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Monitoring a full-scale backward erosion piping field test at Hedwigepolder

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Abstract

Two full-scale backward erosion piping field tests were executed in the Hedwigepolder, The Netherlands. The tests were aimed to further validate the hypothesis that tidal sand has more resistance to piping than fluvial sand. Tidal sand has relatively high percentages of fines (clay, silt), often contains discrete clay and silt layers, is more cohesive, more anisotropic and has a higher critical shear stress than fluvial sand. Piping was initiated by infiltrating water into a completely enclosed body of tidal sand. This was done using infiltration tubes on one side of each test site, while at the other side a ditch was dug down to the tidal sand layer. By gradually increasing water levels in the tubes, an increasingly steep water pressure gradient was formed in the sand initiating backward erosion piping. The piping process was monitored using an array of techniques, including Electrical Resistance Tomography (ERT), Distributed Temperature Sensing (DTS), over 200 piezometers and infrared cameras. After the test the entire site was excavated to track the route of the pipe and to study the subsurface in detail. The combination of different monitoring techniques will allow data fusion and will give complementary insight into the processes that led to piping. This paper gives an overview of the used monitoring techniques, discusses the pros and cons of the different techniques and gives recommendations for future field experiments.

Keywords: piezometers, ERT, DTS, discharge, tidal sand, backward erosion piping, flood defence

1. Introduction

Backward erosion piping is an important failure mechanism for flood defences. It can occur during high water when the hydraulic gradient across the flood defence is high enough to initiate the formation of pipes by flowing water at the interface of a sand layer and a less permeable and more cohesive cover layer. If unmitigated, the erosion channel will progress upstream and may lead to subsequent failure of the flood defence. For the piping process to start it is necessary that the cover layer on the inner side of the flood defence is absent (e.g. at the bottom of a ditch) or has an opening as either the result of a disturbance (e.g. roots, old boreholes, digging activities) or due the head of the groundwater in the sand (bursting). Based on the current evaluation method for piping in The Netherlands, hundreds of kilometres of levees need to be reinforced with respect to this failure mechanism and hence a lot of research has been executed in order to increase the understanding of the mechanism and to create physical-based models to assess the probability of failure (e.g. Van Beek, 2015; Pol et al, 2022).

The characteristics of the sand layer are of great influence on the piping process and in the piping-predicting model used in The Netherlands (Sellmeijer et al., 2011) they are represented by the bulk permeability, layer thickness, and the grainsize (70%-quantile of the grain size distribution by weight) of the upper part of the sand layer. These characteristics vary for different types of sand and depend on the depositional environment in which the sand was laid down. In The Netherlands, sands below most flood defences were deposited in a fluvial or tidal environment. Since >95% of the sand boils in the Netherlands have been observed in the fluvial area, nearly all research has focussed on fluvial sand and the process of backward erosion piping in tidal sand has not been studied, even though the characteristics of these two types of sands vary greatly. Tidal sand is much finer (lower d70), is less permeable, frequently contains thin clay layers, contains more fines (both silt and clay) and is more cohesive. Based on these differences it was hypothesized that tidal sand is less sensitive to backward erosion piping than fluvial sand and based on several small-scale tests and a full-scale test this hypothesis was shown to be true (Hijma, 2019; Deltares and Fugro, 2021). In September 2021 two more full-scale field tests were executed to further substantiate our findings. During these tests an extensive monitoring system was set up to steer the experiment, follow the piping process and ultimately analyse the experimental results leading to a better understanding of backward erosion piping in tidal sands.

In this paper we first present the general design of the field test and will then describe the used monitoring set up. A detailed analysis of the data and recommendations for assessing flood defences resting on tidal sand will be published in follow-up papers.

2. Design of the field test

The field test was executed in the Hedwigepolder, The Netherlands (Fig. 1). This polder is used for research in a Living Lab setting (https://polder2cs.eu/activities) before it will be transformed in a new tidal nature reserve. A site was selected for the backward erosion piping experiments based on boreholes, cone penetration tests (CPT's) and ERT measurements, HPT-AMPT® tests and two trenches in which the local subsurface was investigated in detail. At the chosen location the thickness of both the aquifer and the confining aquitards were largest. In preparation of the experiment sheet piles were installed to create two test sections of approximately 12 by 20 metres in which the tidal sand aquifer was enclosed on all sides. 4 infiltration tubes were installed on the "upstream" side of each section in which the water levels could be regulated using pumps. At the toe of the dike a ditch was created reaching the top of the aquifer (Fig. 1). To prevent leakage all sheet piles were installed using bitumen in the interlocks and the top of the piles was covered by 1 m clay. A large body of sand in combination with BigBags was used to prevent uplift and hydraulic fracturing of the clay cover layers and gave the site the feel of an embankment. By gradually raising and maintaining water levels in the tubes and pumping away seepage water from the ditch, the hydraulic gradient across the tidal sand was gradually increased. At a certain gradient sand boils formed and by further increasing the gradient the piping process proceeded.

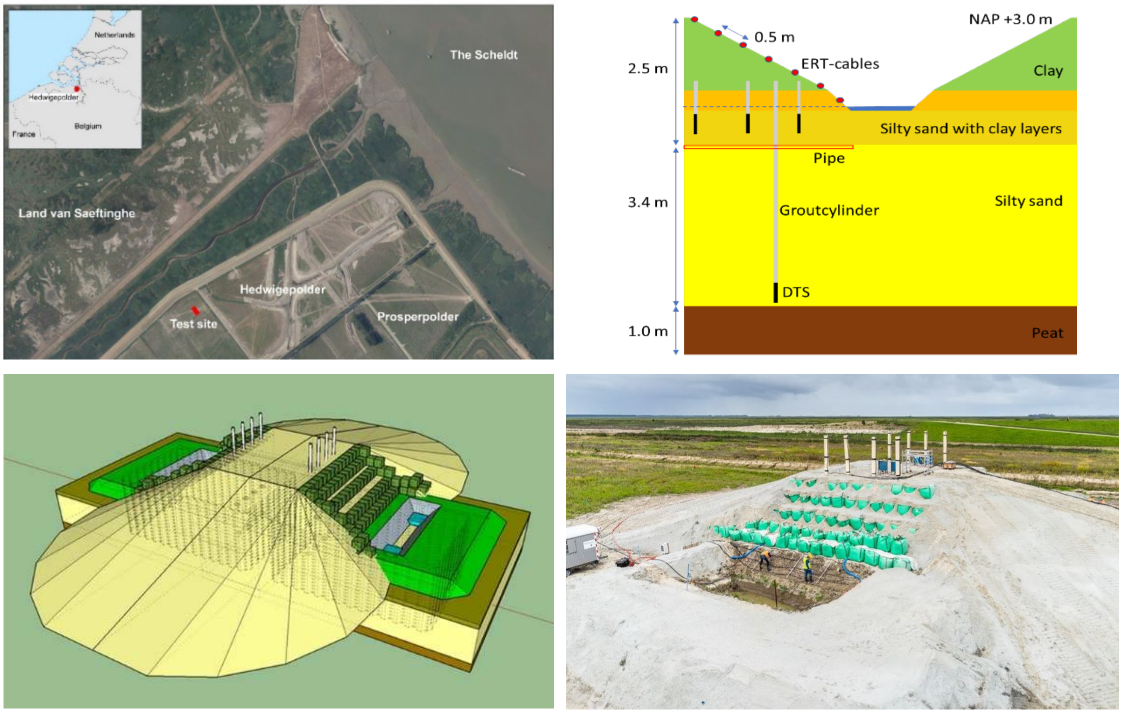

Figure 1: Top left: Location of the Hedwigepolder and test site. Top right: general lay-out of the confined tidal, silty sand aquifer and experimental set up of the monitoring system. Bottom left: design of the test site. Bottom right: Actual test site. The infiltration tubes are visible on the top of the artificial embankment and in the centre one of the ditches is visible. On the other side of the test site a similar ditch is present. Below the mound two rectangular areas of 12*20 m are enclosed with sheet piles, meaning that two separate tests can be executed. In each test section 4 infiltration tubes are used to create a hydraulic gradient in the sand. The two persons are installing the ERT-cables in between the ditch and the BigBags. All the other monitoring was installed before the construction of the artificial embankment and is not visible.

3. Monitoring the field test

3.1 Piezometers

Hydraulic heads were monitored in detail by using over 200 Fugro drive-in piezometers to 1) check the level of saturation of the sand beforehand, 2) to verify whether significant leakages occurred during the tests and 3) to assess if a steady state was reached before the water level in the infiltration tubes was raised. Continuous and real-time monitoring of the hydraulic heads also allowed for the monitoring of the pipe progression and path. Great care was put in designing, testing and creating circumstances that accommodate a high-quality installation with minimal chances of leakage as the water overpressure could be as high as 10 m H_2O during the experiments. The drive-in piezometers were prepared on site, mounted with fine-graded filters and filled with silicon oil to reduce risk of leakage from the pressure chambers. The piezometers were installed from ground level using lightweight CPT equipment. Once the specified depth was reached the casing was raised and the hole filled with drill grout. All monitoring wells and the infiltration tubes were outfitted with polyethylene sleeves to block any leakage path. On top of these sleeves and all piezometer locations a clay layer with a minimum thickness of 0.5 m was added to further minimise the risk on leakages.

In total 204 piezometers and 13 monitoring wells were installed to monitor the hydraulic heads in and outside the two test sections at different depths. According to the different objectives of the head monitoring each test section was divided in segments 'A' to 'E' (Fig. 2). Within segments A, B, D and E piezometers were placed relatively deep in the tidal sand or deeper layers to evaluate pressure build up in the multi-layered tidal aquifer and to check whether leakages through the sheet piles or underlaying peat layer to the surrounding area (Area E lies outside the sheet-pile construction). In order to follow the pipe a total a total of 66 piezometers were installed in a 1 m grid in segment C. The piezometers in this segment were installed just below the top of the tidal sand layer and hence close to the expected pipe level. The 1Hz monitoring data was logged, made available live on site for the field teams as well as online for colleagues off-site using Fugro's visualisation platform.

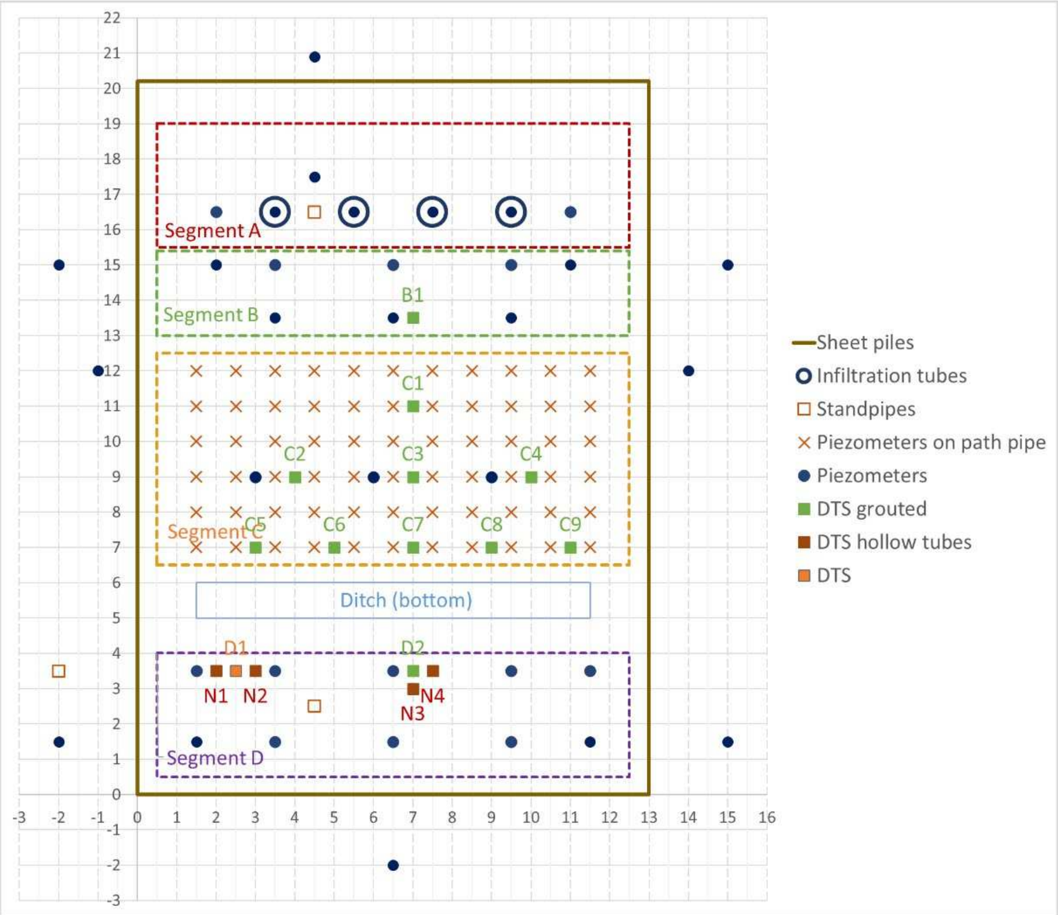

Figure 2: Schematic representation of monitoring set-up piezometers and monitoring wells for one test section. Both test sections are identical with regards to set-up of the experiment and monitoring system.

During the experiments the location of the erosion pipe's tip was determined using relatively sudden local head drops in the piezometers in segment C. The pipe's growth rate is determined by evaluating pairs of piezometers along the trajectory of the pipe from the downstream (ditch) till upstream side (infiltration tubes) of the ground water flow. A peak in head gradient between a pair of piezometers indicates the pipe position at the downstream piezometer. Figure 3 gives these peaks in head gradient for a selection of piezometer pairs; the pipe can be seen growing upstream across monitoring segment C from piezometer row 1 to 6 in segment C.

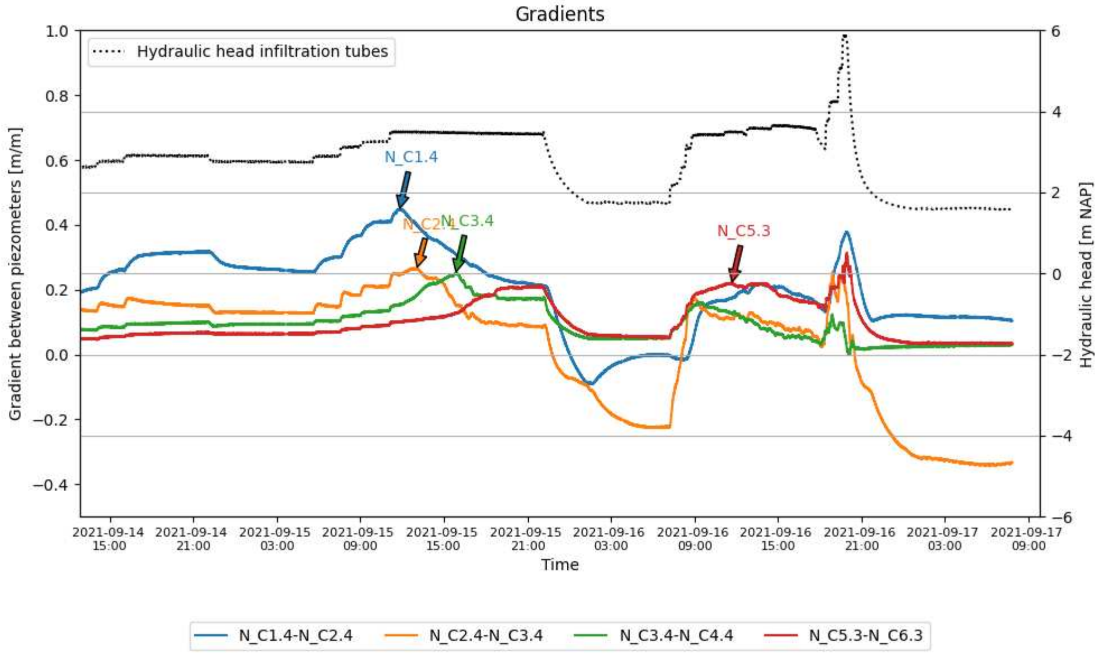

Figure 3: Increase and relatively sudden decrease of head gradients between pairs of piezometers indicating a growing erosion pipe nearby.

Based on the piezometer data the path of the pipe could be determined during the experiments. This was validated during the post-test excavation of the tests (see §3.5) in which the route of the pipe was mapped in detail. It was found that the (predicted) path of the pipe based on the piezometer data matched perfectly with the actual path.

3.2 Discharge

The budget of the in and out flowing water is very important to understand and model the piping process but can also show if there is leakage through the sheet piles or along the monitoring systems. The inflowing water was pumped from containers towards the 8 infiltration tubes (Fig. 4).

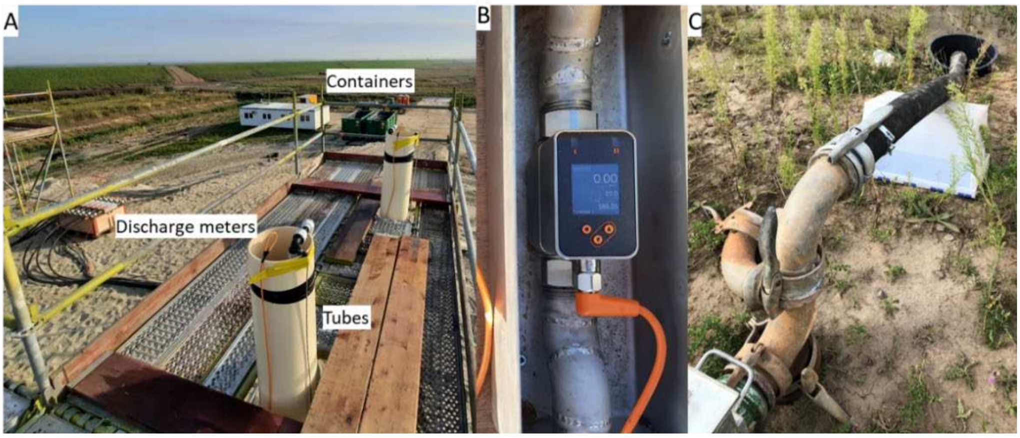

Figure 4 A: Water is pumped from water containers to the infiltration tubes. Each tube had its own pump and each pump has a discharge meter. B: close-up of the digital discharge meter. C: The discharge of the outflow was measured manually by measuring the time needed to fill a container.

The system could be set to automatically maintain a desired water level in the tubes, meaning that the pumps became active when water level dropped to a certain water level. Discharge measurements were stored using a logger but could also be read directly in the field. In addition, a piezometer was placed in the water container to measure the decreasing water level and also from this data infiltration discharges could be calculated. This showed that the discharge meters overestimated the discharge, because they didn't record water flowing back to the container after the pumps stopped.

In both ditches a pump was installed that maintained a water level in the ditch of a 5-10 cm. The water was pumped away to an open container and the overflow of this container was connected to a hose with an analogue discharge meter. The analogue meter was read each 30 minutes, but soon it became clear that it was not working properly. Another approach was used whereby the discharge was measured by timing how fast a 30 l container was filled.

3.3 Electrical resistivity tomography (ERT)

In each test field 7 lines of ERT-cables were placed in between the edge of the ditch and the first row of BigBags (Fig. 5). This area was steeply sloped and hence each line lies at a different elevation and thus distance to the top of the tidal sand. This is not ideal, since this means that the vertical resolution along each line is different at the level of pipe growth. The distance between lines was 0.5 m and the metal pins were placed at 0.25 m intervals. ERT was envisaged to measure the changes in the subsurface in the period before pipe formation started and track the route of the pipe, as pipe growth leads to changing geo-electrical properties. The data could not be used live, but analysis shows that the ERT-data captured the position of the sand boil and the pipe.

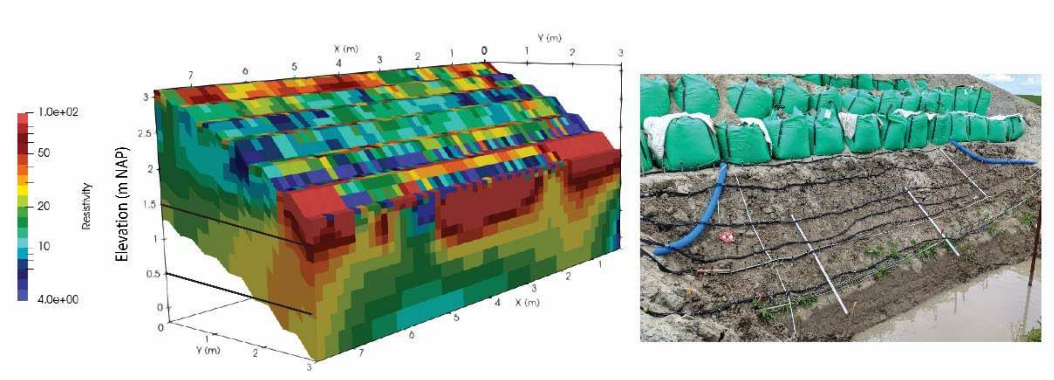

Figure 5: Left: example of the ERT-output. Right: Field site with the black ERT-cables in between the ditch and the first row of green BigBags.

3.4 Distributed Temperature Sensing (DTS)

In the northern test field temperature changes were measured using DTS. At 16 locations active DTS-cables were installed using CPT cones and rods (Fig. 6) by attaching the DTS cable to the cone of the CPT and by pushing the cone to the desired depth and then retracting the CPT-rods while at the same time filling the resulting hole with grout. The hypothesis was that the cooling curve of the heated cables will change (faster cooling) when an erosion pipe is active near a DTS-cable. At present, the analysis is no finished so its it yet unknown whether this hypothesis is true or false.

At 4 locations (Fig. 2: N1 to N4) CPT-rods were installed, which stayed in place during the experiment, serving as hollow tubes accessible for glass fibre cables to perform passive DTS-measurements. To avoid leakage along the rods in the principal test area, the rods were installed behind the ditch, together with a grouted glass fibre cable (D2) and a glass fibre cable directly in contact with the subsoil (D1). This location is suboptimal to detect temperature changes due to piping, however, the objective of these locations was to compare the different measurement techniques.

Figure 6: CPT cones with the attached DTS-cables. The cables were spliced together in order to make a loop. The heating cables were also looped.

3.5 Post-test excavation

After the experiments were finished the test field (Fig. 7) was excavated with the aim to find the pipe and measure its dimensions and route. Soil samples were taken and detailed geological descriptions of the subsurface were made. Before groundwater levels were levelled and excavation started, the exit hole was filled with levelling cement, a material that is used to level floors and hardens in water (Fig. 7).

Figure 7: Left: Overview of the excavated northern test site during excavation phase of the experiment. Right: The hardened exit hole in the field.

5. Discussion

Although the monitoring setup provides useful data, there are learning points and below we list the most important ones for each monitoring system:

- Piezometers: In the dense monitoring grid of segment C, primarily used to follow the path of the pipe, the initial measurements of hydraulic head had a rather large bandwidth of approximately 1 m. This was not expected as all piezometers in this segment were placed at the same level at the top of the tidal sand with an initial constant head across the test section. After the heads were incrementally raised by filling the infiltration tubes, it looks like a certain threshold, different for each piezometer, needed to be exceeded before the piezometer became in agreement with each other. As for now the exact reason for this phenomenon is unclear, but it's likely related to the presence of discrete clayey and silty layers in the tidal sand. This soil layering also caused the pipe to grow approximately 0.5 m lower than expected, below the layered top of the tidal sand. This layering and initial large bandwidth did not affect the usability of the measurements.

- Discharge: The digital discharge meters worked well, but only recorded discharge in one direction. Since the top of the infiltration tubes lies much higher than the container, water flows back to the container, but this negative discharge was not recorded. This can be solved by either using a discharge meter that can record discharge in both ways or install a one-way valve in the hose. For the outgoing discharge, it would be better to install a digital meter instead of an analogue one.
- ERT: the cables were positioned on a steep slope and hence the vertical resolution was different at the elevation where the pipe formed and especially higher up the slope the vertical resolution was too low at the elevation of the pipe to detect it. Next time it would be better to build a wider horizontal plateau next to the ditch, so that all cables lie at the same elevation
- DTS: The DTS-cables were very long (100's of meters) and this introduces increased levels of noise along the cables. It would be better to have more and shorter cables to have a better signal-to-noise ratio.
- It would have been an added value to register the temperature of the incoming and outflowing water, since water temperature affects both the ERT and DTS measurements. Since the tests were performed during a relatively warm summer period, the day-night temperature variations were quite large.

6. Conclusion

Full-scale piping experiments were conducted in the Hedwigepolder to determine the resistance of tidal sands to backward erosion piping. A multi monitoring approach was implemented to steer and adjust the experiment, determine when pipe growth initiated, follow the pipe as it progressed in the subsoil and to analyse the outcomes of the experiment. During construction of the piping experiment, extreme measures were taken to minimize the chance of leakage along the monitoring systems and the sheet piles. This paid off since no leakage was observed nor measured during both tests. The monitoring set up worked very well in general and the formation and growth of pipes have been recorded in detail. The monitoring results from the piezometers, ERT, and DTS are in agreement with each other on time and location of the backward erosion process. The results on location of the erosion pipe were validated in the post-test excavation where it was found that the measured path of the pipe matched perfectly with the location of the excavated pipe. Combination of these results give necessary, high-quality input to ultimately determine the resistance of tidal sands to backward erosion piping.

Acknowledgements

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