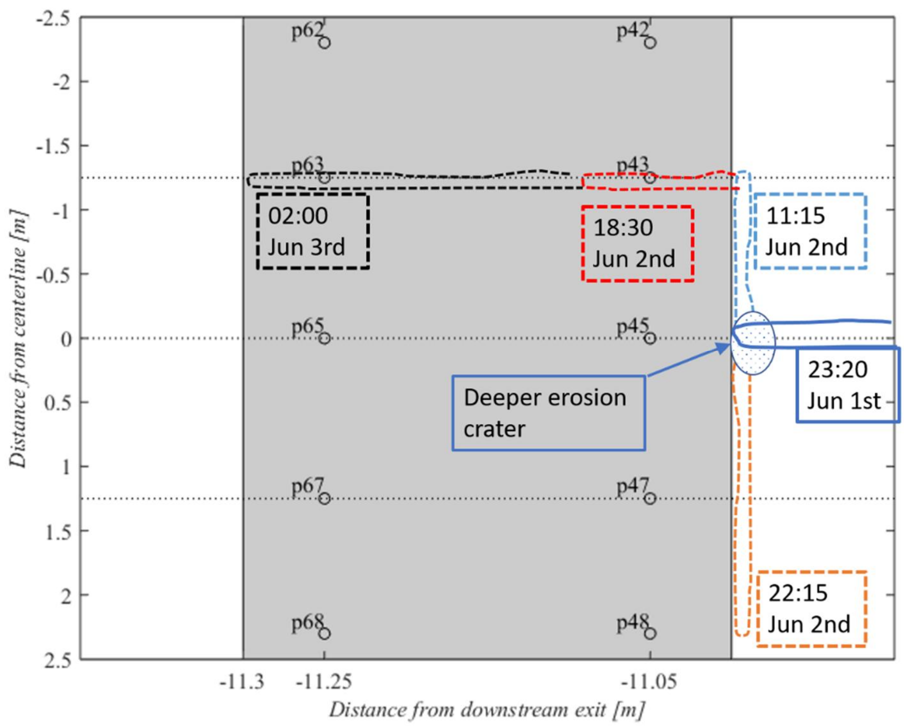

Figure 3.6 Indicative sketch of possible pipe extent during Delta Flume test 2 based on head measurements. The expected minimal extent of the pipe after the progression after *the indicated time steps is shown; it is possible that the pipe progressed further than the locations indicated here.*

What stands out at the excavation after the end of the test is the fact that the northern part of the CSB was not present anymore in contrast to the southern part of the CSB. The clay layer

rested directly on top of the fine sand, whereas the CSB was still visible at the southern side of the flume. This is contradictory to the indicative sketch of the expected location of the pipe according to the water pressure measurements and the visual observations of the eddy at the downstream side during the final phase of the failure, when the eddy in the downstream ditch was first shifting around the head of the ditch and finally moving to the southern flume wall.
Furthermore, layer of fine sand (ca. 1 cm high) was detected on the southern side between the CSB and the blanket layer. The widening process of the pipe seems to be less predictable. A possible explanation for this phenomenon is given in 6.2.

3.2 Head drop in pipe

At the critical progression point, the head measured in the pipe in the barrier in h43 and h45 is ca. 1 metre. This indicates a significant head drop in the pipe downstream of the barrier, which was not observed in the medium-scale or small-scale experiments. This suggests that secondary erosion was still actively deepening and widening the pipe at the critical progression point.
This could possibly account for the fact that the pipe did not progress along the entire width of the model prior to damaging the barrier. With a higher head in the pipe, there would be less convergence of flow from the sides to the pipe, and therefore a relatively lower hydraulic load in the fine sand to the sides of the pipe.
The measured critical gradient in the barrier would not be affected by a higher head in the pipe, however, this critical gradient would occur at a lower overall head drop if the head drop in the pipe were negligible.

4 Piping process during 1st Delta Flume test

The locations of the transducers and the barrier in the first Delta Flume test are shown in Figure 2.4 and Figure 2.5.

The gradients in the barrier parallel to flow during the first Delta Flume test are shown in Figure 4.1 and Figure 4.2. The increase in the gradients at Side #3 and Side #2 indicates that the pipe reaches the barrier at April 19th around 16:30. However, at this point of time no tracers (PIGs) have been observed in the ditch. At this time two sand boils at the northern corner of the ditch and one sand boil at the southern corner were active. There is a gap of measured data in the afternoon of April 20th, during which the upstream head was lowered in order to perform repair activities on the set-up.

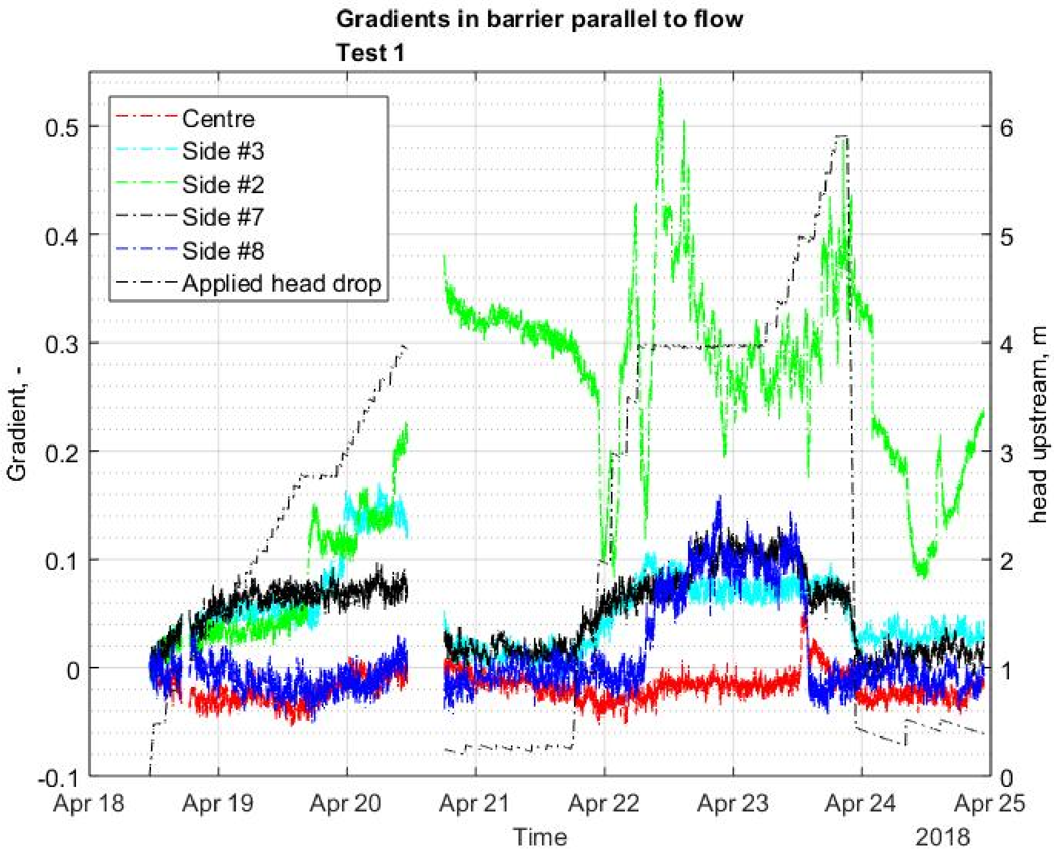

Figure 4.1 Measured gradients inside the barrier during test 1.

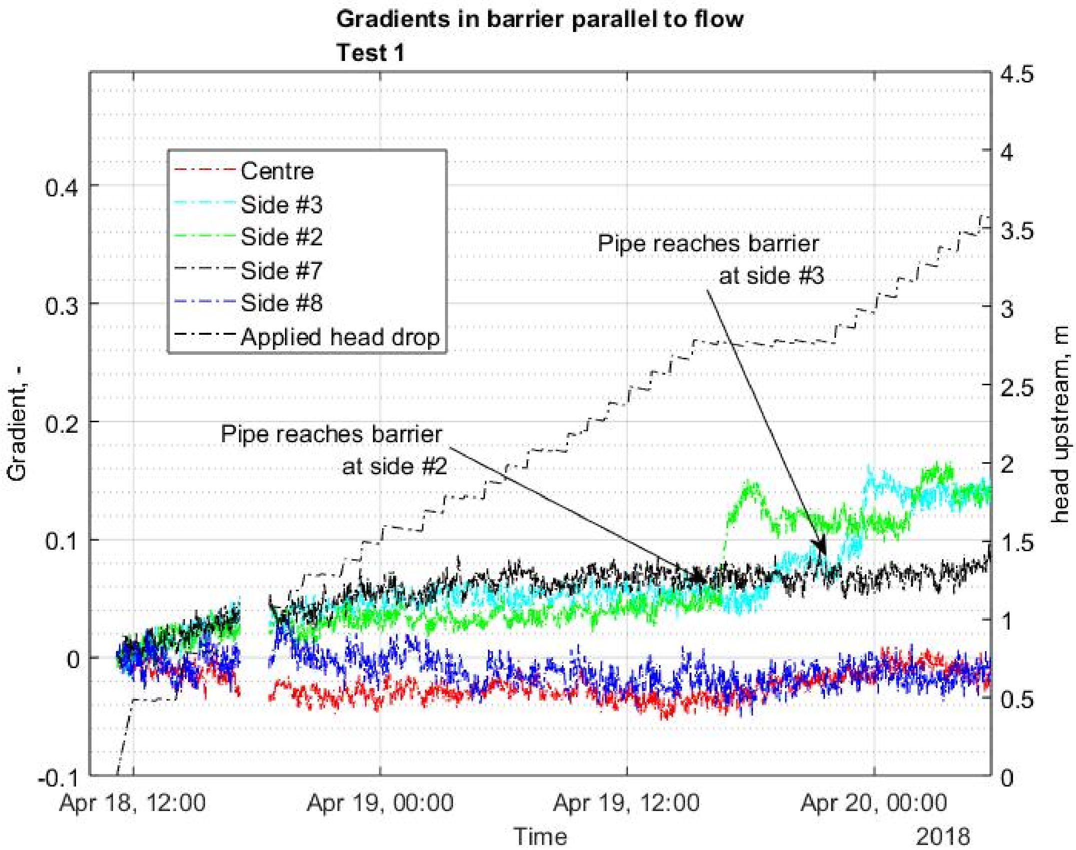

Figure 4.2 Measured gradients inside the barrier during test 1, close up of the time frame in which the pipe reaches the barrier.

Shortly before the interruption in the measurements, the gradient in transducer pair #2 rises. This could possibly be due to some progression of the pipe in the barrier at this side. The local gradient is lower than the gradient at which long growth would be expected, but this could be one of the shorter growth steps which was also observed in the medium-scale tests.
Subsequent to the interruption, there is a significantly higher gradient in this transducer pair. Despite the upstream head being ca. 0.28 m, the local gradient is ca. 0.3. Considering that the gradient is measured over ca. 0.25 m that would indicate a head drop greater than 1 m. This suggests some artefact in the measured data, as the total head drop is only 0.28 m. The other gradients remained low close to 0 as would be expected. Side #2 is the side at which the leakage occurred, however, this was perceived to be further upstream than the location of the barrier.
When the upstream head was increased again, the local gradients at #3 and #7 rose and later also at #8 indicating a pipe progressed close to those transducers. The gradient in #2 spikes erratically after April 21, 23:00.
Since the combined variation of the head measurements in the upstream and downstream sides of the barrier result in the computed gradient, to find the causes for variation in critical gradient, the individual head measurements are shown in Figure 4.3 and Figure 4.4.

Initially, after restarting the test after the interruption, the head on the upstream side of the barrier in P62 was higher than the other heads in the barrier in this row. The value was similar to the head upstream, and therefore has become unreliable. After April 23, 23:00 the head here becomes lower than the other heads in that row. The head in the downstream part of the barrier, in P42 was first similar to the other heads in that row, and subsequently became lower. The presence of a pipe in the downstream part of the barrier would cause a lower head on the downstream side of the barrier.

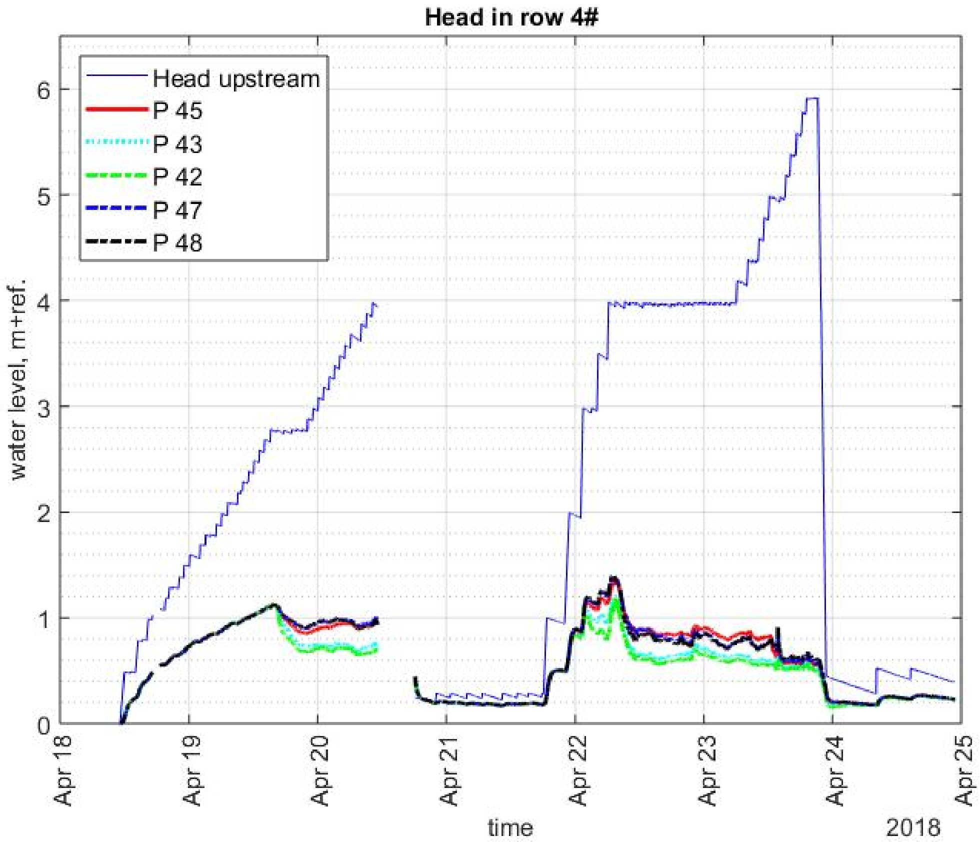

Figure 4.3 Head measured in the downstream row of pore pressure transducers inside the barrier in Delta Flume test 1.

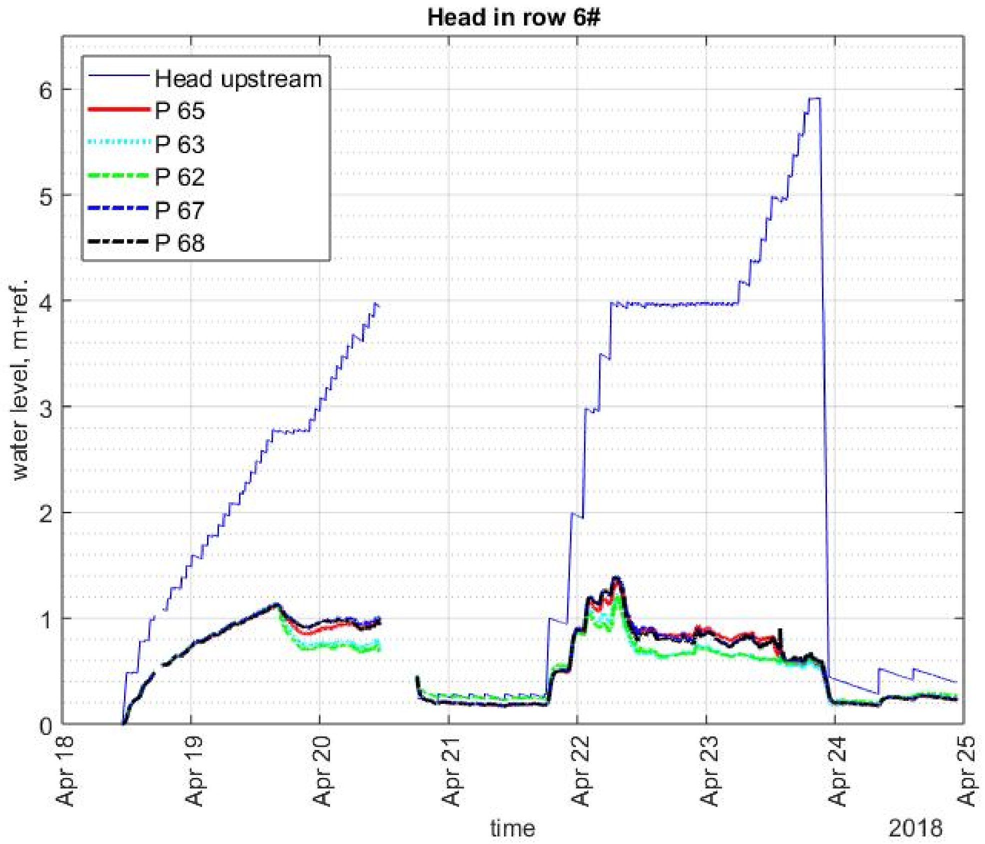

Figure 4.4 Head measured in the upstream row of pore pressure transducers inside the barrier in Delta Flume test 1.

After excavation, the pipe was found to have eroded the downstream part of the barrier at the location of pair #2, thus at the most southern side of the barrier. This would be expected to cause the higher gradient and the lower head measured in the barrier at this point. However, that does not account for the erratic spiking of the gradient or for the high gradient with negligible overall head drop just after the interruption. That rather suggests some measurement error after the interruption.

After excavation, there were still shifted blue PIGs and coarse sand at the downstream side of the coarse sand barrier. The other parts of the coarse sand barrier were still in their original positions (no shifted green and blue PIGs and no eroded coarse sand).

The sudden increase in the gradient prior to the interruption could be due to damage of the barrier and limited pipe formation. The observations also indicate that the pipe did not progress far into the barrier, as would be expected in the critical progression step that was observed in the medium-scale tests. In the medium-scale tests, the gradients continue to rise as there is some damage and short growth of the pipe in the barrier, and then show a clear drop when there is a long progression step. This test only indicates that damage may have occurred, but no long growth step appears to have occurred. This is supported by the observations of the barrier after the test, which indicate some shallow damage but no progression of the pipe through the barrier.
As such this test does not appear to offer the critical condition required for modelling the barrier strength.

Considering the progression of the pipe along the barrier after the interruption, the rise in the gradient in #7 and #3 around April 21, 23:00, and in #8 at April 22, 07:00 suggests that the pipe progressed along the barrier in the vicinity of these transducer pairs at those times. The low gradient in the centre is remarkable indicating that the pipe progressed from the sides to the centre (without reaching the centre), rather than from the centre to the sides as observed in the medium-scale tests.
From the forensic investigation we can conclude that this corresponds to the findings from the excavation of the southern downstream part of the barrier. Two sand boils occurred, both on the Northern and Southern edge of the ditch. The pipe originating from the southern corner was followed until half a meter away from the wall of the Delta Flume, where the pipe turned in the direction of the CSB, parallel to the flume wall. The pipe was also traced during the excavation of the CSB. The blanket layer directly downstream the CSB at the southern flume wall was approximately 5 cm lower in an area of 40 cm wide. It seems that the sand underneath the blanket layer was eroded and that the blanket layer has subsided. The top of the CSB - at the location where the filled up pipe was leading to – was subsided over a length of half a meter. It turned out that the CSB was still intact in the centre. The blanket layer on the northern side of the flume nearby the CSB was also subsided, but the CSB in the northern side was still intact.
Gradients in the transducer pairs other than #2 remained below the values which would be expected to cause damage.
Measured heads in the barrier did not rise significantly when the head was again increased from April 23rd. During the phase from April 23rd until the end of the experiment, the gradients on side #2, #7 and #8 fell, whereas the gradient in the centre shows a brief peak. The reduction of the local gradients coincide with an increase in the overall head drop over the set-up could be due to pipe growth. However, the excavation of the barrier after the experiment indicated that the barrier was intact on the side of #7 and #8. This suggests that the reduction in the local gradients was rather due to the leakage, which was occurring.

What also stands out is the fact that the pipes which were excavated after the test have been preserved as a positive relief in the blanket layer. Thus the pipe growth took also place in the bottom of the blanket layer and was cutting into the clay.

5 Modelling the Delta Flume test 2

5.1 Input

5.1.1 Schematisation

The second Delta Flume test is modelled in DgFlow in order to compute the local critical gradient inside the barrier. This is done using a 2D model, similar to the models used in the medium-scale phase.
Whereas a 2D model may be applicable to model the medium-scale tests with a barrier that extends the full depth of the model and where the pipe has progressed along the entire width of the barrier interface, the flow field in the Delta Flume is expected to be of a more 3D nature. Because the depth of the barrier is relatively smaller, there is more flow that does not exit to the pipe but flows to the ditch. Furthermore, it appears that the pipe has not progressed along the entire width of the barrier in the Delta Flume test.
However, even in the medium-scale tests, when the long growth step was modelled the pipe had progressed some distance into the barrier, resulting in a 3D flow field upstream of the pipe. By modelling this in a 2D model to derive a local critical gradient that can be considered as the strength criterion for 2D models, a degree of calibration for 3D flow inside the barrier at the pipe tip is included in the strength criterion. Especially for modelling field situations it is highly desirable to be able to use a 2D flow model. Therefore, the Delta Flume test is used to analyse whether indeed the modelled local critical gradient supports the medium-scale strength criterion.
In this analysis, as in the medium-scale analyses, the outflow boundary is modelled from the outflow point to the barrier. This would correspond to a 3D model where the pipe has an infinite width, which contributes to an over estimation of the flux. A more appropriate schematisation might be to only model the pipe that has progressed parallel to the barrier as an outflow. The effect of this is analysed in in Appendix 7B. That analysis shows that a with a shorter outflow area, a higher hydraulic conductivity contrast is required in order to match the measured heads. This affects the estimated relative density of the barrier materials. Since the actual relative density was not measured in the test, this is a fitting parameter that is used to match the measured heads. The fit to the measured heads is used to compute the critical gradient, and the computed gradient is therefore not significantly affected by modelling a shorter or longer outflow barrier. The strength criterion is affected however, since the gradient is related to a different relative density

5.1.2 Boundary conditions

As in the medium-scale models, the pipe is modelled as a boundary condition with zero head loss in the pipe along the entire length of the top boundary from the barrier downstream. The pipe is modelled with zero depth but with a certain length inside the barrier that characterises the interface between the barrier and the pipe that has established due to crumbling of the barrier and possible damage of the barrier. As opposed to the medium-scale tests, where the pipe length inside the barrier could be observed, the distance that the pipe progressed into the barrier at the critical step is unknown. Therefore, computations of the head profile are done for different pipe lengths in the barrier. In the medium-scale phase, a tentative strength criterion was suggested with a 4 cm pipe in the barrier, this is used as the basis simulation to which other pipe lengths are compared.

The value of the head at this boundary condition is the head that is measured inside the barrier at P 43 (at -11.05 m), because the pipe progresses into the barrier on this side. This head is 1.11 m. Note that this head is practically identical to the head in the centre in P45, and lower than the other transducers that are at -11.05 m.

The upstream head is the head measured in the upstream reservoir (by DCTM01), 3.10 m.

5.1.3 Hydraulic conductivity

The hydraulic conductivity of the background sand during the Delta Flume test is estimated by modelling the initial situation, prior to piping, in a 3D model of the test at a period where the head drop and flux are effectively constant for a period of 6 hours. This is shown in Appendix 7A. As the average air temperature measured during the test is 14°C, the fluid viscosity at this temperature is used. The water is modelled as an incompressible fluid, assuming full saturation of the soil.
This results in a hydraulic conductivity of 1e-4 m/s (intrinsic permeability of 1.18e-11 m^2), which corresponds to a relative density of approximately 0.8 in the column permeability test that was performed on this sand. This is higher than the estimated values of 0.35-0.65 as measured during preparation.

It is important to note that there was heavy rainfall during the first part of this test. This appears to have infiltrated into the clay layer and from there also contributed to flow in the sand body, and flow from the clay layer also discharged into the outflow ditch. This would have resulted in a higher measured flux inside the ditch at the point that it modelled. However, later in the test, there would have been piping and the 3D model without a pipe would not be appropriate any more. In the first Delta Flume test, the sand body was largely the same as in the second test, and therefore the hydraulic conductivity of the sand would be similar. However, during that test there was no period in which the head drop was maintained constant for an extended period of time prior to piping.

Therefore, the modelled hydraulic conductivity of the barrier is the 1e-4m/s is used to model the critical step for this analysis. Probably the actual hydraulic conductivity of the background sand was lower due to the errors related to rain, however, it is unclear how large this difference is. Considering that the relative density that corresponds to this hydraulic conductivity is 80% it would not be expected that the hydraulic conductivity is much lower. Measurements of the relative density that were made at the end of the first Delta Flume test indicate a relative density of the background sand of 35 - 65%.
For modelling the head profile, the hydraulic conductivity contrast, rather than the absolute hydraulic conductivity of the materials is of importance. The absolute value of the hydraulic conductivity is only relevant for estimating the achieved RD of the background sand and barrier material in the test, and therefore to relate the barrier strength to its relative density. This is therefore qualitatively done in the conclusions.

The hydraulic conductivity of the barrier is unknown, this has no strong effect on the flux. However, for the basis simulation, the value that corresponds to the same relative density of 0.8 is used, 8.4e-4 m/s (intrinsic permeability of 1.0 e-11m^2) giving a hydraulic conductivity contrast of 8.4. The fit to the measured head profile depends on both the length of the pipe inside the barrier and the hydraulic conductivity of the barrier. Therefore, a sensitivity analysis to the effect of the hydraulic conductivity of the barrier is performed using conductivities in the range between relative density 0.6 and 1.0. The combination of variation in pipe length and hydraulic conductivity is used to estimate the pipe length and hydraulic conductivity contrast that were likely to prevail at the critical point during the test.

5.1.4 Mesh

The model uses an unstructured mesh with triangular elements of 2.5 cm for the background sand, due to the geometry of the Delta flume tests. The barrier is modelled with a structured mesh with square 1 cm elements. A close-up is shown in Figure 5.1.

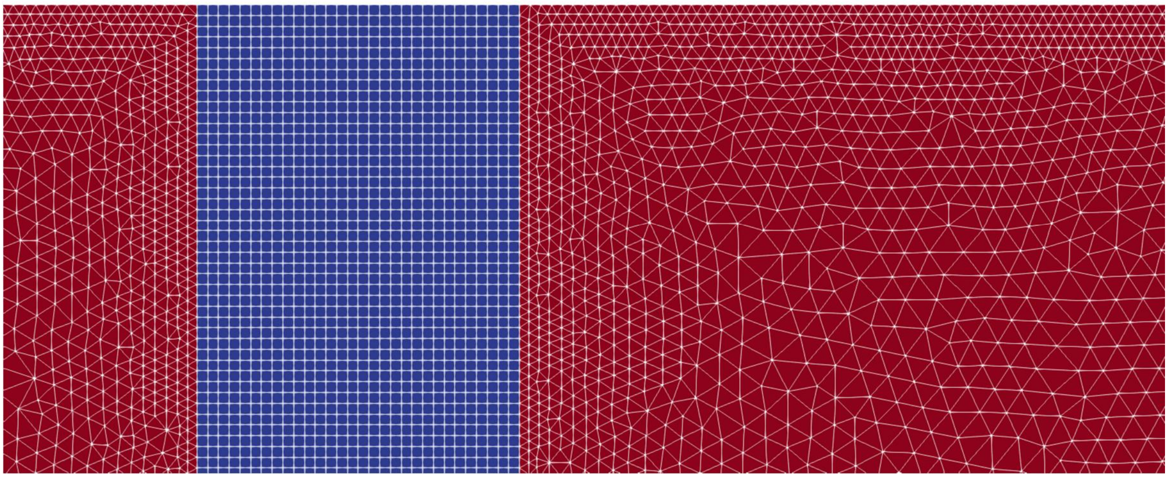

Figure 5.1 Close-up of the barrier and the mesh in the Delta Flume model, barrier is blue, background sand is red

5.1.5 Overview of computations

A summary of the 2D computations is shown in Table 5.1.

Table 5.1 Overview of models

Model name	Description	Hydraulic conductivity background m/s	Hydraulic conductivity barrier m/s	Contrast	Pipe length in barrier cm
M2D	Basis model RD barrier ca. 80% Pipe length in barrier 4 cm	1.0E-04	8.4E-04	8.4	4
M2D_kb	Lower hydraulic conductivity background sand	7.6E-05	8.4E-04	11.1	4
M2D_kb2	Higher hydraulic conductivity background sand	1.3E-04	8.4E-04	6.3	4
M2D_kB60	RD barrier ca. 60%	1.0E-04	1.1E-03	11.3	4
M2D_kB70	RD barrier ca. 70%	1.0E-04	9.9E-04	9.9	4
M2D_kB90	RD barrier ca. 90%	1.0E-04	7.0E-04	7.0	4
M2D_kB100	RD barrier ca. 100%	1.0E-04	5.6E-04	5.6	4
M2D_p02	Pipe length in barrier **2** cm	1.0E-04	8.4E-04	8.4	2
M2D_p06	Pipe length in barrier **6** cm	1.0E-04	8.4E-04	8.4	6
M2D_p08	Pipe length in barrier **8** cm	1.0E-04	8.4E-04	8.4	8
M2D_p10	Pipe length in barrier **10** cm	1.0E-04	8.4E-04	8.4	10
M2D_p15	Pipe length in barrier **15** cm	1.0E-04	8.4E-04	8.4	15

5.2 Results and analysis

5.2.1 Flux

The flux is significantly overestimated using the basis hydraulic conductivity of the background sand, by a factor 1.6 regardless of the modelled pipe length or hydraulic conductivity of the barrier. This is probably to a large extent due to the over estimation of the hydraulic conductivity of the background sand. Additionally, this is a 2D model in which the pipe is present from the ditch to the barrier. Appendix 7B shows that the hydraulic conductivity is still over estimated with a shorter outflow area, indicating that the hydraulic conductivity of the background sand was probably lower, i.e. the relative density of the background sand was higher than 80%.

The discrepancy between the RD corresponding to this value and to the RD determined from samples might be in part due to the uncertainty in the RD measurements. The material contains shell fragments and is difficult to sample. Besides this it is possible that the saturation during the test was not 100%, which would also reduce the hydraulic conductivity.

5.2.2 Head profiles

5.2.2.1 Over the entire model

The modelled head profiles along the top of the model are compared to the measurements. The modelled head profile for the different hydraulic conductivities of the background sand is shown in Figure 5.2.

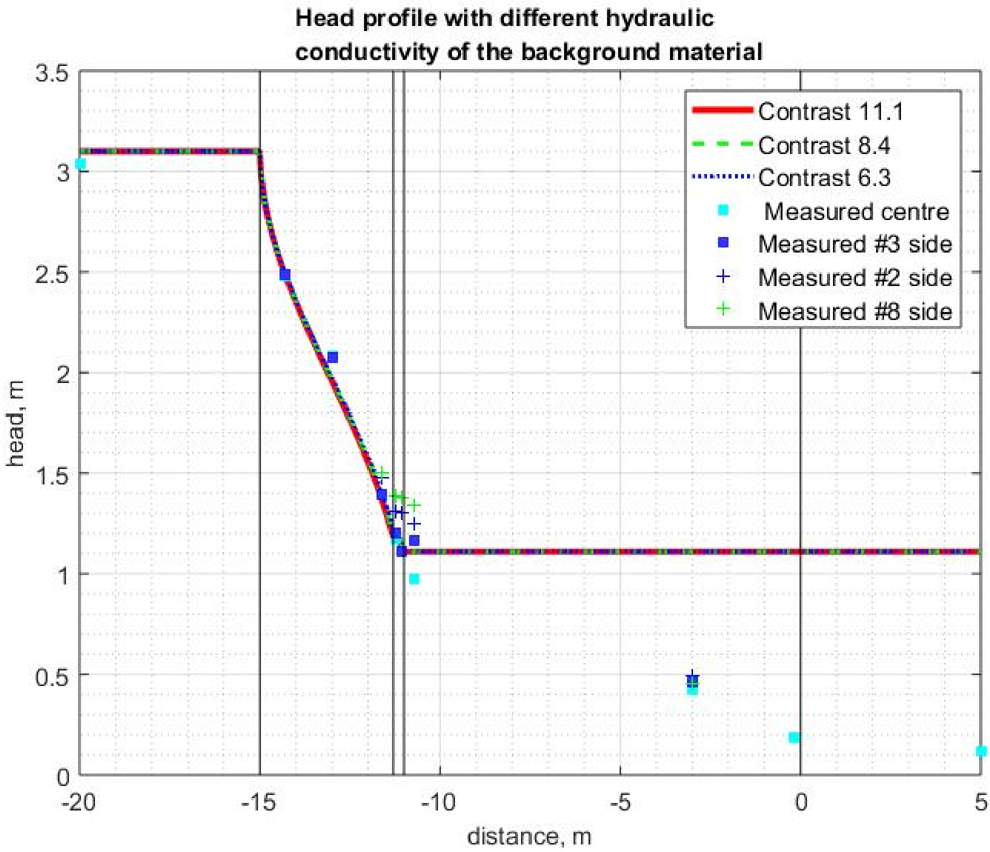

Figure 5.2 Modelled head profile along the top of the Delta Flume with different hydraulic conductivity values for the background sand. Hydraulic conductivities of the background sand are 1.3e-4 m/s (contrast 6.3), 1.0e-4 (contrast 8.4) and 7.6e-5 (contrast 11.1).

Figure 5.2 shows that the overall head profile upstream of the barrier is not significantly affected by altering the hydraulic conductivity of the background fine sand. This is also the case for the effect of altering the hydraulic conductivity of the barrier and the length of the pipe in the barrier (not shown here). The profile upstream of the barrier is relatively well modelled. The head at -13 m is over estimated by ca. 10 cm, but the head at -14.3 m is well matched. The head at the upstream boundary condition is also slightly higher than the head that is measured just at the surface in the sand.
On the downstream side of the barrier, there is a decline in heads downstream of the barrier, which is cannot be shown in the model as a constant head boundary is used. This effect could be captured by modelling a gradient in the pipe rather than a constant head boundary. However, considering that the model is a 2D simplification of a 3D situation, this would not necessarily make the results more reliable. The objective is to model the head profile in the

barrier and upstream of this, and for this the current model appears adequate. The evaluation of the strength criterion is not affected by this simplification.

Although head measurements were made on the upstream and on the downstream side of the model at a depth of 2 m these could not be used to fit the head profiles. The head measured at 2 m depth in P90 was practically identical to the head measured in P99 at the surface and further upstream. According to the basis simulation this head should be in the order of 30 cm lower as shown in Figure 5.3. A probable cause of this higher head is the fact that the sand above the hole that was made to place the transducer was not densified. This would result in a higher hydraulic conductivity that the remainder of the sand, which was densified after placement.

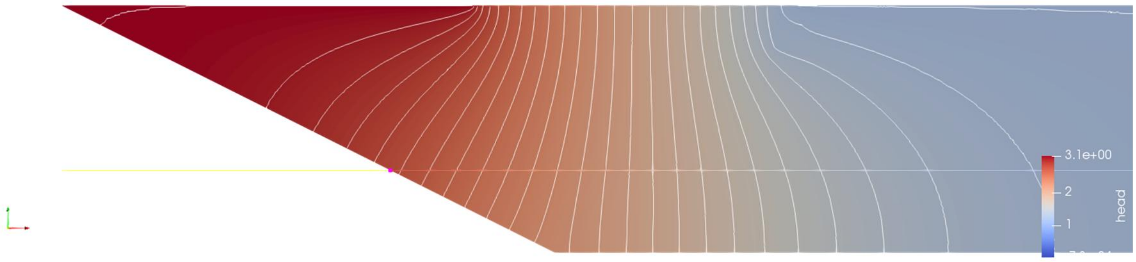

Figure 5.3 Close up of the left side of the basis model, colour shows head and contour lines are spaced 10 cm. The measurement in P 90 is located at 2 m depth (indicated by horizontal line) at the edge of the model.

Due to modelling the downstream head boundary as a constant head equal to P43, the downstream head measurement at depth is strongly overestimated, similar to the heads at the top of the model downstream of the barrier.

5.2.2.2 In the barrier

As the focus is on the fit of the heads inside and close to the barrier, the results are shown only for this region to analyse the effects of pipe length and hydraulic conductivity contrast (by changing the hydraulic conductivity of the background sand or of the barrier sand). As the heads along the line of transducers P #3 and in the centre are most representative of the situation upstream of the pipe, therefore these measurements are shown as solid squares, for reference the measurements in the #3 side and #8 side are also shown. Inside the barrier the measurements in P67 and P47 were considered unreliable therefore these are not shown.

Hydraulic conductivity contrast

A different hydraulic conductivity contrast can be realised by changing the hydraulic conductivity of the background sand or of the barrier. The effect of different hydraulic conductivity values of the background sand is shown in close up in Figure 5.4. A lower contrast results in a higher gradient inside the barrier. The head profile at the side #3 corresponds most closely to the calculated heads at a contrast of 6.3, i.e. a hydraulic conductivity of the background sand of 1.3e-4 m/s. However, the 3D analysis of the flow prior to piping indicated that the hydraulic conductivity of the background sand was probably lower, 1.0 e-4 m/s. The head profile is also affected by the conductivity of the barrier sand, and by the length of the pipe inside the barrier. Currently the values for these are the hydraulic conductivity of the barrier that corresponds to a relative density of 80% (the same RD of the background sand) and a pipe length of 4 cm (the same length as used in the preliminary failure criterion). These parameters are investigated in the next Section.

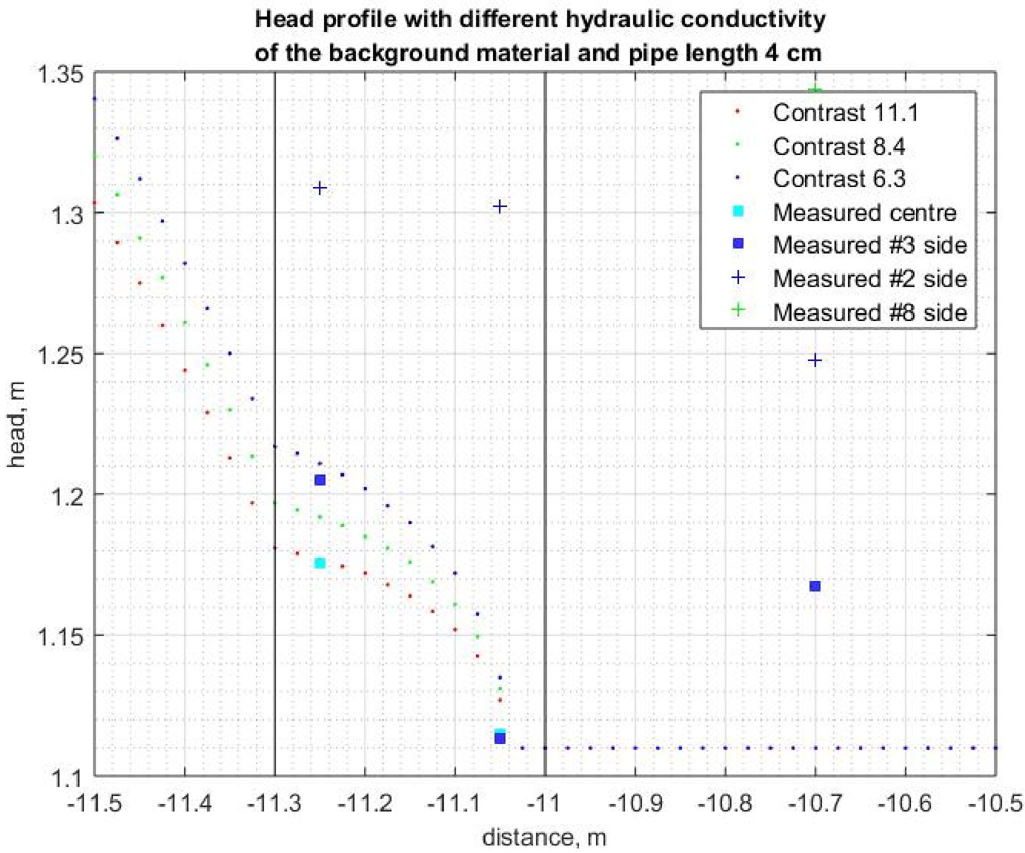

Figure 5.4 Head profile modelled inside the barrier with different hydraulic conductivity of the background sand. Hydraulic conductivities of the background sand are 1.3e-4 m/s (contrast 6.3), 1.0e-4 (contrast 8.4) and 7.6e-5 (contrast 11.1).

Hydraulic conductivity of the barrier

The effect of a different hydraulic conductivity contrast due to a different hydraulic conductivity of the barrier on the computed head profile is shown in Figure 5.5.

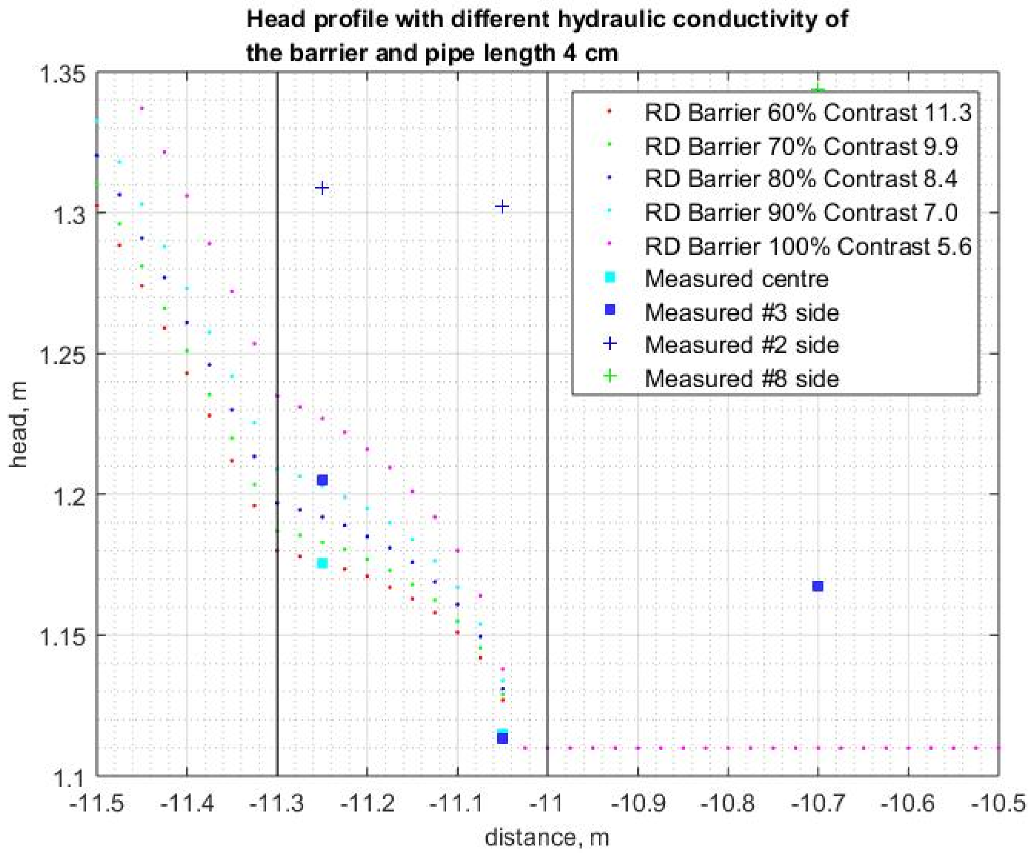

Figure 5.5 Head profile modelled inside the barrier with different hydraulic conductivity of the barrier.

With the modelled pipe length of 4 cm, the computed head profile matches the measurement at the # 3 side best with a relative density of the barrier of 90% (contrast 7.0). This could indicate that the barrier was very well densified during the test, as was the intention. Considering that the hydraulic conductivity of the background sand may have been lower than estimated based on modelling the measured flux in Appendix 7A, due to the additional flux from rainfall, this would also mean that the hydraulic conductivity of the barrier is even lower, approaching 100%. This appears unlikely, especially considering the relative density measurements. However, the length of the pipe in the barrier also affects the computed head profile.

Pipe length

With the hydraulic conductivity of the barrier at 80% RD the head at P63 is best modelled with a pipe length of only 2 cm inside the barrier. This would mean that the pipe is not below the most downstream transducer, and that transducer is used to set the head in the pipe in the model. However, the pipe will be close to the transducer therefore the assumption is made that the measured head in the transducer is comparable to in the pipe (and as in all models it is assumed that there is no head loss in the pipe). This is very short and would suggest that there had been little to no damage of the barrier at this point prior to the critical step. Typically, in the medium-scale tests, a pipe with a length of ca. 4 to 10 cm was present in the barrier prior to the long growth step. As the formation of a short pipe in the barrier is not expected to affect the measured head profiles, it is not possible to determine whether this had occurred during the Delta Flume test. Therefore, the fit based on an adapted relative density of 90% and a length of 4 cm is more plausible, compared to a reduction in pipe length.

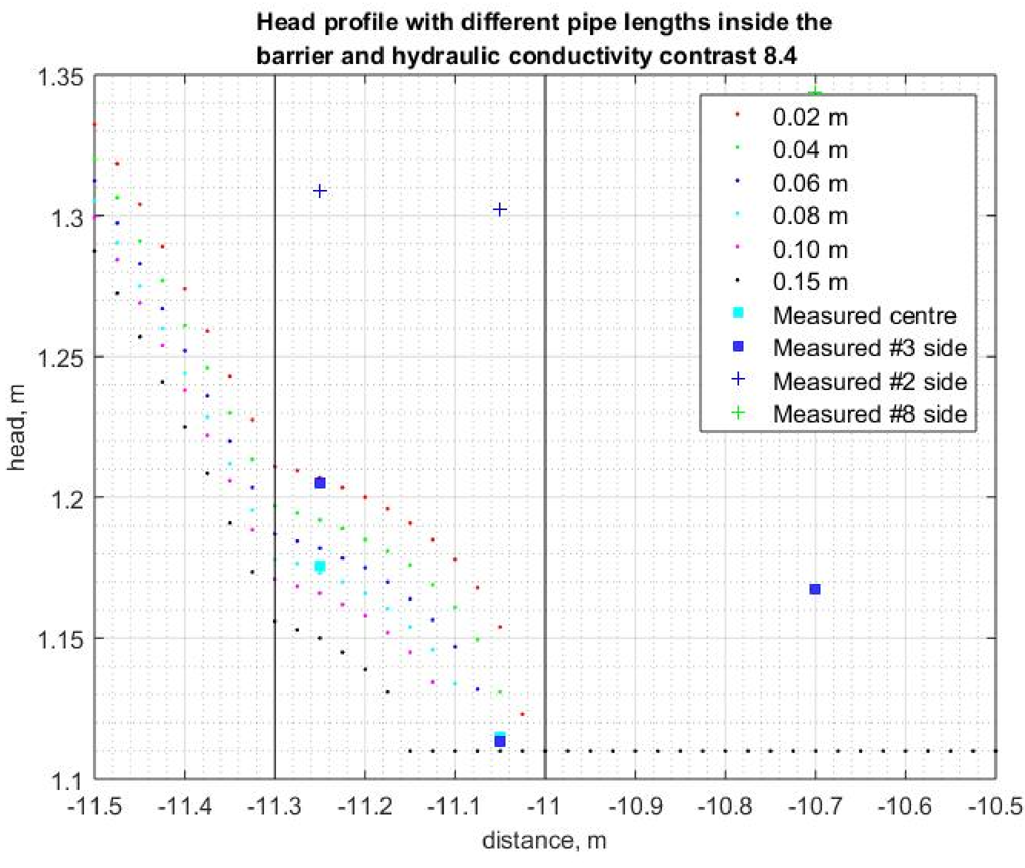

Figure 5.6 Head profile modelled inside the barrier with different pipe length inside the barrier

5.2.2.3 *Comparison to medium-scale head profiles*

Figure 5.7 shows the head profiles that were modelled upstream of the pipe tip for the medium-scale tests with GZB 2, tests MSP 24 (Baskarp 25) and MSP 28 (Metselzand) and for the Delta flume test (for barrier RD 90% and 4 cm pipe progression into the barrier).

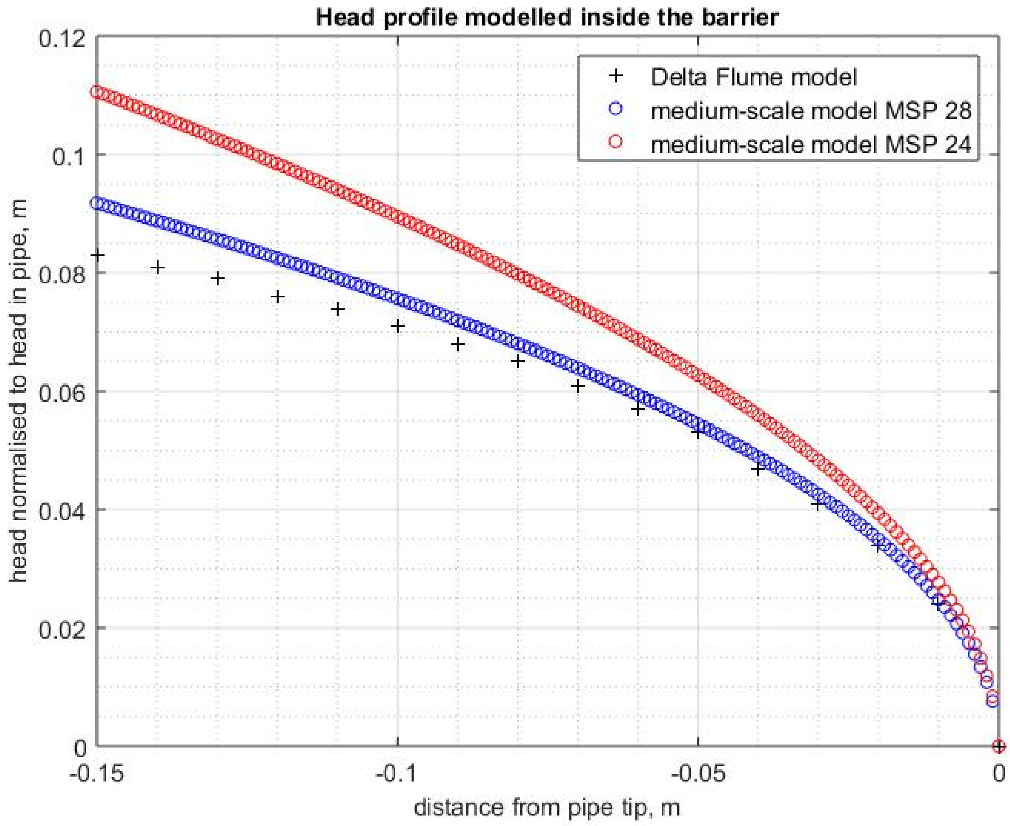

Figure 5.7 Modelled head profiles for medium-scale tests MSP 24 and MSP 28 and for the Delta Flume test. Distances are normalised to the distance from the pipe tip and heads are normalised to the head in the pipe.

The modelled gradients are similar close to the pipe tip but start to diverge already a short distance from the tip. The gradient modelled in the Delta Flume test is (slightly) lower than for the two medium-scale tests, and the difference increases with increasing distance from the pipe tip.

5.2.2.4 Discussion and Conclusions

There is no indication whether or not there was a pipe in the barrier at the critical point preceding the long growth step. During the medium-scale tests, this pipe was present, and it formed without significantly affecting the measured heads. Therefore, it might indeed be the case that a pipe was present in the barrier in the Delta flume test as well.

The relative density of the background sand and barrier were not measured in the second test, but it can be assumed that the values were similar to those in the first tests (measured relative density background sand 35-65%, measured relative density barrier (73-74%). For verification, the hydraulic conductivity of the background sand had to be estimated using a 3D model of the situation prior to piping. The flux and measured head profile were used to fit the hydraulic conductivity of the background sand, resulting in a hydraulic conductivity that corresponds to a relative density of 0.8. However, the measured flux is probably in part due to rainfall during the early stage of the test. This means that the hydraulic conductivity of the background sand would have been even lower and the relative density even higher. It is unclear how large this effect is. The discrepancy between the value based on the modelled flux and the RD tests might be due to a combination of the uncertainty involved in the RD measurement, and possibly the level of saturation of the background sand.

The objective of the models is to reproduce the head profile inside the barrier and compute the critical gradient that caused piping. This does not depend on the absolute value of the hydraulic conductivity of the barrier or the background sand but on the contrast between these. Therefore the estimated hydraulic conductivity based on the flux could still be used in the analysis.

With this background hydraulic conductivity, the combination of a pipe of 4 cm length, with a hydraulic conductivity contrast that corresponds to a barrier material with a relative density of approximately 0.9 fits the measured head profile at the location where the pipe appears to have progressed best. If the hydraulic conductivity of the background sand was indeed lower, as is indicated by the computed flux at the critical point, the hydraulic conductivity of the barrier would likewise be lower, indicating an even higher relative density of the barrier material. For longer pipes inside the barrier, an even lower hydraulic conductivity would be expected, which would be difficult to realize in the experiment, and is therefore unlikely.

An additional analysis was made to consider the effect of modelling the outlet boundary only as the pipe that has progressed parallel to the barrier, i.e. over a distance of 10 or 30 cm instead of over a distance of 16 m. This could be considered as a better 2D schematisation of the 3D situation. This shows that a 4 cm pipe with a hydraulic conductivity contrast whereby the barrier has a relative density of 0.7 fits best. Again, assuming that the hydraulic conductivity of the background sand was in reality lower than modelled, the relative density of the barrier would be higher. Due to the small effect shown in the sensitivity analysis for the analysis of the strength criterion the basis model with a pipe from the ditch to the barrier is used.

In conclusion the model could be used to model the head profile, but there are a number of uncertain factors:
- the length of the pipe inside the barrier is unknown;
- the relative density of the barrier material and the background sand were not measured and are fitting parameters. The values that were measured in the first experiment could be used as an indication;
- the flux used to estimate the hydraulic conductivity of the background sand is affected by additional flux due to rainfall;
- the length of the boundary condition of the pipe downstream of the barrier that is required to appropriately model the 3D situation in a 2D model is uncertain, therefore extremes of 0.1 and 0.3 m (i.e. neglecting the ditch which is present in reality) and of 16 m (i.e. assuming an infinitely wide pipe and ditch) are considered.

However, the fits to the measured heads indicate that:
- the relative density of the background sand is high, corresponding to a relative density of 0.8 or higher;
- the measured critical head profile inside the barrier can only be modelled with a good match for the measurement data using a combination of a low relative density barrier (0.7 or higher) and a relatively short pipe.

In the numerical analysis in the phase of the small-scale tests, it was shown that the 2D model can represent the local gradient in the barrier for situations where the pipe has widened along the width of the barrier, prior to the pipe entering the barrier.
If the pipe has not widened along the entire width of the barrier, the 2D model will underestimate the head profile in the barrier. The sensitivity analysis shows that modelling the pipe downstream of the barrier also affects the head profile, but that this effect is relatively small. In the Delta Flume test, the pipe had not widened along the width of the barrier, and

thus it is possible that the current model also underestimates the head profile in the barrier to a greater extent than in the medium-scale models.
In the medium-scale models, after the pipe has entered the barrier at discrete points the 2D model will also underestimate the head profile as compared to the 3D situation. This implies that in all 2D models there is some degree of underestimation of the local gradients. This effect of conversion from 3D to 2D is present in all models (the models that are used to derive the criterion; the models which are used to test the criterion (the Delta Flume model); and the models that will be used for prediction of the field situation) and can therefore be considered as a calibration effect. Comparison of the critical local gradient over the distance of the criterion in the Delta Flume tests to the computed strength criterion in the medium-scale tests should indicate whether a similar local gradient is indeed found. This would support the assumption that the use of 2D models to derive the strength criterion, and to model the field, is applicable.

Based on the considerations discussed above the model with a pipe of 0.04 m into the barrier, a hydraulic conductivity contrast of 7.0 and a RD of the barrier of 0.90 is considered as the best fit for the data.

5.2.3 Local gradients

This analysis is performed using the models in which the pipe is modelled along the entire length of the top of the model, as also used in the medium-scale models. If a shorter distance were used, corresponding to only the pipe parallel to the barrier, the hydraulic conductivity contrast would be higher but modelled head profiles would be similar as shown in Appendix 7B.

5.2.3.1 Strength criterion

Based on the analysis of the fit of the head profile, a hydraulic conductivity contrast of 7.0 (corresponding to a relative density of 0.90 for the barrier) in combination with a pipe length of 4 cm fits the measured head profile in the barrier at the location of the growth step best. The effect of hydraulic conductivity contrast for a 4 cm pipe in the barrier is shown in Figure 5.8.

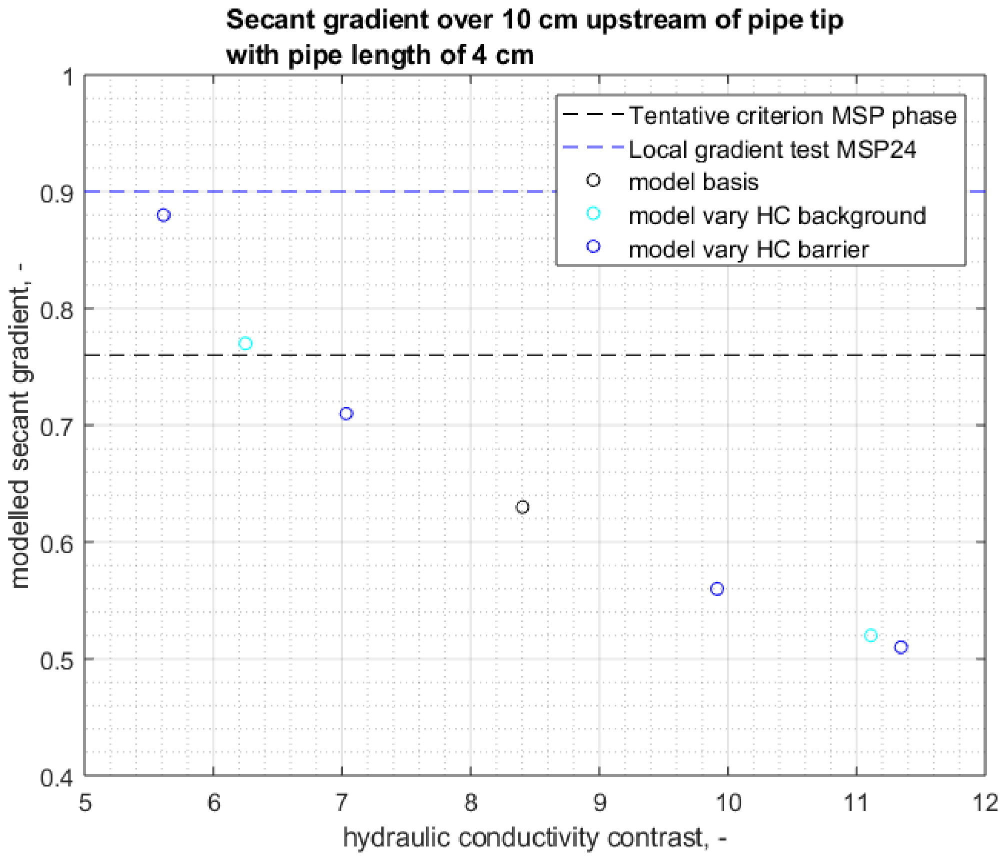

Figure 5.8 Effect of hydraulic conductivity contrast on the modelled secant gradient over 10 cm upstream of the pipe tip (circles). Dashed lines indicate gradient over 10 cm upstream of the pipe tip from the medium-scale tests (MSP tests), the lowest of these was selected as the tentative strength criterion for GZB 2.

Figure 5.8 shows that the modelled gradient over 10 cm upstream of the pipe tip for a hydraulic conductivity contrast of 7.0 (corresponding to a RD of the barrier 0.9 in combination with a background sand RD of 0.8) is only slightly less than the tentative criterion from the medium-scale tests. The criterion is 0.76 and the modelled local gradient in 0.71, i.e. a difference of only 0.05. This difference is smaller than the difference between the two medium-scale tests, which is 0.14.
Although a higher relative density of the barrier would result in a higher local gradient, it does not seem likely that such a high relative density of the barrier was realized in the field.
As discussed in the previous Section, the hydraulic conductivity of the barrier and background sand are probably already overestimated due to the additional flux from rainfall. However, the over estimation due to that is offset to some extent by the effect of modelling the outflow boundary over the entire to of the model.

The temperature that was used to model these tests was based on the measured air temperature during the tests, on average 14°C. It is possible that the temperature of the water in the set-up was slightly lower, as water was sourced from a large storage basin. This would increase the viscosity of the water, which means that the computed intrinsic permeability would be slightly higher, corresponding to a slightly lower relative density of the barrier material. If the temperature was 10°C instead of 14°C this would mean intrinsic permeabilities were 10% higher. Although this does not affect the conductivity contrast, the relative density of the barrier may be slightly lower than expected.

5.2.3.2 *Secant gradients over other distances*

In order to see whether the computed local secant gradients from the pipe tip are more similar over a different distance than the failure criterion (10 cm), these secant gradients are shown as a function of distance from the pipe tip in Figure 5.9.

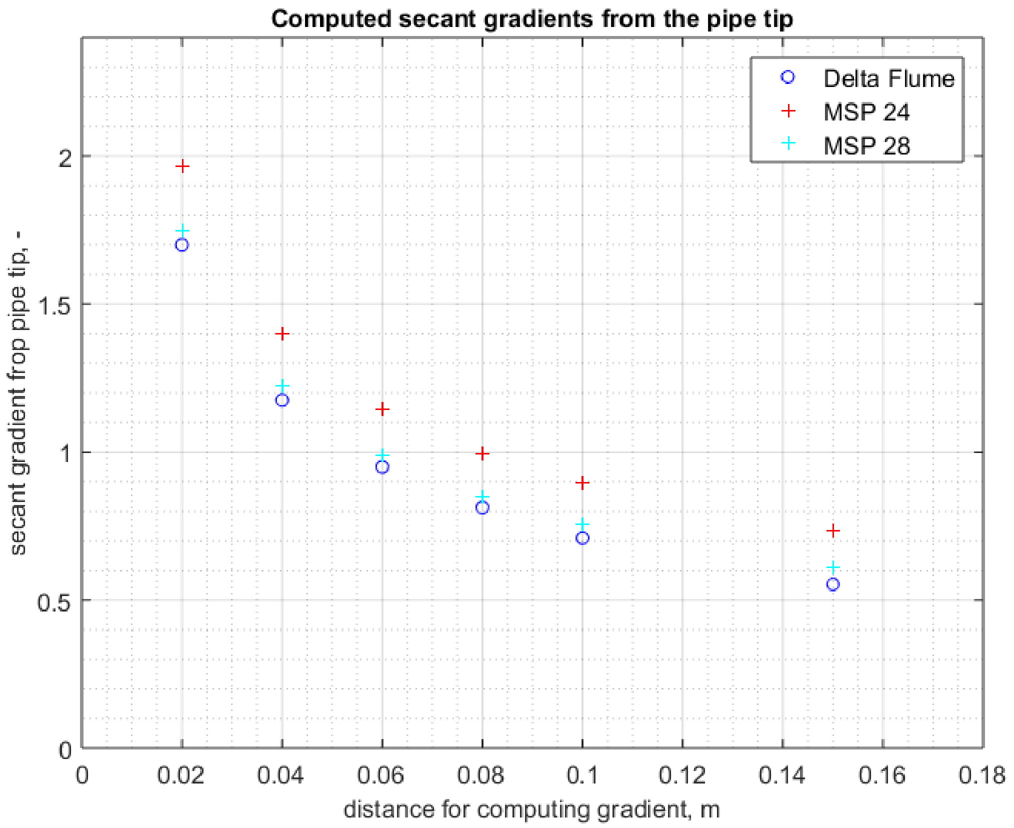

Figure 5.9 Secant gradients from the pipe tip for medium-scale tests MSP 24 and MSP 28 and for the Delta Flume.

The difference between the secant gradients for the Delta Flume and MSP test 28 is small, and comparable over different distances. Therefore, there is no indication that a different distance would be more appropriate as a strength criterion.

5.2.3.3 *Conclusions*

The barriers in the medium-scale tests had a relative density of 0.83 (the test which led to the tentative strength criterion) and 1.05 (test MSP 24). Based on the models of the head profiles in Section 5.2.2, it appears that the barrier in the Delta Flume tests had a comparable relative density (in the range of 0.7 to >1). Therefore, a comparable critical gradient can be expected, and the model indeed predicts a critical gradient upstream of the barrier that is comparable to the strength criterion when a 4 cm pipe is modelled with a barrier hydraulic conductivity in corresponding to 90%. This supports the hypothesis that a local critical gradient derived in 2D medium-scale models can be used to model the Delta Flume in a 2D model.

6 Conclusions, discussion and recommendations

6.1 Conclusions

Two large-scale tests were conducted in the Delta Flume, using the same type of background- and barrier material. During the first test, the pipe did not progress through the barrier, since the test had to be abandoned because of leakage. The distance of the coarse sand barrier with respect to the entry point was shortened in the second test, in order to be certain that failure of the barrier will be reached at head differences attainable in the flume. Indeed, the barrier collapsed at the end of the second test.

The tracers which were used to indicate the progress of pipe growth did only reliably work in the first test. The progress of pipe growth, followed by the appearance of tracers at the sand boils, was in agreement with the findings during the excavation of the pipes and the barrier afterwards. The pipe growth into the barrier stopped in the downstream part of the barrier. The other parts of the barrier were still intact.

During the second test almost no tracers were detected until the final loading phase. Only at the very end of the test a high amount of tracer particles originating from all marked positions along the longitudinal section of the set-up appeared in the ditch at once, namely on the brick of dike failure. Hence, the moment of reaching the barrier and of the breakthrough could only be deduced from the change in gradient of the pore pressure transducers. In this test the used tracers seemed to be insufficient to indicate the current position of pipe growth and to alert to the moment of failure.

What also stands out is the fact that the pipes which were excavated after the test have been preserved as a positive relief in the blanket layer. Thus the pipe growth took also place in the bottom of the blanket layer and was cutting into the clay. At the moment, there is no explanation for this phenomenon and the possible consequences are unknown.

Based on the models of the head profiles, it appears that the barrier in the Delta Flume tests had a comparable relative density (in the range of 0.7 to >1) to that of the barriers in the medium-scale tests (the test which led to the tentative strength criterion – a local critical gradient measured over 10 cm from the pipe tip). Therefore, a comparable local critical gradient can be expected, and the model indeed predicts a critical gradient upstream of the barrier that is comparable to the strength criterion when a 4 cm pipe is modelled with a barrier hydraulic conductivity in corresponding to 90%. This supports the hypothesis that a local critical gradient derived in 2D medium-scale models can be used to predict the progression of a pipe in a barrier at larger scale. According to the water pressure measurements, the pipe progressed through the barrier at the southern side of the flume. However, the excavation illustrated that the barrier was completely eroded at the northern side.

6.2 Discussion

The fact that the northern part of the CSB was not present anymore during the excavation of the barrier in contrast to the southern part of the CSB seems contradictory to the location of the pipe according to the water pressure measurements and the visual observations of the eddy at the downstream side during the final phase of the failure, when the eddy in the downstream ditch was first shifting around the head of the ditch and finally moving to the southern flume wall.

A possible explanation for this phenomenon could be found in the extent of the erosion hole on the upstream side of the dike after excavation. During the failure phase a huge eddy was occurring at the upstream side of the bulkhead. This was a result of the strong current towards the coarse sand barrier, leading to backward erosion of the sand directly below the upstream clay slope along the whole width of the Delta Flume. After the pipe has broken through the barrier at the most southern side and reached the entry point, the widening process of the pipe started. As a result of the very high permeability of the barrier, the pipe during the widening process was successively shifted to the northern side, removing sand from the upstream part of the aquifer along the whole upstream side of barrier. This also explains the erosion of the upstream clay slope over the full width of the flume. Besides, when the widening pipe had reached the northern flume wall the downstream current was so intense that the barrier was completely eroded.
Towards the ditch, the main flow still went through the already formed and enlarged pipe close to the Southern flume wall, hence the eddy in the ditch gradually migrated upstream along this pipe (channel) and ended at the Southern wall once the upstream reservoir had been emptied sufficiently to stop the erosion.

6.3 Recommendations

The ADTS measurements have not been included yet in the analysis. At the moment, this implies a more advanced analysis because of the very limited experience interpreting this type of measurements for near-surface erosion problems.

7 References

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A Modelling hydraulic conductivity of background sand of Delta Flume test 2

As the relative density of the background sand was not measured, the hydraulic conductivity of the background sand in the second Delta Flume test is uncertain. Therefore, a 3D model is used to model the situation at the start of the test prior to piping to fit the hydraulic conductivity.

The moment which is modelled is selected so that there is a relatively steady state flow situation based on the flux (Figure A.1). The head measurements in the downstream row of transducers (Figure A.2) indicate that the pipe only passed this row of transducers around 11:00 on June 1st. Therefore, the head profile and flux are modelled for June 1st 00:00.

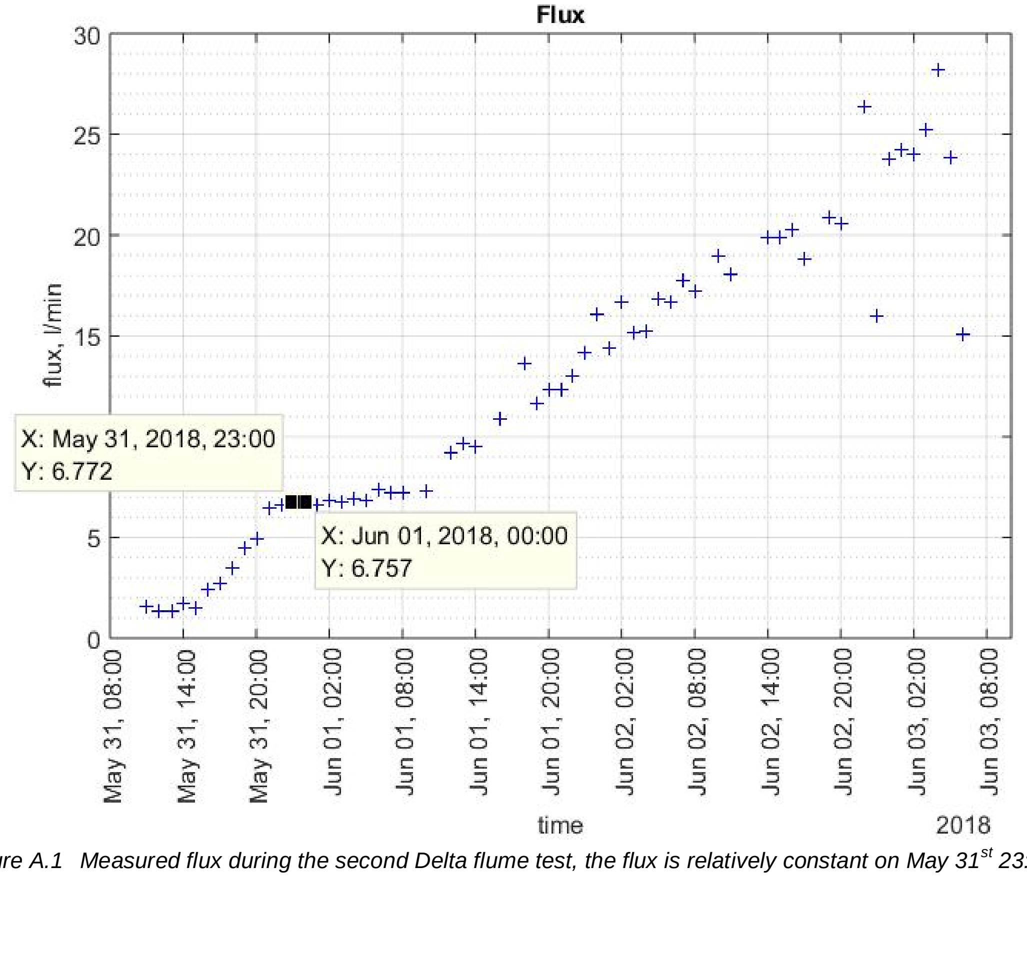

Figure A.1 Measured flux during the second Delta flume test, the flux is relatively constant on May 31st 23:00.

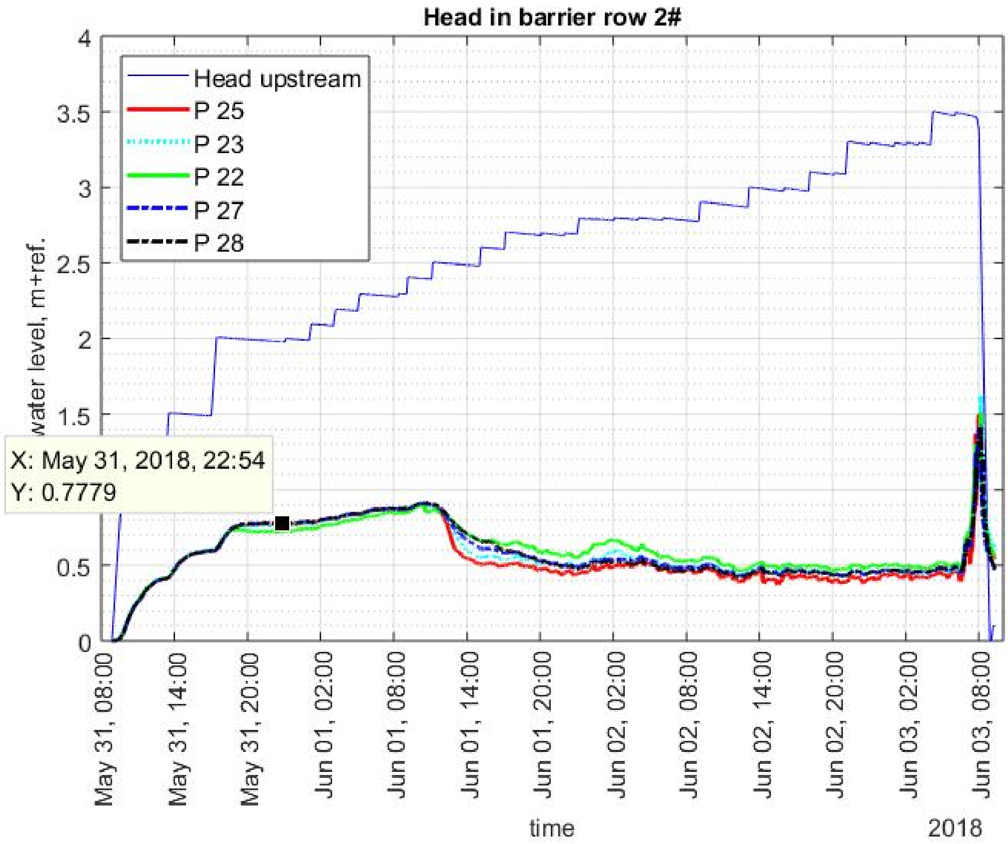

Figure A.2 Modelled heads on the downstream side of the sample in row 2#.

A.1 Schematisation

Only the sand body, not the cohesive cover layer, is modelled. As the barrier has a minor impact on the flow, the Delta Flume is modelled using only the background sand. As in the 2D models, the end of the ditch is the centre of the axis system and the sand body is present between x = -20 and +5 m. The maximum depth of the model is 3 m and the sides slope with a 2:1 slope. The model is 5 m wide. Figure A.3 shows the model.

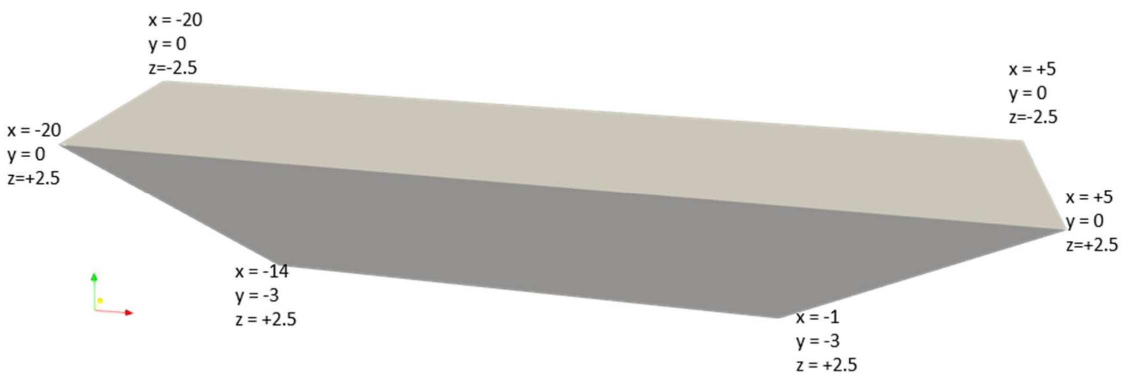

Figure A.3 Model of the sand body for the Delta Flume test.

A.2 Boundary conditions

The cohesive cover layer and the sides and bottom of the model have a no flow boundary. The ditch is modelled as a boundary condition at the surface of the sand based on the dimensions of the bottom of the ditch (0.5 m wide and from the downstream end of the model at x = +5 m, to x = 0 m). The upstream boundary condition is present at the surface of the model between x = -20 m to x = -15 m. The boundary conditions are shown in Figure A.4.

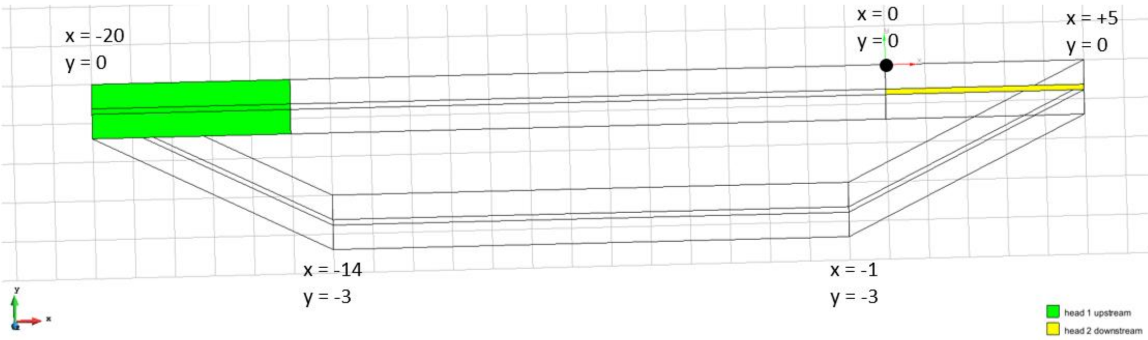

Figure A.4 Boundary conditions, upstream boundary (green) downstream boundary (yellow)

The upstream head, measured in DCTM01 is 1.99 m, the downstream head measured in transducer P09 near the surface of the ditch is 0.12 m.

A.3 Mesh

A preliminary mesh analysis shows that the computed flux is sensitive to the mesh refinement. Therefore, an unstructured mesh is used with a basis element size of 0.5 m, whereby the top surface of the model on the side of the upstream and the downstream boundary conditions is refined to have an element size of 0.1 m. The mesh is shown in Figure A.5.

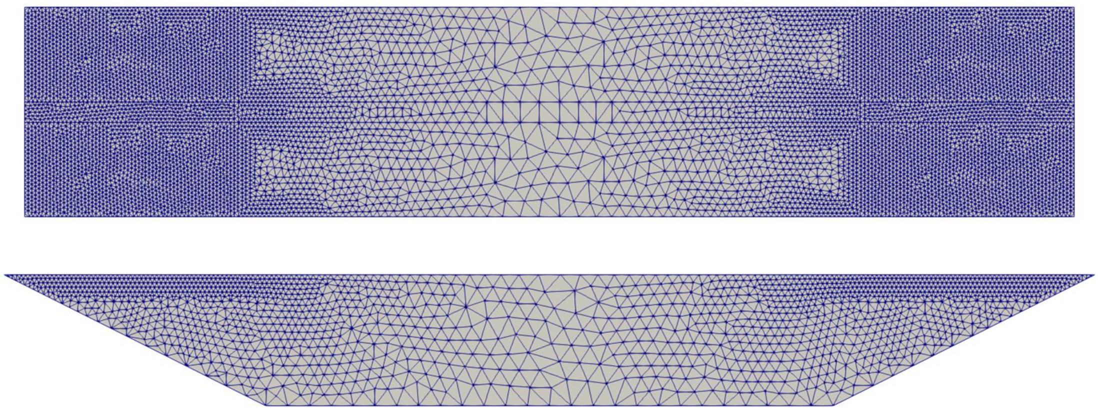

Figure A.5 Mesh of the 3D Delta Flume model, local refinements are on the surface on the sides of the upstream and downstream boundary conditions and the mesh gradually coarsens away from these surfaces

A.4 Results

A.4.1 Hydraulic conductivity

The influx in the model is computed by integrating the velocity in the y direction over the inflow area. The hydraulic conductivity of the background sand is modified to match the measured influx of 6.76 l/min. This results in an intrinsic permeability of 1.19 e-11 m/s (hydraulic conductivity 1 e-4 m/s).

A.4.2 Head profile

The modelled head profile is shown in Figure A.6. The model matches the measurements well indicating that indeed the presence of the barrier does not strongly affect the overall profile and that there was no pipe formation yet.

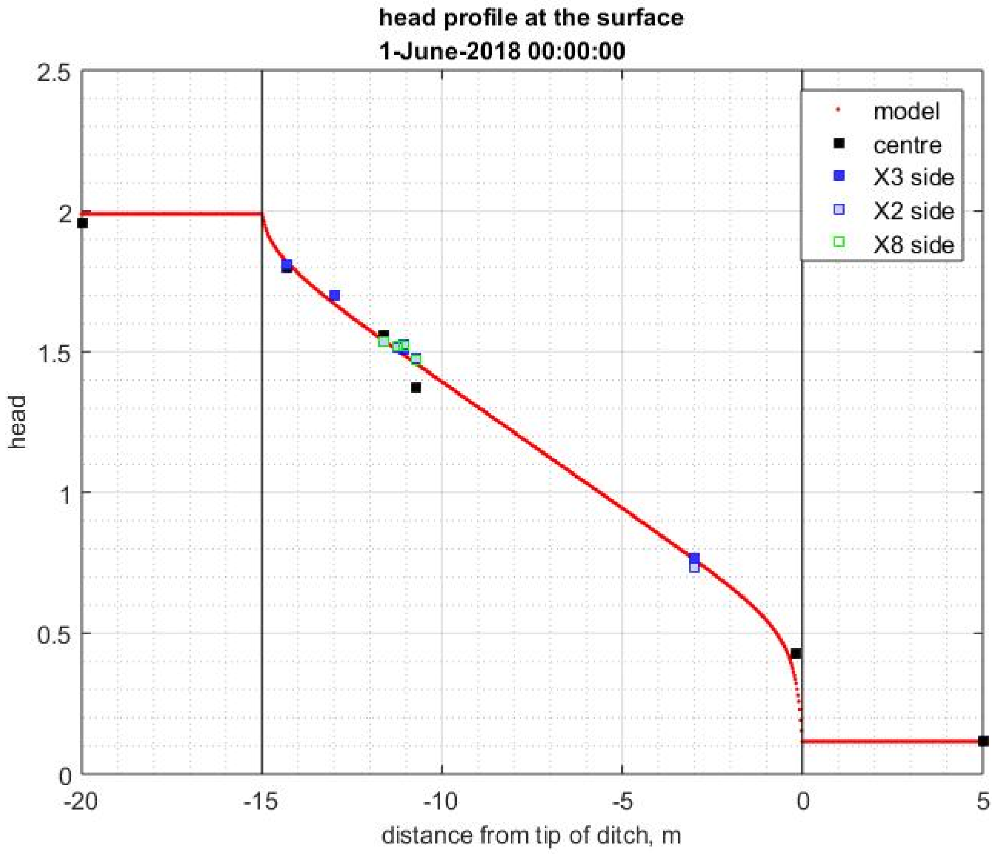

Figure A.6 Modelled head profile in the second Delta Flume test (the transducer in the centre at -10.7 m gave a lower reading than the other transducers throughout the test and therefore appears to be unreliable).

B Modelling only the pipe at the barrier

In the 2D models used in this report to model the Delta Flume test, the pipe is modelled as a boundary condition extending from the ditch to the barrier. This would correspond to an infinitely wide pipe in a 3D model, which means that the outflow area is modelled to be much larger than it is in reality. A more realistic representation, while retaining the 2D approach, would be to model only the pipe that has formed parallel to the barrier in the 2D models. This would mean that the outflow line rather than being 16 m from the ditch to the barrier would be a much shorter distance. The width of the pipe at the barrier is unknown. This will depend on the flow through the pipe.
In medium-scale tests the width of the pipe at the barrier was largest at the point where the pipe reached the barrier and decreased towards the sides of the model. The width was in the order of centimetres. For the Delta Flume as there is a larger aquifer, more flow is expected and therefore the pipe at the barrier can be expected to be wider.

This appendix analyses the effect of modelling a pipe of 0.10 m and 0.30 m downstream of the barrier, rather than the 16 m pipe. The model is the same model that is used in the main report, and the pipe length inside the barrier is 4 cm based on the analysis in the main report. Results for two hydraulic conductivity contrasts are shown, of 7.0 (hydraulic conductivity of the background sand 1.0 e-4 m/s (RD 80%) and hydraulic conductivity of the barrier 7 e-4 m/s (RD 90%)), which was found to best fit the results with an outflow boundary condition from the ditch to the barrier in the main report, and 11.3 (hydraulic conductivity background sand 1.0 e-4 m/s and hydraulic conductivity of the barrier 1.1 e-3 m/s (RD 70%)), which provided a good match with a smaller outflow boundary.

The schematisation with the 0.3 m wide pipe is shown in Figure B.1.

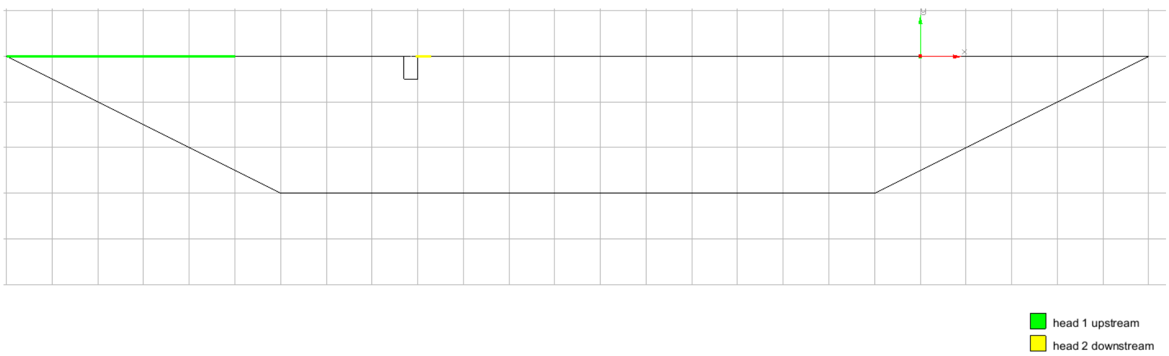

Figure B.1 Schematisation of Delta Flume model with 0.3 m pipe width in front of the barrier.

Due to the narrower pipe, the flow profile is different as shown in Figure B.2.

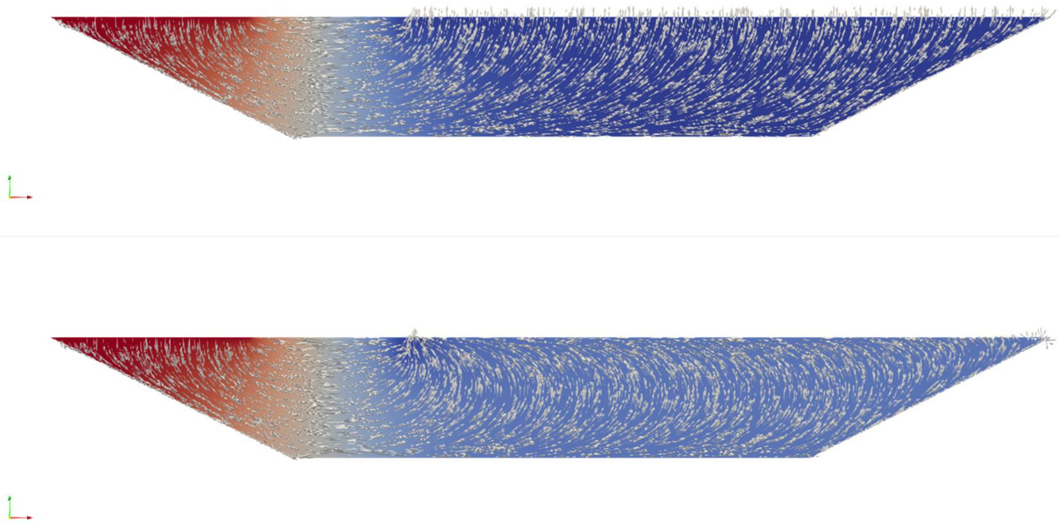

Figure B.2 Velocities indicate flux for models with hydraulic conductivity contrast of 11.3 for Delta Flume test 2 with an outflow boundary from the ditch to the barrier (top) and with an outflow boundary of 0.3 m only at the barrier (bottom).

The modelled head profile inside the barrier is shown in Figure B.3. With a downstream boundary condition from the ditch to the barrier (16 m), results with a hydraulic conductivity contrast of 7 match the measured head in the #3 side, where the pipe progresses, best in this model, with a 4 cm pipe inside the barrier. With a shorter downstream boundary condition, a higher hydraulic conductivity inside the barrier is required in order to match the measured head at #3, and therefore the contrast 11.3 matches best.

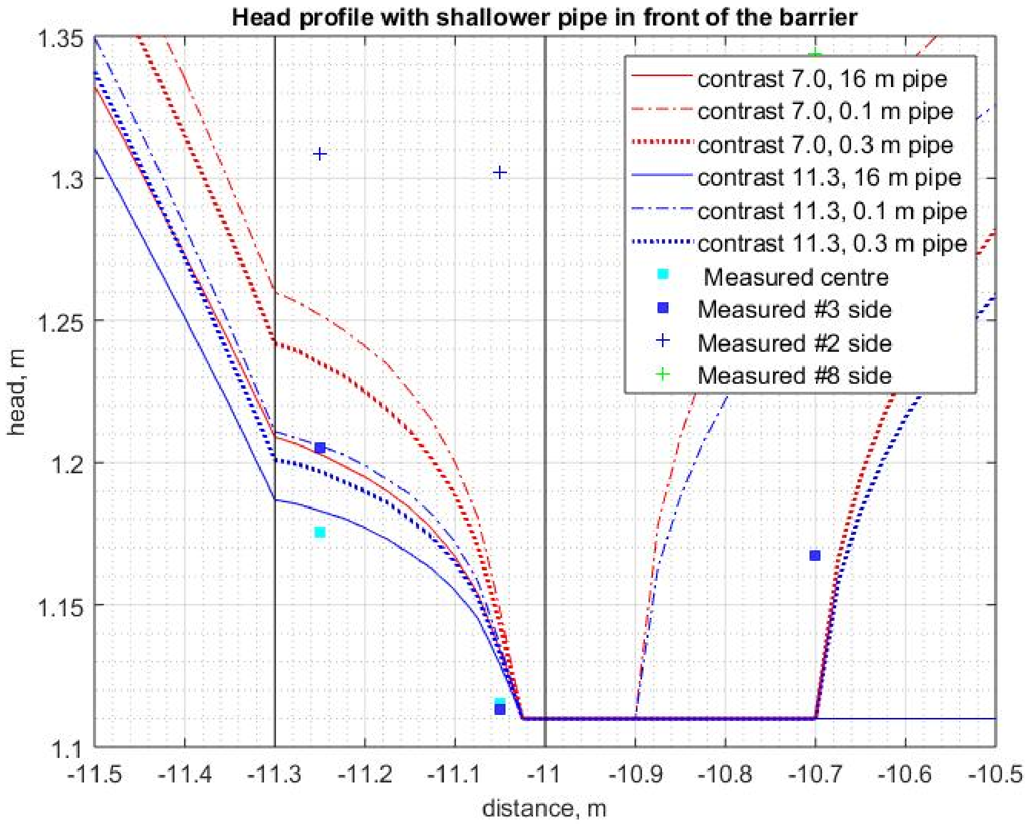

Figure B.3 Modelled head profiles for Delta Flume test 2 for barrier with 4 cm pipe length inside the barrier.

The flux modelled with a shorter outlet boundary is smaller than with the longer outlet boundary. The difference is relatively small as shown in Figure B.4.

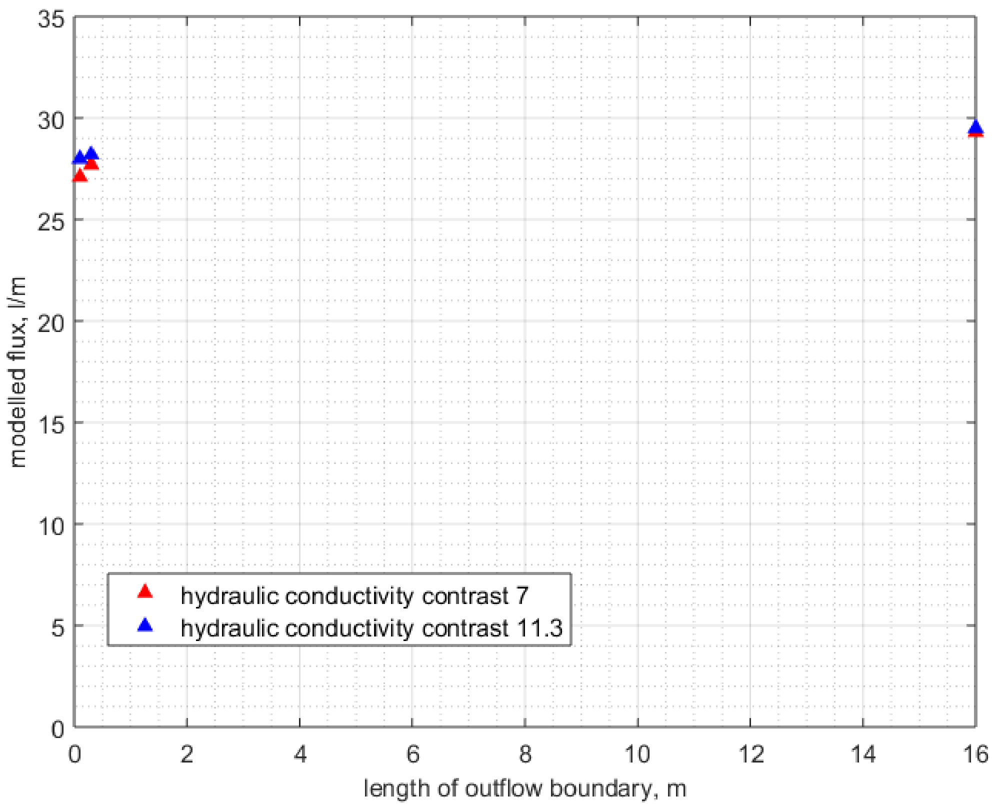

Figure B.4 Modelled flux with different lengths of outflow boundary,