

Effect of fine fraction on Backward Erosion Piping

Factual report of small-scale tests with various fine fractions



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Summary

The failure mechanism of piping significantly contributes to the high calculated flood probabilities for many dikes in the river area. The presence of a fine fraction, whether or not combined with a broader gradation, in river sands can lead to greater resistance against backward erosion than is currently accounted for in the existing approach. When applying the Decision Support Framework for Piping, it has been shown in various projects in the river area that this additional resistance can have a relevant impact on flood probability. However, research has been mainly focused on tidal deposits so far and experience for river deposits is limited, especially with non-plastic fines in stable samples.

Two small scale piping experiments, SSP-300 and SSP-301, were conducted in the Geohal laboratory at Deltares to investigate the influence of fine content on backward erosion piping (BEP). This report presents the factual data of these experiments. The tests were performed using Baskarp B15 sand with silt contents of 5% and 10%, respectively. Prior to the piping experiments, dry density and permeability tests were carried out to characterise the test materials.

During the experiments, a hydraulic head difference was applied across the test box and increased in discrete increments while piezometric head and outlet discharge were continuously monitored. Pipe initiation, development, and failure were also documented through a logbook. The critical head difference was determined from the experiment and corrected for local hydraulic losses at the inlet filter and at the outlet opening.

The results show that an increase in fine content leads to a higher critical head difference, indicating increased resistance to backward erosion piping. The material with higher silt content also exhibited lower permeability. These findings are consistent with previous experiments with B15 sand mixed with silt and confirm the role of fine content in controlling BEP behavior.

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1 Introduction

Backward erosion piping (BEP) is a critical internal erosion mechanism that can threaten the stability of flood defences such as dikes and levees under sustained hydraulic loading. When a sufficient hydraulic head difference develops across a sandy foundation, soil particles may be detached and transported towards an exit point, leading to the formation of erosion channels or pipes (Van Beek, 2015). Progressive pipe development can eventually result in loss of material support beneath the structure and lead to failure of the flood defence system. The resistance to BEP is influenced by hydraulic conditions and soil properties, including grain size distribution, permeability, relative density, and the presence of fines.

The presence of a fine fraction, whether or not combined with a broader gradation, in river sands can lead to greater resistance against backward erosion than is currently accounted for in the existing approach. When applying the Decision Support Framework for Piping, it has been shown in various projects in the river area that this additional resistance can have a relevant impact on flood probability. However, research has been mainly focused on tidal deposits so far and experience for river deposits is limited, especially with non-plastic fines in stable samples.

Small scale piping experiments (SSP) are used to investigate the role of fines in BEP under controlled laboratory conditions. Previous SSP studies have shown that variations in fine content can lead to differences in critical head difference and pipe development behaviour (Fugro NL Land B.V. & Deltares, 2022; Deltares, 2025a, Deltares, 2025b). The present study focuses on the effect of fine content by comparing two tests performed with similar sand material but different silt fractions and complements the experimental results analysed in Deltares (2025b).

Two SSP experiments, SSP-300 and SSP-301, were conducted using Baskarp B15 sand with silt content of 5% and 10%, respectively. The primary objective of the tests was to assess how an increase in fine content influences pipe development, critical head difference, and critical pipe length, and to compare the results with those obtained in earlier studies. This report presents the factual data of these tests.

1.1 Approach

Prior to the piping experiments, dry density tests were conducted to determine the relative density of the test materials. Permeability tests were performed before each piping test to quantify the permeability of the soil mixtures.

During the piping experiments, a head difference was applied across the experimental box and increased at a fixed rate. Piezometric head was measured continuously using standpipes distributed along the box, and the outlet discharge was recorded throughout the test. A logbook was kept to document the test progression, included in Appendix A.

The critical head difference was determined based on observed pipe development and failure. To correct for local hydraulic losses not representative of the internal soil response, corrected critical head differences were calculated. These corrections accounted for head losses at the inlet filter and the outlet opening. The critical pipe length was estimated from visual observations and photographic documentation. The measured and corrected critical head differences were analysed in relation to critical pipe length, relative density, and permeability to assess the influence of fine content on backward erosion piping behaviour.

1.2 Reading guide

Chapter 1 of this report provides the background and objectives of this test series. Chapter 2 describes the test setup and the materials used, Chapter 3 includes the preparation, execution and end of test stages. Chapter 4 presents the analyses carried out with the test data. Chapter 5 presents the results of the small scale piping tests. Chapter 6 includes summary and recommendations.

2 Experimental setup

2.1 Test setup

The experimental setup is shown in Figure 2-1. The test is conducted in a small scale piping (SSP) box, supplied with a controlled hydraulic head difference. Water is pumped from a lower reservoir to an elevated water source with a constant water level, which provides the upstream or inlet head to the test box. A pump and overflow system ensure that this water level remains constant throughout the test.

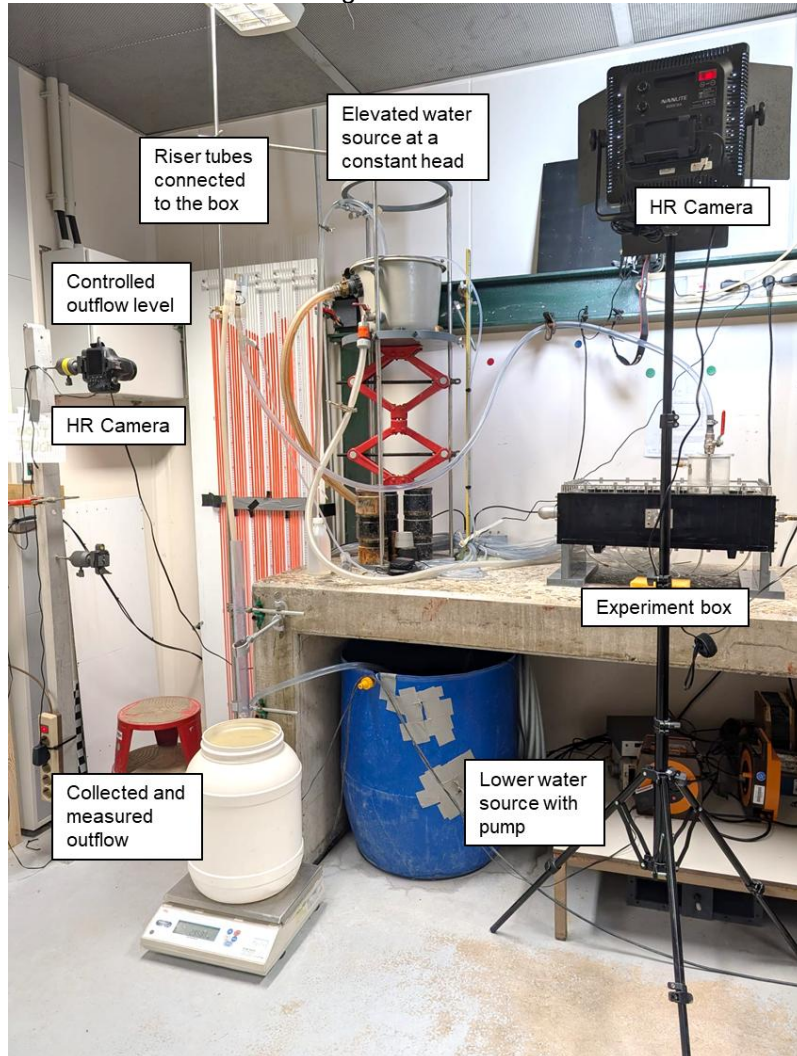


Figure 2-1. Small scale piping test set up from the GeoHal at Deltares.

Water enters the box through the inlet on the upstream side. Immediately downstream of the inlet and upstream of the hinterland outlet, filters are installed to ensure a uniform head distribution across the width of the box and to prevent soil loss.

At the downstream side, water exits the box through a circular outlet in the top plate, simulating an uplift channel. The downstream head is controlled by an overflow hose connected to the outlet cylinder. This hose can be lowered at a predefined rate, allowing a controlled increase of the hydraulic gradient across the box. The discharged water is collected in a container placed on a digital weighing scale, which continuously records the

water weight over time. In addition, a high resolution camera is mounted above the box to record visual changes at the soil surface and the development of pipe patterns during the experiment.

2.2 Small scale piping box

Figure 2-2 shows the SSP box. It consists of aluminium sidewalls and a transparent acrylic top plate. The top plate acts as a cohesive cover layer and contains a circular outlet opening. This represents a local defect, simulating a 3D situation. A vertical cylinder is placed above the outlet to collect the sand transported by the sand boil and to guide the outflow.

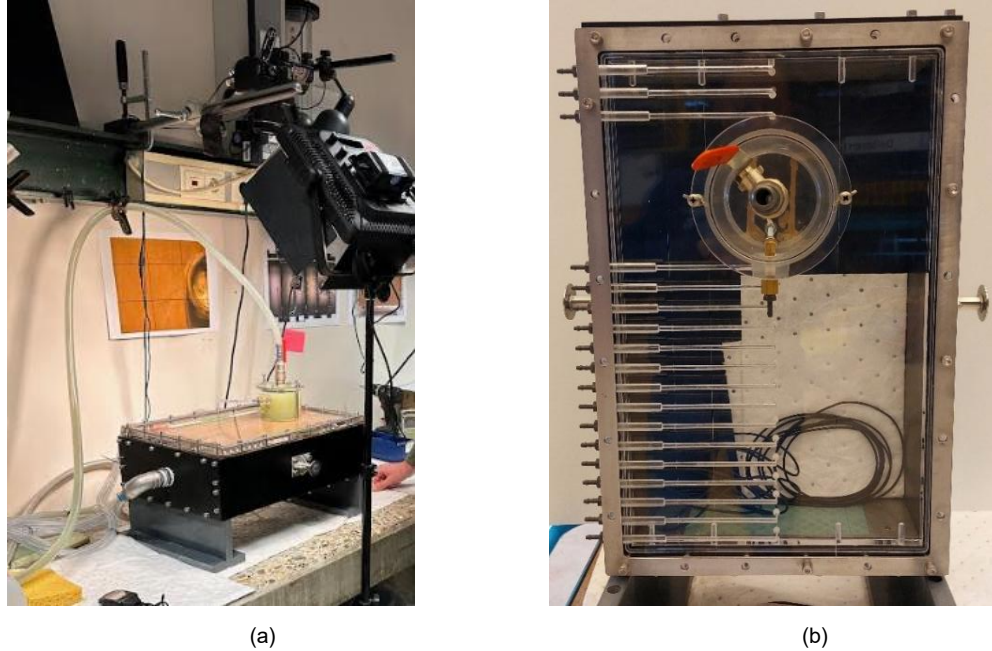


Figure 2-2. a) Test setup of the small-scale piping experiment; b) Top plate view

The walls of the box are connected using M6 bolts and are made watertight using O rings fitted into grooves along the joint surfaces. The filters installed at the inlet and hinterland outlet consist of nylon mesh with a mesh width of 15 μm in the outlet and 15 μm at the inlet. Likewise, an additional valve and hose are present at the downstream side of the box. This outlet is only used for permeability tests and remains closed during piping experiments.

The dimensions of the experimental box are provided in Table 2-1.

Table 2-1. Dimensions of piping arrangement.

Internal dimensions of test setup	Symbol	Dimensions (m)
Length of piping box	L	0.48
Depth of piping box	D	0.10
Width of piping box	W	0.30
Exit hole diameter	d	0.24
Vertical distance in drainage hole	t	0.10
Seepage length (to centre and edge of drainage hole)	L_s	0.36 - 0.348
Length of hinterland (from centre of hole to end of the box)	$L_{\text{hinterland}}$	0.12

2.3 Instrumentation and monitoring

In order to register the head development during the experiment, 26 riser tubes are connected to the box through the top and bottom plates. The locations of all measurement points are listed in Table 2-2. Head readings are obtained by photographing the riser tubes at an interval of five seconds. The images are further processed to extract numerical head values. Likewise, the discharge from the outlet cylinder is continuously monitored by a weighing scale. Moreover, a camera is installed above the experimental box to capture top view images of the test at five second intervals.

For the purpose of describing the pipes directions, it was chosen that the outlet side of the box adopts a North direction, while the inlet is the South.

Table 2-2. Locations of pressure transducers for riser tubes.

Measuring point (riser tubes)	Position relative to inflow filter (mm)	Position relative to top sand layer (mm)	Position relative to central axis A top plate (mm)
RT1	10	0	0
RT2	30	0	0
RT3	50	0	0
RT4	70	0	0
RT5	90	0	0
RT6	110	0	0
RT7	130	0	0
RT8	150	0	0
RT9	170	0	0
RT10	190	0	0
RT11	210	0	0
RT12	230	0	0
RT13	250	0	0
RT14	270	0	0
RT15	290	0	0
RT16	330	0	0
RT17	430	0	0
RT18	450	0	0
RT19	470	0	
RT20	10	-100	0
RT21	110	-100	0
RT22	210	-100	0
RT23	344	-100	0
RT24	470	-100	0
RT25 (Inlet)	-	-	-
RT26 (Top outlet)	-	-	-

2.4 Materials

The following materials were used in the small-scale piping tests (characteristics presented in Table 2-3 and Figure 2-3):

- Baskarp B15 sand
- Silt
- Clean, de-aired water

Table 2-3. Parameters of pure Baskarp B15 sand (from Terwindt et al., 2020).

Parameter	B15	silt
Particle density, ρ_s (kg/m ³)	2650	-
Minimum void ratio, e_{min} (-)	0.52	-
Maximum void ratio, e_{max} (-)	0.89	-
Grain size, d_{50} (mm)	0.130	0.046

For these tests, B15 sand and silt were mixed at different ratios and their respective parameters were determined from maximum and minimum dry density tests. The resulting values are shown in section 5.2.

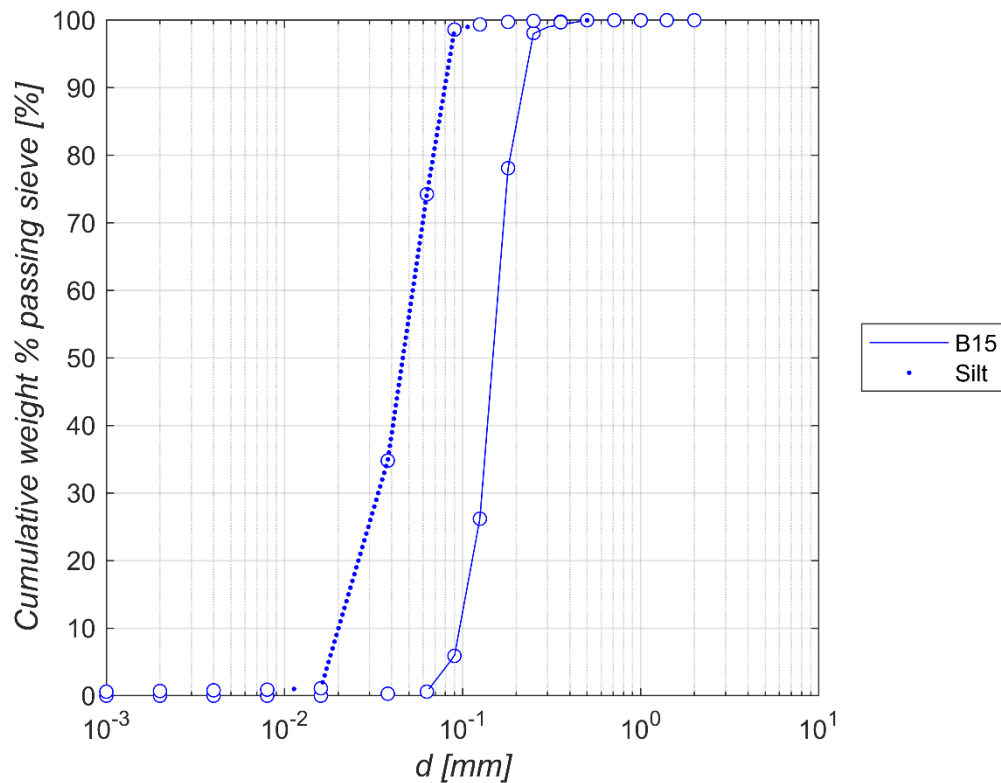


Figure 2-3 Particle size distributions of silt and B15

3 Test execution

3.1 Dry density determination

Dry density tests were performed prior to the piping experiments to determine the minimum and maximum densities of the sandy soil. The tests were carried out using the test soil, a digital scale, a cylindrical mould with known dimensions and volume, a funnel, and a vibrating device.

For the minimum density determination, dry soil was poured into the mould using the funnel and allowed to settle under gravity. Excess material forming above the rim of the mould was carefully removed to ensure a level surface, after which the mass was recorded. For the maximum density determination, the vibrating device was activated before filling the mould. Soil was gradually poured into the mould while vibrating until it was completely filled and levelled. The vibration facilitated particle rearrangement into a dense packing. The mass of the filled mould was then measured.

Both procedures were repeated multiple times to obtain representative values. The resulting minimum and maximum dry densities were used to calculate void ratios and relative densities. Further details on the test procedure can be found in Knudsen et al. (2020) and NGI Geolabs (2019).

3.2 Prior to testing

Before each test, the box was installed and connected to the riser tubes. The box was then filled with water to ensure that all filters were fully saturated. The riser tubes and their corresponding hoses were also checked to confirm the absence of trapped bubbles. Further, a leakage test was performed to verify watertightness in the setup.

3.3 Soil pack preparation

A homogeneous dense soil pack was prepared using a mix of silt and Baskarp B15 sand with a target relative density of 90%. For test SSP-300, the soil composition was 95% sand and 5% silt. For test SSP-301, the composition was 90% sand and 10% silt.

The preparation was done with the box upside down as stated by Deltares (2025). A thin layer of degassed water was first introduced at the bottom of the box through a hose, and the soil was poured from the top into fine layers. Soil was then tamped with a rod to achieve a dense and saturated condition while avoiding trapping air, until the box was filled. On top of the sand pack a saturated geotextile was installed. Further, the box was closed and rotated into the test position.

3.4 Permeability test

Prior to the piping test, a permeability test was performed using the same experimental setup. After the soil preparation, water was allowed to flow from the inlet to the hinterland outlet, while the outlet cylinder was closed. The permeability test was conducted by applying hydraulic head differences of 10 cm, 20 cm, and 30 cm at a fixed rate. For each head difference, a steady flow condition was established and the discharge was recorded. The measured flow rates were used to determine the permeability of the soil pack.

3.5 Test execution

All riser tubes were calibrated to the same reference level, and the setup was checked for leaks. Likewise, the cameras, pump, and weighing scale were confirmed working. The initial room temperature was registered, as it is assumed that the test setup reached thermal equilibrium with the surrounding environment. Further, the monitoring systems were activated. These included the outflow weight scale, the camera trigger system, and stopwatch.

The test was performed by creating a head difference between the inlet and outlet. At the start, both were at the same high level. Subsequently, the head difference was applied, at a 1 cm increment every 5 minutes or after the pipe formation stabilised. The test stopped once the pipe had reached the inlet filter, and failure due to piping was observed.

Throughout the experiment, the cameras continuously photographed the standpipe levels and the experiment, while outflow weight was also monitored. Manual logs (found in Appendix A) were kept to record changes in input head, soil behaviour, pipe development, and any anomalies observed in the setup.

3.6 End of test

At the end of the test, the valve connecting the water supply and the test box was closed. The system also stabilised before any components were taken apart. All data and photos were downloaded and stored for further analysis. The measuring pipes were closed, and the setup was cleaned and prepared for the next test.

4 Analysis

4.1 Determination of soil parameters

Since mixtures of sand and silt were tested at different ratios, maximum and minimum dry unit weight, void ratio, and relative density tests were performed for each respective sand-silt combination.

The dry unit weight is calculated via the following formula:

$$\gamma_d = \frac{m_d}{V} * g \quad \text{Eq. 1}$$

where γ_d (kN/m³) is dry unit weight, m_d (kg) is dry mass, V (m³) is volume, and g is gravity (9.81 m/s²).

The relative density is calculated via the following formula:

$$D_r = \frac{\gamma_d - \gamma_{d,min}}{\gamma_{d,max} - \gamma_{d,min}} \cdot \frac{\gamma_{d,max}}{\gamma_d} \cdot 100\% \quad \text{Eq. 2}$$

Where D_r (%) is relative density, γ_d (kN/m³) is dry unit weight maximum, minimum, and from the sample, respectively.

The void ratio is calculated via the following formula:

$$e = \frac{G_s g}{\gamma_d} - 1 \quad \text{Eq. 3}$$

where e (-) is void ratio and G_s (kg/m³) is density of solids.

4.2 Permeability

Permeability is determined on the basis of a flow test performed prior to the test or on the basis of the rise height measurements from the test (section 3.4). Darcy's law (Eq. 4) is used for this purpose:

$$k = \frac{Q}{i A} \quad \text{Eq. 4}$$

where k (m/s) is the permeability, Q (m³/s) is the flow rate, i (-) is the horizontal gradient, and A (m²) is the surface area perpendicular to the flow.

4.3 Correction of critical head

The critical head difference measured during the test may deviate slightly from the actual critical head difference due to head loss across the inflow filter and through the outlet opening.

These head losses can be quantified using the piezometric head measurements recorded either at the moment the critical head difference is reached or immediately prior to that moment. The choice depends on the rate of pipe development. In particular, for estimating the head loss at the outlet opening, it is essential that the pipe length has stabilised, such that equilibrium conditions are present. If the pipe develops rapidly after reaching the critical head difference, the head measured at that moment may not accurately represent the true hydraulic conditions.

The head loss at the inlet filter was determined by fitting a linear regression through the upstream piezometers, and the corrected head at the inlet location was estimated by extrapolating this trend to the inlet position. The difference between this extrapolated head and the imposed upstream head represents the head loss across the inflow filter.

Further, the head loss through the outlet opening was assessed by comparing the head measured at the downstream outlet with the piezometric head measured closest to the outlet opening, as there is no measurement point directly inside the outlet opening. When the head distribution near the outlet exhibits non-linear behaviour, the closest piezometer was used instead of a linear extrapolation to avoid misrepresentation of the local hydraulic conditions.

The corrected critical head was then calculated as:

$$H_{c,corrected} = H_{c,test} - \Delta h_{inlet} - \Delta h_{outlet\ opening} \quad Eq. 5$$

where H_c (m) is critical head corrected and measured during the test, respectively, and Δh (m) is head loss across the inlet filter and the outlet opening, respectively. For both cases, the head losses are obtained as:

$$\Delta h = h_{extrapolated} - h_{measured} \quad Eq. 6$$

This correction procedure was applied consistently to all tests. The critical pipe length corresponding to the corrected critical head difference was determined from top view photographs taken during the experiments.

5 Results

5.1 Overview of tests

This chapter includes the results of the two completed SSP tests performed with different fine contents. SSP-300 consisted of 95% sand and 5% silt, while SSP-301 consisted of 90% sand and 10% silt. The following aspects are presented:

- Soil parameters derived from dry density tests
- Permeability determined from the permeability tests
- Piezometric head development during the piping tests
- Flow rate behaviour during the test
- Determination of the critical and corrected critical head difference
- Observations of pipe development based on visual monitoring

5.2 Soil parameters

Table 5-1 presents the parameters for mixes of B15 sand and silt at different ratios, obtained from the dry density tests.

Table 5-1. Calculated parameters for mixes of B15 sand and silt at different ratios

Calculated parameters	5% silt, 95% sand SSP-300	10% silt, 90% sand SSP-301
Particle density, ρ_s (kg/m ³)	2650	2650
Minimum void ratio, e_{min} (-)	0.57	0.55
Maximum void ratio, e_{max} (-)	0.90	0.89
Soil pack void ratio, e (-)	0.60	0.58
Relative density, D_r (%)	90.6	89.8
Dry unit weight (kN/m ³)	16.25	16.45

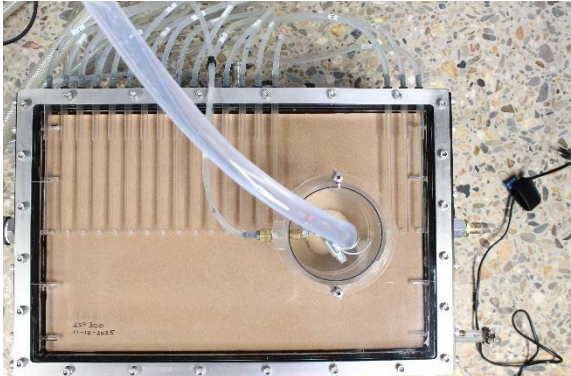
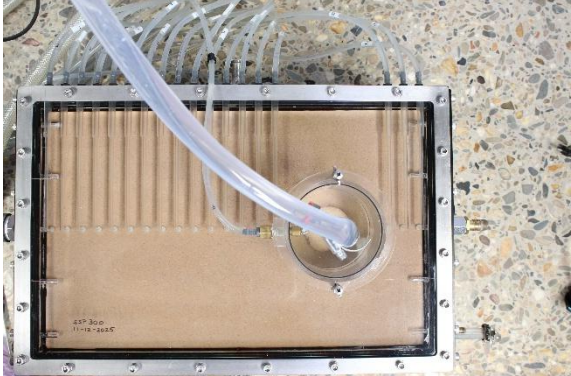
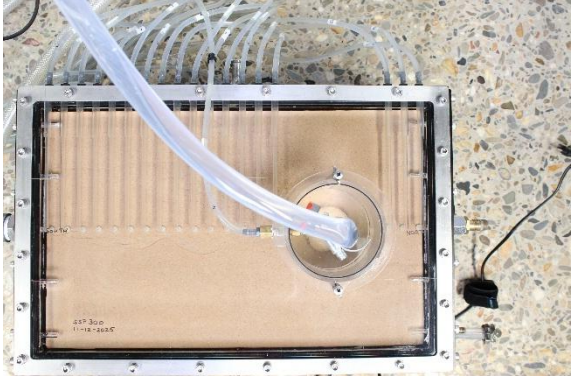
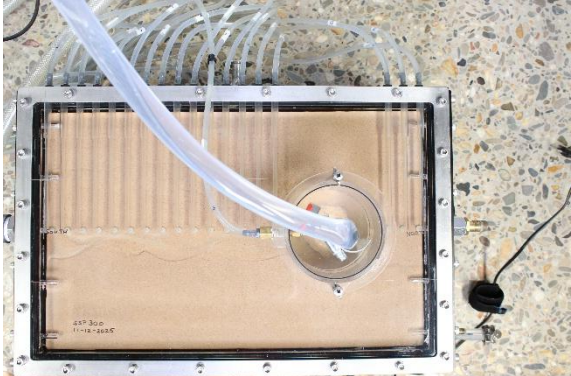
5.3 SSP-300

5.3.1 Test progression

Test SSP-300 had a total duration of 100 minutes. The applied head difference was increased in increments of 1 cm every 5 minutes, or kept constant when required to allow pipe development to stabilise. Table 5-2 includes photos of key findings during the experiment. Pipe initiation was first observed after approximately 30 minutes at an applied head difference of 7 cm. A single pipe branch formed near the centre of the box and propagated upstream from the well. At this load step, the pipe required approximately 15 minutes to stabilise before the head difference was increased further.

Upon increasing the head difference to 8 cm, pipe growth continued without stabilising and other additional branches began to develop from the exit hole. At 90 minutes, while the applied head difference remained constant at 8 cm, the first pipe reached the upstream filter, while one of the secondary branches had grown until RT 3 (28 cm in length). Complete failure occurred 10 minutes later, at 100 minutes, with no further increase in head difference. It must be highlighted that during preparation of the test setup, a minor loss of sand occurred at the outlet opening. This may have resulted in a small pre formed void, introducing uncertainty in the precise moment of initial pipe development, but is not expected to affect the critical head.

Table 5-2. Photos during the experiment. SSP-300.

Time after test start (min)	Description	Photo
30	Pipe began formation. $\Delta H = 7$ cm	
45	Critical head is reached. $\Delta H = 8$ cm	
90	Pipe reaches the back of the box.	
100	Failure occurs.	

5.3.2 Permeability test

Prior to the piping test, a permeability test was conducted prior to the piping experiment by applying controlled head differences of 10 cm, 20 cm, and 30 cm between the inlet and hinterland outlet. Almost-steady state discharge measurements were used to determine the permeability of the soil pack. Figure 5-1 presents the total outflow weight and flow rate of this test. During the test, piezometric head readings were obtained from the standpipes distributed across the piping box, as shown in Figure 5-2.

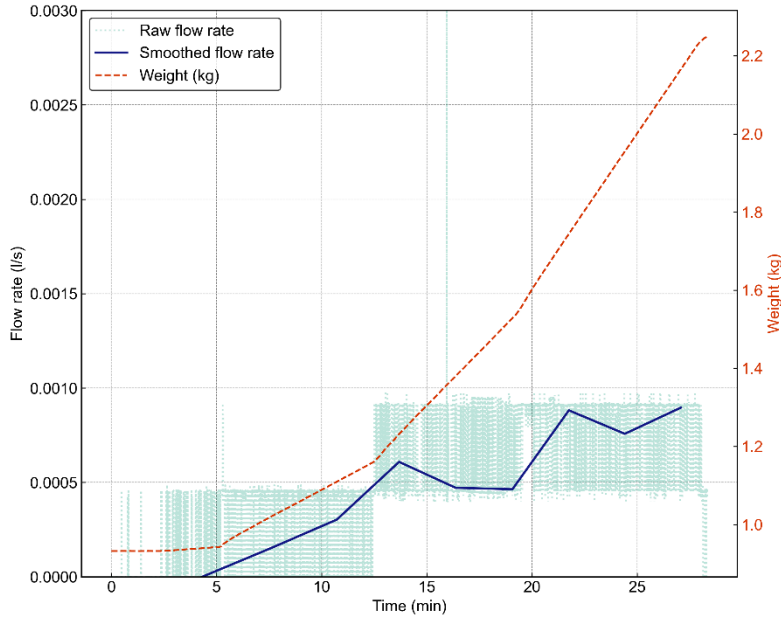


Figure 5-1 Flow rate vs time for permeability test. SSP-300.

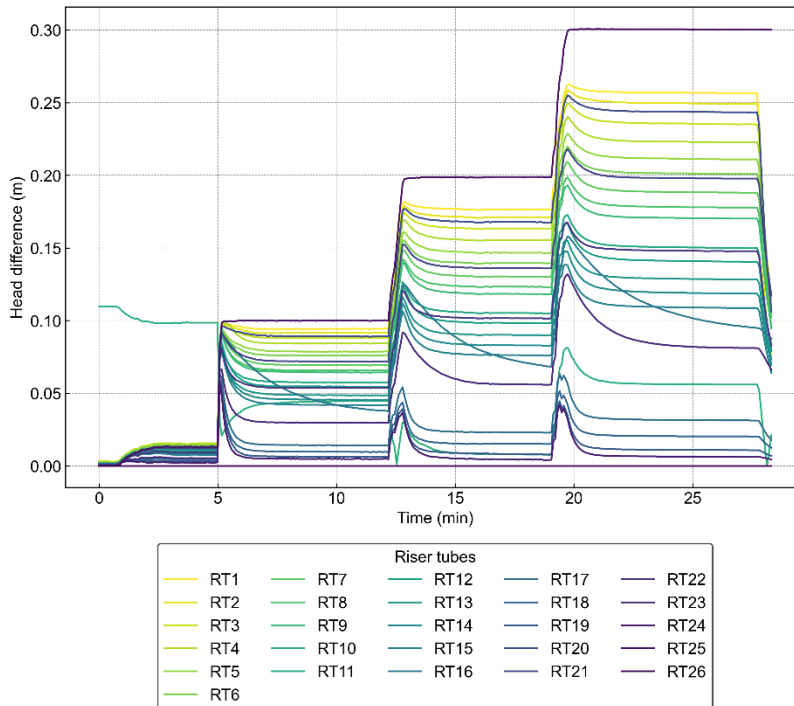


Figure 5-2. Head difference vs time for all standpipes during permeability test. SSP-300.

Permeability was calculated using Darcy's law, following the procedure described in section 4.2, for successive pairs of riser tubes along the box. These results were compared with the permeability obtained using only the applied head difference between the inlet and outlet (RT 25 and 26), and shown in Figure 5-3. It must be highlighted that during the test, riser tube 9 was not responding accurately and therefore it was excluded from the permeability calculations.

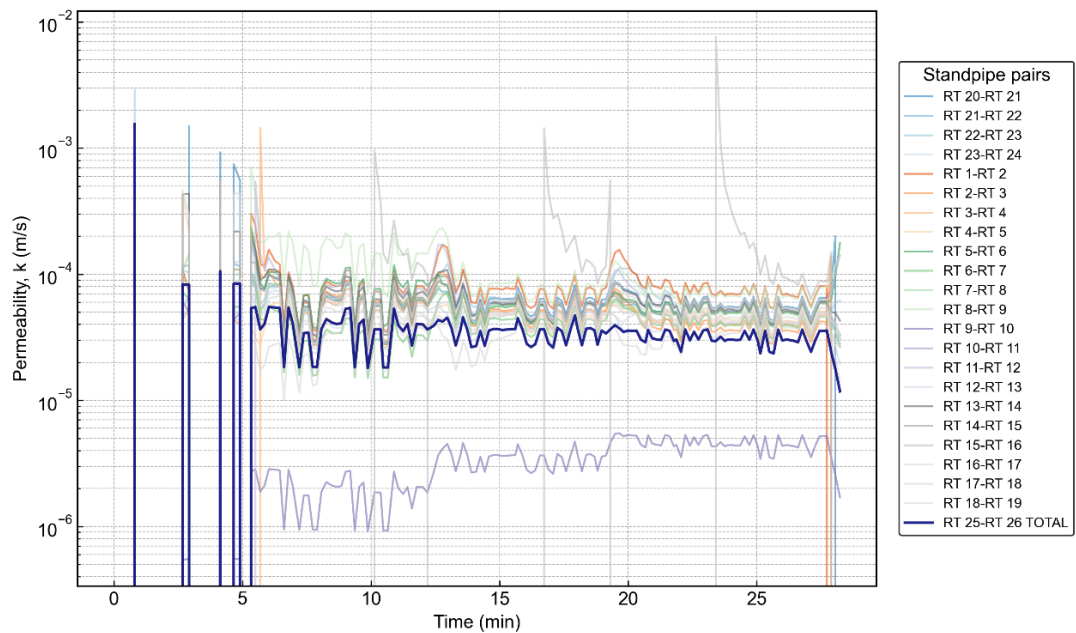


Figure 5-3. Permeability vs time calculated for all subsequent riser tube pairs and the total applied head, during the permeability test. SSP300.

It was found that the permeability derived from the inlet-outlet head difference is representative of the overall soil pack. The permeability for the soil mixture consisting of 95% Baskarp B15 sand and 5% silt is 3.2×10^{-5} m/s, which corresponds with previous permeability estimation for similar soil compositions (Fugro NL Land B.V. & Deltares, 2022) (Deltares, 2025).

5.3.3 Head measurements

The head difference measurements are presented in Figure 5-4.

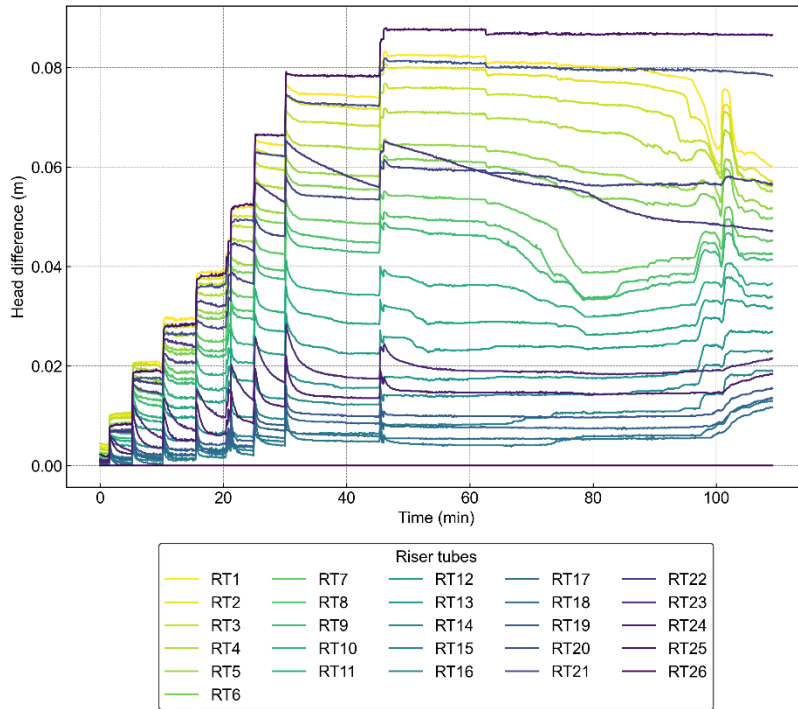


Figure 5-4 Head difference vs time for all standpipes. SSP-300.

Figure 5-5 shows the evolution of measured head vs X across the setup box. Initial pipe formation occurred at a head difference of 7 cm. The pipe subsequently developed in the upstream direction in a straight backward manner. Final erosion occurred at a measured head difference of 8 cm.

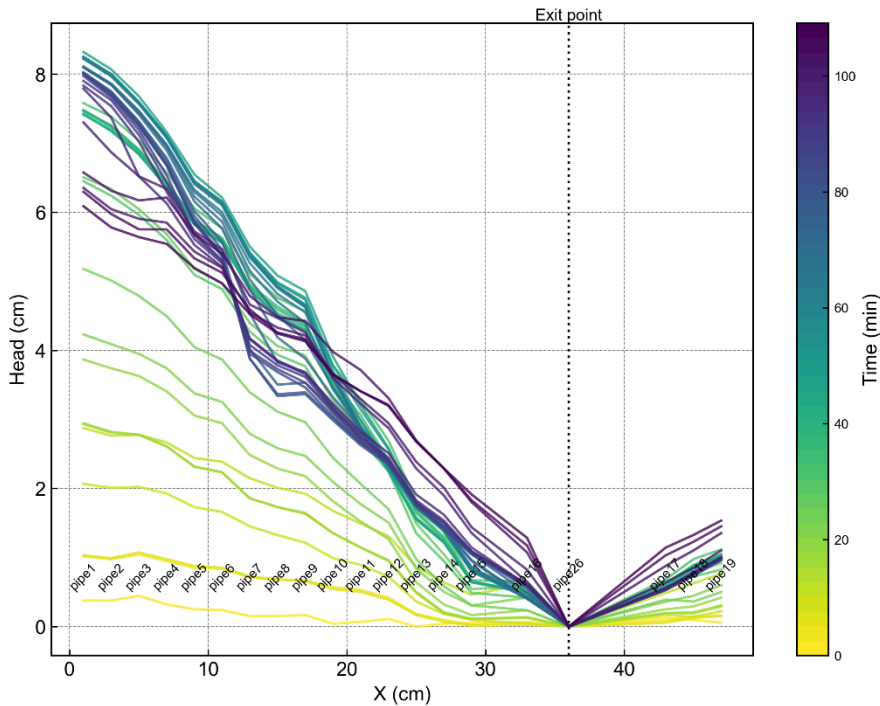


Figure 5-5 Evolution of measured head vs X across the setup box. SSP-300.

5.3.4 Head and flow rate measurements

The measured outflow weight and flow rate are shown in Figure 5-6. The flow rate remained approximately stable between 30 and 90 minutes, during which the pipe was developing. At 90 minutes, when the pipe reached the inlet filter, the flow rate increased by approximately a factor of 3.5.

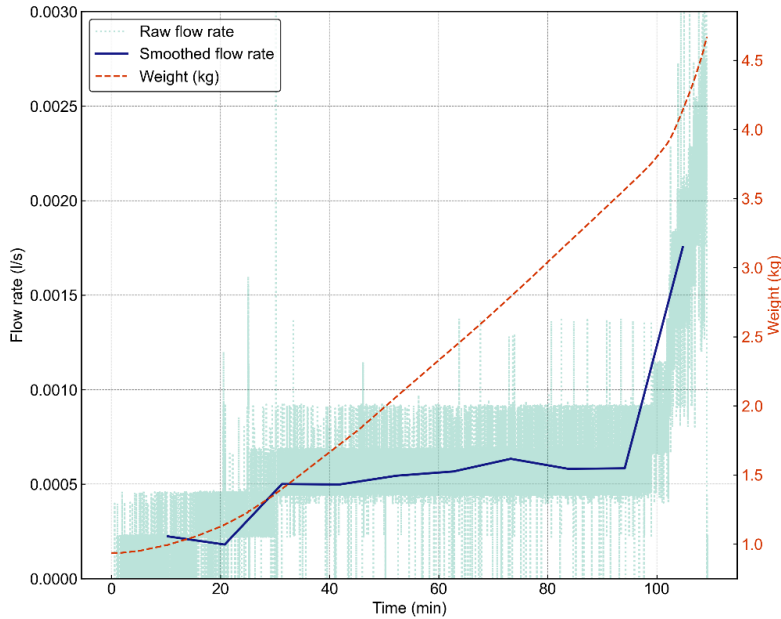


Figure 5-6 Outflow weight (red) and flow rate over time (blue). SSP-300.

5.3.5 Critical head correction

The measured critical head difference at which the pipe initiates growth is 8.0 cm. This value was corrected for head losses across the inflow filter and the outflow hole following the procedure described in section 4.3. The corrected result is shown in Figure 5-7.

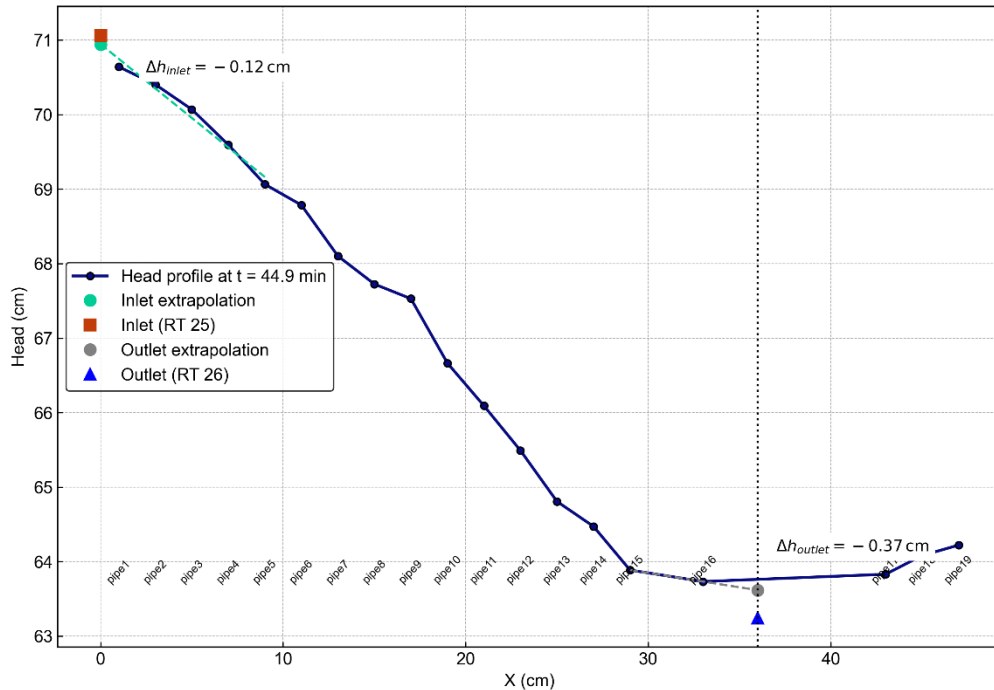


Figure 5-7. Correction of critical head due to inlet and outlet losses. SSP300.

The head profile used for correction is taken just before critical head is reached, at 44.9 min. The head loss across the inflow filter was determined by linear extrapolation of the first six riser tubes closest to the inlet, at the moment when the pipe reached the inflow filter. This results in a head difference of -0.12 cm at $x = 0$. The head loss at the outflow hole was estimated using a linear fit through riser tubes 15 and 16, resulting in a loss of 0.37 cm at $x = 0.36$ m. After correction, the critical head difference at full pipe growth is reduced from 8.0 cm to 7.51 cm.

For comparison with earlier test series (Deltares, 2025), the critical head difference excluding outlet losses is also reported, which in this case, is reduced to 7.88 cm.

5.3.6 Critical length

The critical pipe length was derived from photographs taken from above the setup and is approximately 14 cm at this drop.

5.4 SSP-301

5.4.1 Test progression

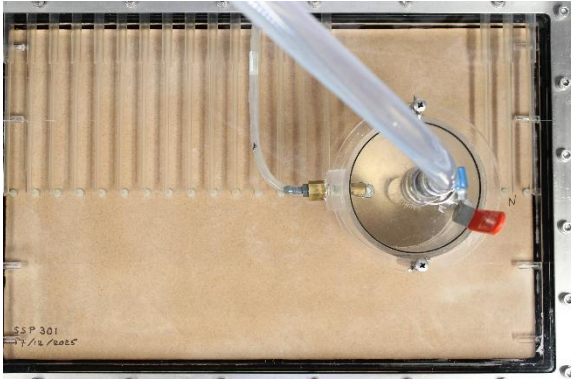


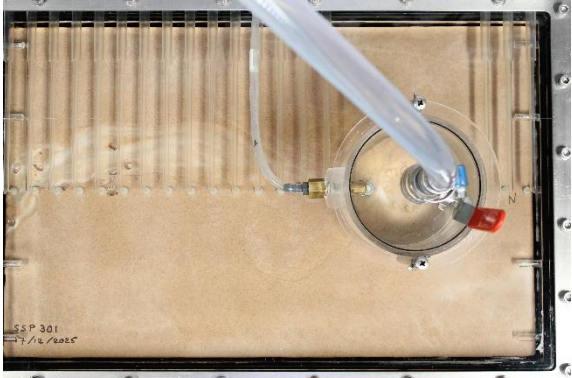
Test SSP-30 had a total duration of 189 minutes. The applied head difference was increased in increments of 1 cm every 5 minutes, or kept constant when required to allow pipe development to stabilise. A sequence of photos taken during the test is shown in Table 5-3. Pipe initiation was first observed after approximately 35 minutes at an applied head difference of 6 cm. Two diverging pipe branches formed from the exit hole towards the upstream side, to the southeast and southwest of the box respectively. At this load step, the pipe required 10 minutes to stabilise before the head difference was increased further.

Further, the hydraulic head difference was increased in successive increments. Each increment required progressively more time for the pipe development to reach an approximately stable condition. At 85 minutes, an applied head difference of 11 cm was reached. At this stage, two pipes were observed, each with an approximate length of 7 cm. One pipe propagated towards the southwest side of the box, while the other developed towards the southeast.

This head difference did not stabilise and both pipes continued to develop upstream. At 125 minutes, the pipe oriented towards the southeast appeared to stabilise, exhibiting reduced erosion. In contrast, the pipe propagating towards the southwest continued to grow and reached an approximate length of 22 cm, extending beyond riser tube RT7.

At 170 minutes, while the applied head difference remained constant, the pipe reached the upstream filter. Complete failure occurred at 189 minutes, without any further increase in the applied head difference.

Table 5-3. Photos during the experiment. SSP-301.

Time after test start (min)	Description	Photo
35	Pipe began formation. $\Delta H = 6$ cm	
85	Critical head is reached. $\Delta H = 11$ cm	
170	Pipe reaches the back of the box. The pipe diffracted, creating 2 smaller branches that grew towards the inlet. However, they join again at the filter.	
189	Failure occurs.	

5.4.2 Permeability test

Prior to the piping test, a permeability test was conducted prior to the piping experiment by applying controlled head differences of 10 cm, 20 cm, and 30 cm between the inlet and hinterland outlet. Figure 5-8 Figure 5-1 presents the total outflow weight and flow rate of this test. During the test, piezometric head readings were obtained from the standpipes distributed across the piping box, as shown in Figure 5-9.

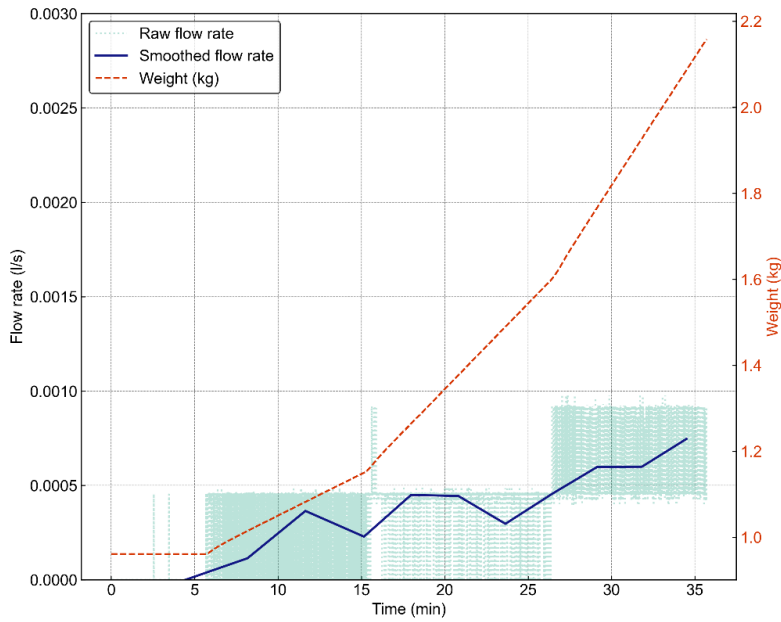


Figure 5-8 Flow rate vs time for permeability test. SSP-301.

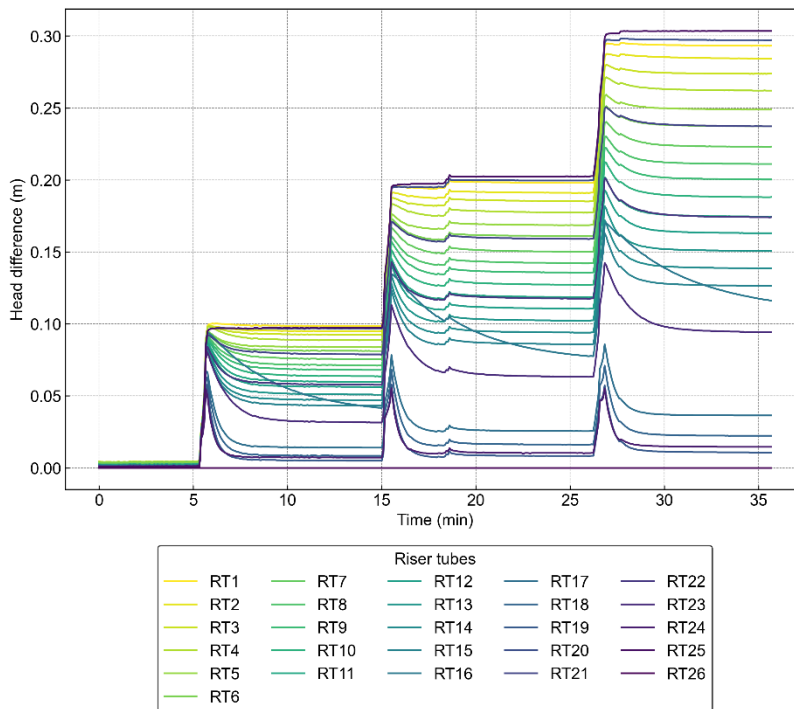


Figure 5-9. Head difference vs time for all standpipes during permeability test. SSP-301.

Permeability was calculated using Darcy's law, following the procedure described in section 4.2, for successive pairs of riser tubes along the box. These results were compared with the permeability obtained using only the applied head difference between the inlet and outlet (RT 25 and 26), and shown in Figure 5-10.

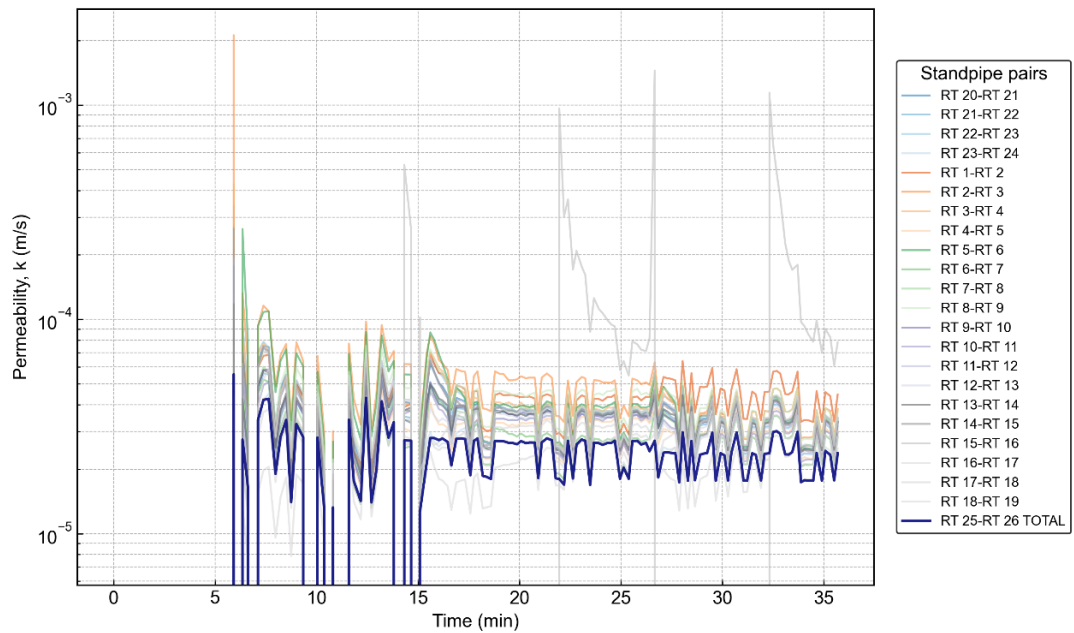


Figure 5-10. Permeability vs time calculated for all subsequent riser tube pairs and the total applied head, during the permeability test. SSP301.

It was found that the permeability derived from the inlet-outlet head difference is representative of the overall soil pack. The permeability for the soil mixture consisting of 90% Baskarp B15 sand and 10% silt is $2.5e-5$ m/s, which corresponds with previous permeability estimation for similar soil compositions (Fugro NL Land B.V. & Deltares, 2022) (Deltares, 2025). Likewise, this soil pack proves to be more impermeable than the one consisting of 95% Baskarp B15 sand and 5% silt, due to a larger fine content.

5.4.3 Head measurements

The head difference measurements are presented in Figure 5-11.

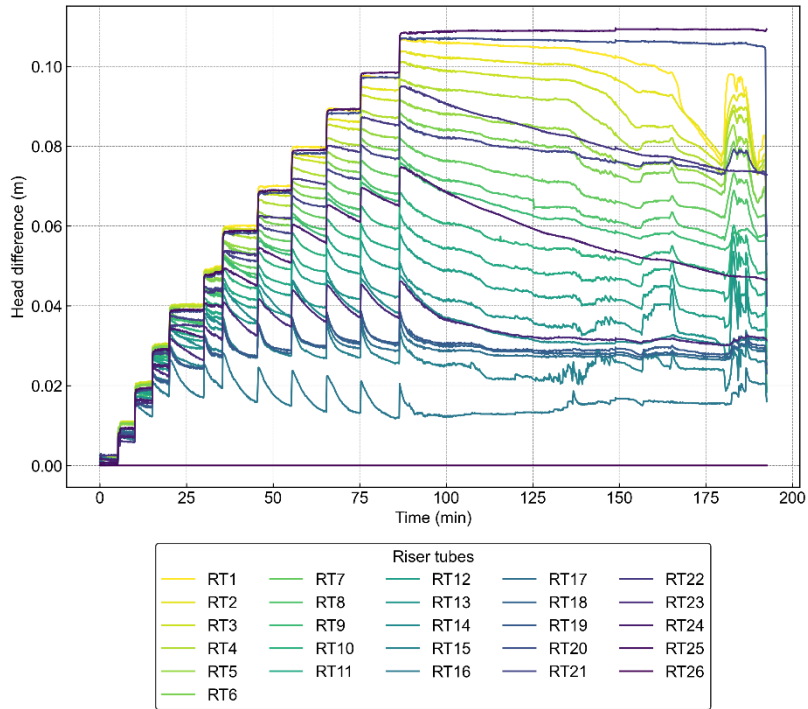


Figure 5-11 Head difference vs time for all standpipes. SSP-301.

Figure 5-12 shows the evolution of measured head vs X across the setup box. Initial pipe formation occurred at a head difference of 6 cm. The pipe subsequently developed in the upstream direction in a straight backward manner. Final erosion occurred at a measured head difference of 11 cm.

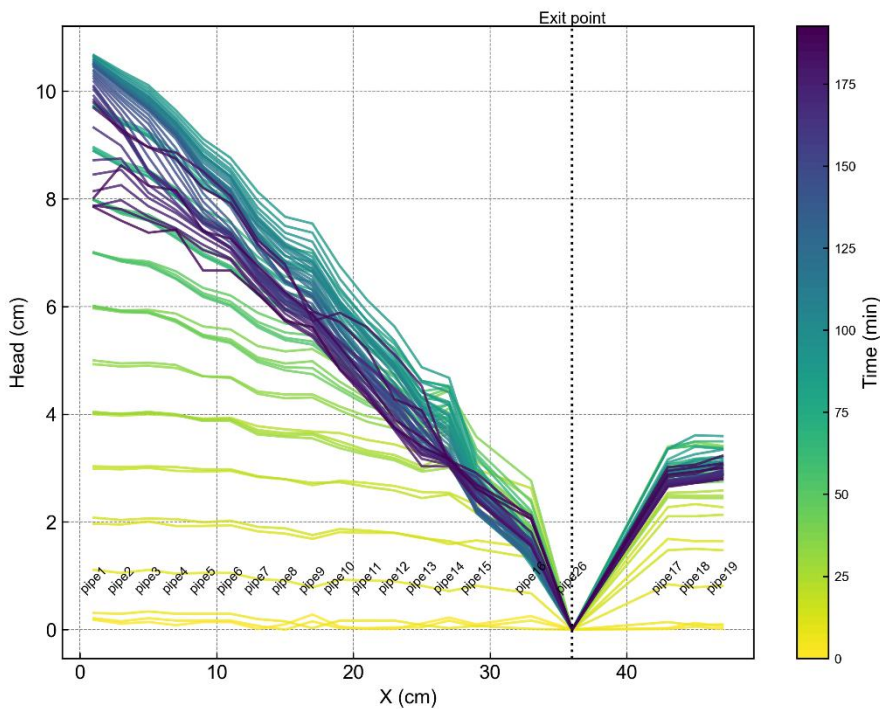


Figure 5-12 Evolution of measured head vs X across the setup box. SSP-301.

5.4.4 Head and flow rate measurements

The measured outflow weight and flow rate are shown in Figure 5-13. The flow rate remained approximately stable between 30 and 180 minutes, during which the pipe was developing.

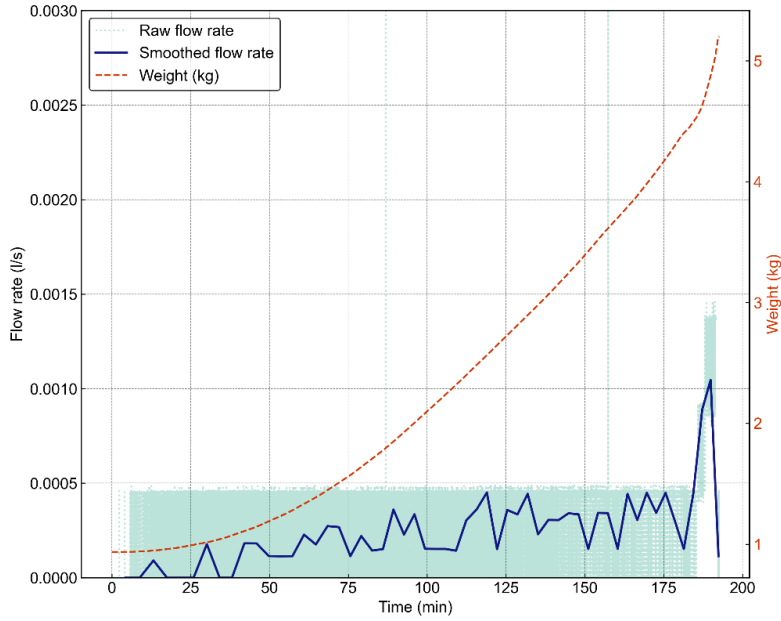


Figure 5-13 Outflow weight (red) and flow rate over time (blue). SSP-301.

5.4.5 Critical head correction

The measured critical head difference at which the pipe initiates growth is 11.0 cm. This value was corrected for head losses across the inflow filter and the outflow hole following the procedure described in section 4.3. The corrected result is shown in Figure 5-14.

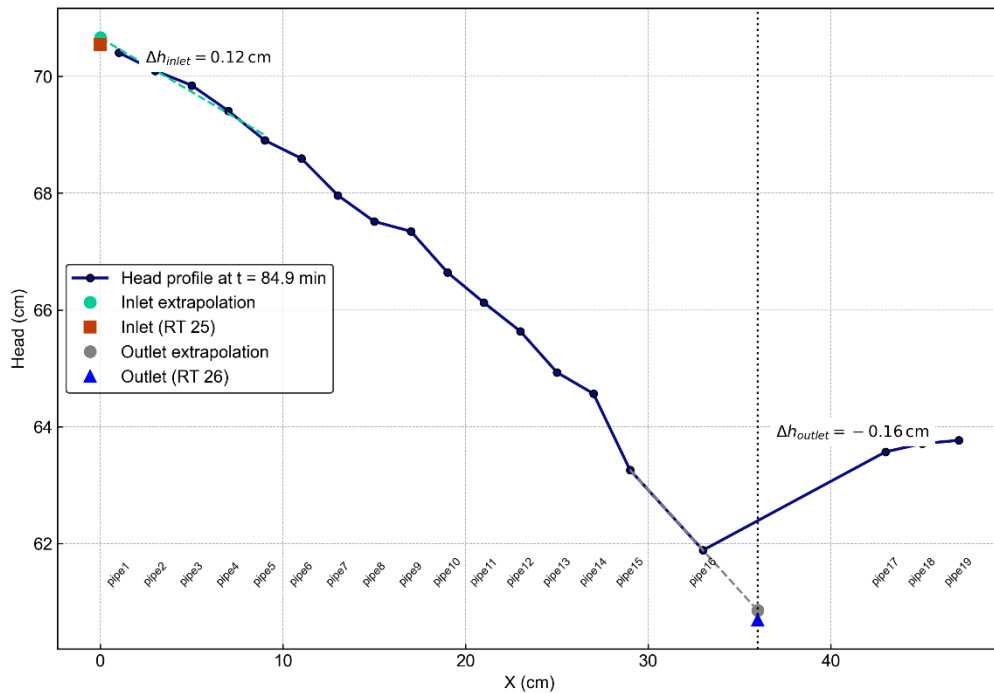


Figure 5-14. Correction of critical head due to inlet and outlet losses. SSP301.

The head profile used for correction is taken just before critical head is reached, at 84.9 min. The head at the inlet is even lower than the extrapolated head based on the riser tubes, but

the difference is very small and within the accuracy of the riser tubes. It was therefore concluded that there was no head loss at the inlet filter. The head loss at the outflow hole was estimated using a linear fit through riser tubes 15 and 16, resulting in a loss of -0.16 cm at $x = 0.36$ m. After correction, the critical head difference at full pipe growth is reduced from 11.0 cm to 10.84 cm.

For comparison with earlier test series (Deltares, 2025), the critical head difference excluding outlet losses is also reported, which in this case is equal to the measured head of 11.0 cm.

5.4.6 Critical length

The critical pipe length was derived from photographs taken from above the setup and is approximately 7 cm at this drop, reaching the position of riser tube 15. In comparison with SSP-300, the critical length of the pipe is smaller for a soil pack with a larger fine content. Likewise, for this test, the pipe grew wider initially and got smaller as it progressed towards the inlet filter. In contrast, for test SSP-300, the pipe always maintained a slim line shape.

6 Summary and recommendations

Two SSP tests, SSP-300 and SSP-301, were conducted in the Geohal at Deltares. The tests differed in fine content: SSP-300 consisted of 95 % sand and 5% silt, while SSP-301 consisted of 90 % sand and 10 % silt.

The objective of testing was to record the effect that different fine content levels have on pipe development and compare with previous SSP experiments where this has been studied (Fugro NL Land B.V. & Deltares , 2022) (Deltares, 2025).

Prior to the piping experiments, dry density tests were performed to determine the relevant soil parameters. In addition, permeability tests were carried out before each piping test. During the piping tests, piezometric head was measured across the experimental box throughout the entire test duration. The discharge at the outlet was also continuously recorded. In parallel, a logbook was maintained to document the progression of each test, including observations of pipe development, supplied input head, and any notable behaviour. The critical head difference was determined experimentally for each test. In addition, corrected critical head differences were calculated by accounting for head losses at the inlet filter and, where applicable, at the outlet opening.

Table 6-1 presents a summary of results. It can be seen that an increase in silt content from 5% (SSP-300) to 10% (SSP-301) resulted in a higher measured and corrected critical head difference, indicating increased resistance to pipe initiation and progression. At the same time, the critical pipe length decreased with increasing fine content, suggesting that pipe development was more localised and less extensive in the soil with higher silt content, although the number of tests was insufficient to confirm this trend. These trends are consistent with the observed lower permeability of the material with higher fine content and confirm the stabilising effect of fines on piping development.

Nonetheless, during preparation of the test setup of SSP-300, a minor loss of sand occurred at the outlet opening. This may have resulted in a small pre formed void, introducing uncertainty in the precise moment of initial pipe development.

Table 6-1. Summary of results.

Test	Material	Measured critical head (cm)	Corrected critical head for inlet and outlet (cm)	Corrected critical head for inlet (cm)	Critical length (cm)	Relative density, D_r (%)	Permeability, k (m/s)
SSP-300	5% silt, 95% Baskarp B15 sand	8.0	7.51	7.88	14.0	90.6	3.2e-5
SSP-301	10% silt, 90% Baskarp B15 sand	11.0	10.84	11.0	7.0	89.8	2.5e-5

It is recommended to perform duplicate tests for each soil composition to assess the repeatability of the observed critical head and length differences, and to quantify the influence of experimental variability on the results.

7 References

- Deltares. (2025). *KIA Piping op Veldschaal - WP1.3. Feitelijk rapport pipingproeven*. Delft. Fugro NL Land B.V. & Deltares . (2022). *Piping in getijdenzand - Hedwigeproject. Analyse kleine en medium schaalproeven*.
- Knudsen, S., Powell, J., Lunne, T., Thomsen, N. V., Krogh, L., & Barwise, A. (2020). *Development of new robust procedures for the determination of maximum and minimum dry densities of sand*. Oslo: Deep Foundations Institute.
- NGI Geolabs. (2019). *Recommended method statement. Determination of maximum dry density sands*.
- NGI Geolabs. (2019). *Recommended method statement. Determination of minimum dry density sands*.
- Van Beek, V. (2015). *Backward erosion piping - initiation and progression. Ph.D.-thesis*. Delft: TU Delft.

A Logbooks

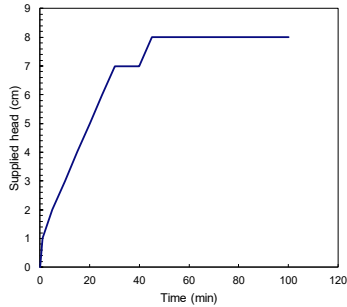
A.1 SSP-300

Permeability test

Test	300	Time (min)	Time (hh:mm)	Increment (cm)	Total head difference (cm)	Observations
Description	Permeability test for soil pack of 5% silt and 95% sand		0	0	0	
Date	11-12-2025		1	1	1	
Added B15 sand and silt (kg)	24.0069		5	9	10	
			12	10	20	
			19	10	30	
			27		30	End of test
Soils for unit weight	2					
Length (m)	0.483					
Width (m)	0.3					
Depth (m)	0.1					
Box volume (m3)	0.0145					
Unit weight dry (kN/m3)	16.25					
Unit weight max (kN/m3)	16.58					
Unit weight min (kN/m3)	13.65					
Sample Dr (-)	90.6%					
Void ratio, e (-)	0.60					
Porosity, n (-)	0.37					
T ini (deg)	19.4					
Top load (kg)						

Piping test

Test	300	Time (min)	Time (hh:mm)	Increment (cm)	Total head difference (cm)	Observations
	Normal box, circular outflow, soil pack of 5% silt and 95% sand					
Description		0	11:51:00	0		0 Start of test
Date	11-12-2025	1	11:52:00	1		1
		5	11:56:00	1		2
Added B15 sand and silt (kg)	24.0069	10	12:01:00	1		3
		15	12:06:00	1		4
		20	12:11:00	1		5
Soils for unit weight	2	25	12:16:00	1		6
Length (m)	0.483	30	12:21:00	1		7 Pipe began formation, one single branch in the center and going towards the west
Width (m)	0.3	35	12:26:00	0		7 Pipe is around tube 11
Depth (m)	0.1	40	12:31:00	0		7
						8 Pipe keeps progressing towards tube 12, exactly in the middle of 11 and 12; secondary smaller and finer branches are growing from the exit point towards the west, reaching tubes 13 and 14 respectively, no erosion in the outlet
Box volume (m3)	0.0145	45	12:36:00	1		8 One of the west branches is growing towards tube 11; east pipe is widening; no activity in the outlet
		50	12:41:00	0		8
Unit weight dry (kN/m3)	16.25	55	12:46:00	0		8
						8 West pipe became more active eraching between tubes 9 and 10, while the first east pipe stabilised. At 12:55, 8 pipe reaches between tubes 8 and 9
Unit weight max (kN/m3)	16.58	60	12:51:00	0		8 West pipe reaches tube 8, and now the other existing east pipe also reactivated and erosion is visible (reaching tube 9)
Unit weight min (kN/m3)	13.65	65	12:56:00	0		8 West pipe is almost reaching tube 7, while initial east pipe is at tube 8
Sample Dr (-)	90.6%	70	13:01:00	0		8
Void ratio, e (-)	0.60	75	13:06:00	0		8
						8 Now activity in outflow, east standpipe at 7, while the west pipe is going at tube 5. At 13:15, west pipe is reaching tube 3 and 4
Porosity, n (-)	0.37	80	13:11:00	0		8
		85	13:16:00	0		8
T ini (deg)	19	90	13:21:00	0		8 West pipe begins to reach the back of the box, east pipe between 3 and 4 and continues widening.
						8 East pipe at 2. Active soil transportation and widening of the east pipe.
Top load (kg)		95	13:26:00	0		8 East pipe has reached inlet filter side of the box.
						8 Transportation of soil increases. Sand model fails.
		100	13:31:00	0		8 End of test

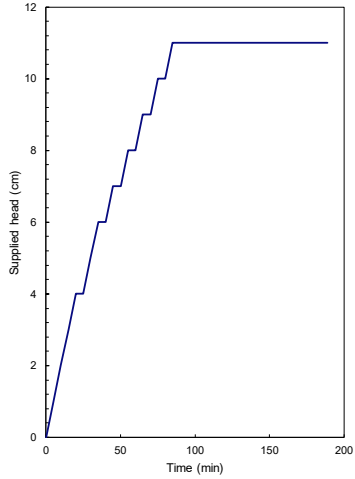


Permeability test

Test	301	Time (min)	Time (hh:mm)	Increment (cm)	Total head difference (cm)	Observations
Description	Permeability test for soil pack of 10% silt and 90% sand					
Date	17-12-2025					
Added B15 sand and silt (kg)	24.253	0	10:09:00	0	0	
		5	10:14:00	10	10	
		15	10:25:00	20	30	
		25	10:35:00	30	60	
		35	10:45:00		60	Stop the test
Soils for unit weight	2					
Length (m)	0.483					
Width (m)	0.3					
Depth (m)	0.1					
Box volume (m3)	0.0145					
Unit weight dry (kN/m3)	16.45					
Unit weight max (kN/m3)	16.82					
Unit weight min (kN/m3)	13.78					
Sample Dr (-)	89.8%					
Void ratio, e (-)	0.58					
Porosity, n (-)	0.37					
T ini (deg)	19.1					
Top load (kg)						

Piping test

Test	301	Time (min)	Time (hh:mm)	Increment (cm)	Total head difference (cm)	Observations
Description	Normal box, circular outflow, soil pack of 10% silt and 90% sand	0	11:49:00	0		0 Start of test
Date	17-12-2025	5	11:54:00	1		1
		10	11:59:00	1		2
Added B15 sand and silt (kg)	24.253	15	12:04:00	1		3
		20	12:09:00	1		4 Slight boiling of sand in the outlet hole. Formation of 2x 2 cm pipes just south of the outlet hole
		25	12:14:00	0		4 Stabilised
Soils for unit weight	2	30	12:19:00	1		5 The slight boiling reactivated with the head increment
						With the increment, two pipe branches started growing from the exit hole, towards the south and south east of the box, respectively. Sand boiling activity remains. At 1:27 the exit hole resembles a snow flake with multiple
Length (m)	0.483	35	12:24:00	1		6 branches to several directions
						A prominent pipe towards the SW of the box barely exits the cylinder and now is visible in the box. However it is
Width (m)	0.3	40	12:29:00	0		6 stable. Thickness about 1 cm.
Depth (m)	0.1	45	12:34:00	1		7 Pipe becomes active again, along with some sandboil activity.
Box volume (m3)	0.0145	50	12:39:00	0		7 Stabilised
		55	12:44:00	1		8 At this point, the pipe ends between standpipes 15 and 14
Unit weight dry (kN/m3)	16.45	60	12:49:00	0		8 Pipe reached standpipe 14, it seems stable, but the exit hole has some sandboil activity still
Unit weight max (kN/m3)	16.82	65	12:54:00	1		8 Pipe towards the SW becomes wider. There is also a 2nd pipe forming from the exit hole towards the SE, just
Unit weight min (kN/m3)	13.78	70	12:59:00	0		9 coming out of the cylinder.
						9
Sample Dr (-)	89.8%	75	13:04:00	1		10 Another pipe is growing from the exit hole towards the outlet filter (hinderland), while the two other pipes keep
Void ratio, e (-)	0.58	80	13:09:00	0		10 widening rather than increasing in length
						10
Porosity, n (-)	0.37	85	13:15:00	1		11 Pipe to SW reached standpipe 15, while pipe on the SE is at the location of standpipe 14. Both keep developing
		90	13:19:00	0		11 wider. The pipe at the N (back) seems stable.
T ini (deg)	20.2	95	13:24:00	0		11
Top load (kg)		100	13:29:00	0		11 SW pipe reaches riser tube 11, and SE pipe is around 13.
		105	13:34:00	0		11 SW pipe reaches riser tube 10, and SE pipe is around 12.
		110	13:39:00	0		11
						SW pipe reaches riser tube 10, and SE pipe is around 12. The pipe shapes are also becoming more defined
		115	13:44:00	0		11 towards the inlet, while towards the exit they are wider
		120	13:49:00	0		11
						SE pipe seems stable, but SW pipe keeps growing now reaching between riser tubes 7 and 8 and it has a white-ish color uncovered, thus showing silt
		125	13:54:00	0		11
		130	13:59:00	0		11
						Sandboil is active at the exit point, the SW pipe is almost reaching standpipe 5. SE pipe also reactivated and sometimes presents erosion too.
		135	14:04:00	0		11 SW pipe reaches standpipe 4
		140	14:09:00	0		11
		145	14:14:00	0		11 SW pipe reaches between standpipes 2 and 3
		150	14:19:00	0		11 SW pipe reaches between standpipes 1 and 2
		155	14:24:00	0		11
		160	14:29:00	0		11
						At 11:36 SW pipe already passed standpipe 1, almost about to reach inlet filter
		165	14:34:00	0		11 Erosion appears to be at a faster rate; somewhere around standpipe 3, SW pipe diffracted, creating 2 smaller branches that grew towards the inlet. However, they join again at the filter.
		170	14:39:00	0		11 The pipe now grew horizontally at the filter
		175	14:44:00	0		11 SE pipe became active again after being stable so long. It has grown up to riser tubes 11 and 12. There seems to be a bubble trapped at the inlet filter that makes the erosion slow down
		180	14:49:00	0		11
		185	14:54:00	0		11
						Erosion becomes faster now and the dominant pipes are also faster. Failure occurred.
		186	14:55:00	0		11
		189	14:58:00	0		11 End of test
						*Riser tubes 9 and 14 are very slow, possibly at the test were also responding slower



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