Chapter 24
Multiple Flow Slide Experiment in the Westerschelde Estuary, The Netherlands

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Abstract Flow slides form a major threat to flood defences along coastlines and riverbanks in the Netherlands. Due to the uncertainties with respect to the process in combination with the severity of the consequences and costs for prevention measures, there is a need to improve existing models for prediction or occurrence of, and damage by, flow slides. One of the key questions to be answered is whether slope failure by a flow slide is caused by up-slope migrating breaches or by static liquefaction. Although fundamentally different mechanisms, both result in a flowing sand-water mixture or turbidity current that eventually redeposits on a gentle slope. Over the last decades numerical models have been developed for both mechanisms, based on flume experiments. Upscaling these experiments is complex, as scaling rules are different for the various processes involved. To evaluate the failure mechanism on a natural scale, validate numerical models and test new technology to monitor the occurrence of flow slides, a large, controlled field test was performed.

The test site was situated in the Westerschelde estuary, in the south-western part of the Netherlands (Fig. 24.1). Several flow slides of 10^5–10^6 m^3 have occurred in this area in the past. In advance of the experiment, cone penetration tests and boreholes were performed on the test location. Pore water pressure sensors were installed in the sand. Triaxial tests and grain size distribution measurements were performed on collected soil samples.

The flow slides were initiated by means of steepening of the slope by dredging. Eventually several autonomously retrogressing flow slides were observed, running several hours over a maximum distance of about 100 m and resulting in a total displaced volume of several 10^3 m^3 of sand. During the test the evolution of the

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slope topography was monitored continuously by three multibeam survey vessels. This resulted in a full multibeam survey of the area almost every quarter of an hour and, assisted with other advanced instruments, enabling us to witness the early development of a flow slide.

24.1 Introduction

Flow slides are a mainly subaqueous type of landslide in sandy and silty slopes along coasts, estuaries and rivers, which transform steep slopes into more gentle slopes. Flow slides can result in much longer, partly subaerial retrogression lengths in banks or foreshore, compared to other geotechnical slope failure mechanisms and can cause significant damage when occurring in the vicinity of dikes, levees and river banks or hydraulic structures (Van den Ham et al. 2014). Risk indications are oversteepened slopes due to erosion at the toe or deposition at the top, lack of protection of the surface to waves or currents, presence of loosely packed and recently deposited fine sand mixed with silt or clay layers, extreme low water, heavy rainfall and human interventions like dredging.

There is a 200 year history of flow slide observations in the Netherlands, especially in the Schelde estuary (Wilderom 1979), however, the events were generally observed only after the event had occurred. This means that final geometries of flow slides are well known, but the actual development of the slides over time was seldom witnessed, let alone measured. Over 40 years, many research programmes have been focussed on flow slides worldwide and field observations were described (De Groot et al. 1987). Elements of the flow slide process, such as liquefaction (resulting in slope deformations in very loosely packed sand), or the retrogression of a steep wall in densely packed sand during dredging (breaching), have been reproduced in flume tests and described with numerical models (Van den Ham et al. 2014). However, even in large scale laboratory tests it has never been possible to reproduce the full process of a flow slide autonomously retrogressing into a sandy slope and depositing sand over a large distance as observed in the field.

Combining geotechnical investigations, probabilistic methods, statistics of characteristics of past flow slides and physics-based models, can help assess the probability of occurrence of, and damage due to a flow slide. For instance slope height and steepness, relative density and grain size distribution are generally considered as soil mechanical criteria for a flow slide hazard (Van Duinen et al. 2014). However, the actual nature of the failure mechanism, required for sound numerical modelling, has never been determined in full scale flow slides so far.

Two types of flow slide failure mechanisms are generally considered in literature: static liquefaction followed by a shear slide, and retrogressive breaching, generating a sustained turbidity current downslope of the location of initiation. Theoretically, both types of flow slide failure will result in a similar slope profile, although the evolution over time is very different. Static liquefaction is related to loosely packed sand layers in the subsurface that lose their strength instantaneously due to excess pore water pressure, whereas breaching is related to more densely packed fine sand layers at the soil-water interface and may slowly retrogress over several hours. Both result in a flowing sand-water mixture or turbidity current that eventually redeposits on a gentle slope.

In September 2014 a field test was performed in The Netherlands as part of the flood defence policy framework (Van den Ham et al. 2015). The main reasons to perform this field test to induce and monitor a flow slide were:

- Monitoring the 'birth' and development of a flow slide;
- Testing sensor and monitoring technology;
- Produce field-scale benchmark data for validation of numerical models.

24.2 Field Test Set-Up

The test site should have favourable natural conditions for flow slides, yet not carry a risk of damaging a dike or any other civil construction. Such a test site was found in the Westerschelde estuary on the slopes of the Plaat van Walsoorden tidal flat (see Fig. 24.1). The Westerschelde is a highly active morpho-dynamic system with

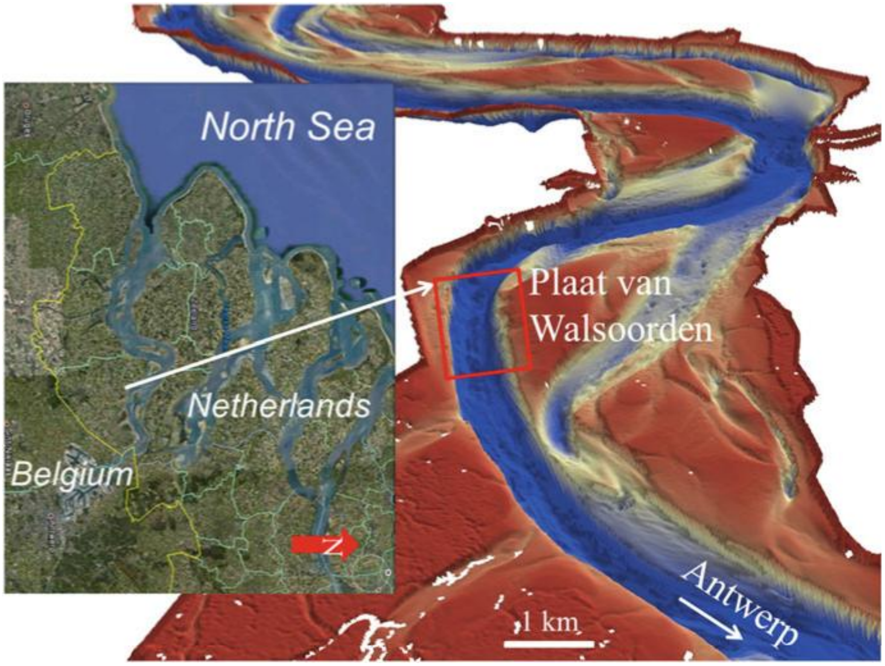

Fig. 24.1 Westerschelde estuary (inset shows map of location), seen downstream in western direction with test area indicated in *red square*, see Figs. 24.2 and 24.3

Fig. 24.2 View towards the South from Plaat van Walsoorden sand flat at location of 22nd of July 2014 flow slide. Inset aerial view. Scar of flow slide clearly visible. *Blue dot* is position of photo. Test area indicated by *red square*, see also Figs. 24.1 and 24.3

strong tidal currents (over 1.5 m/s), almost 5 m tidal range and an abundance of sediments, mainly fine sand, resulting in continuous sedimentation on the tidal flats. Natural flow slides are reported here once every couple of years.

Most recently a large flow slide (almost 1 Million m^3) occurred on 22nd of July 2014 (see Figs. 24.2 and 24.3), exactly at the originally proposed test site. After a week, on 28th of July 2014, further activity was observed on the shoreline, where gullies incised the tidal flat. Vertical slabs of sand were observed to gradually fall into the water. The duration of the event was at least several hours, but probably lasted for over 24 h (Van den Ham et al. 2015). The eroded sand was deposited into the shipping channel, leading to a decrease in the water depth of more than 5 m. As a result, the minimum navigation depth needed to be restored by dredging to the depth required by the Antwerp Port authorities. The bulk of the sand is still present after 6 months and will erode by reworking through tidal currents. The scarp that was created forms a natural bay (see Fig. 24.2) and is being filled in with loosely packed fine sediments. Given the occurrence of this recent failure, the test site was relocated 400 m to the east (see Fig. 24.3), where almost identical pre-failure conditions were found.

A soil investigation programme was performed at the site before and after the experiment. Before the test, borings were made, both regular and seismic cone penetration tests (CPT) were taken (Van Duinen et al. 2014) and geophysical

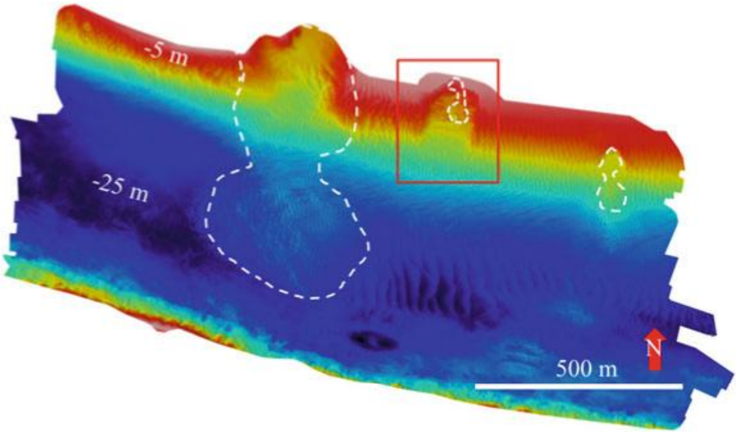

Fig. 24.3 Multibeam survey of complete test area (*red square* in Figs. 24.1 and 24.2): *left* flow slide 22nd of July 2014, *middle* dredging location (in *red square*, see Fig. 24.4), *right* dumping location

surveys (multibeam and sub-bottom profiling) were performed. Pore-water pressure meters were installed in the boreholes at about 5 m depth below the surface for continuous monitoring during the test. After the test vibrocore drillings and additional CPT's were taken. The soil investigation showed a generally uniform fine sand (d_{50} about 140 µm, d_{60}/d_{10} about 1.5) with low clay content and some loosely packed layers at about 10 m depth below the surface. In the tidal zone, clay layers and organic material were found.

To create the conditions for a flow slide in the available test period, continuous excavation of the slope was performed by dredging with a 750 m^3 trailing suction hopper. This aimed to steepen the slope over a certain height, approaching natural oversteepening by erosion as close as possible and to excavate the slope to a depth where loosely packed sand layers were expected, based on the CPT data. It was anticipated that the triggering mechanism would be the dredging itself, creating a small breach or shear slide or inducing liquefaction in a loosely packed sand layer. It was predicted from experience that a flow slide could develop spontaneously in fine sand if the slope steepness was at least 1:3 over a height of at least 5 m with a total slope height of at least 15 m. Continuous monitoring of the seabed with survey vessels was required during the dredging period, as the moment and location of initiation remained uncertain.

24.3 Applied Instrumentation

While the dredger progressively steepened the 1:12 slope over a width of about 100 m with the lower base at about -13 m, two vessels equipped with multibeam sensors for seabed mapping surveyed the area continuously, resulting in a combined

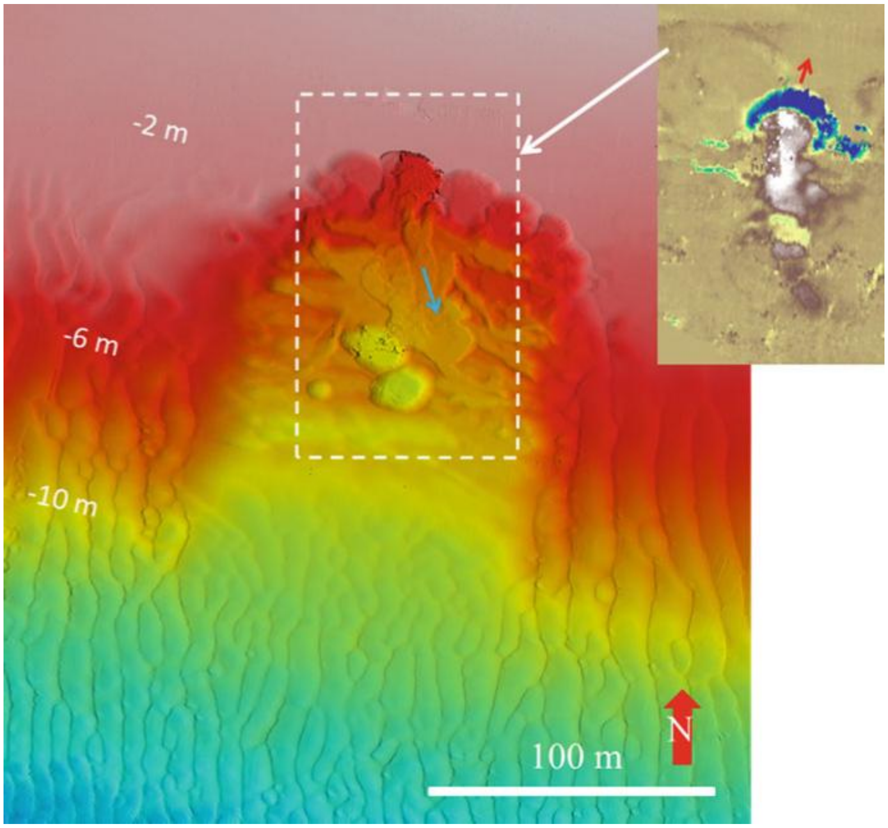

Fig. 24.4 Multibeam detail dredging area (*red square* in Fig. 24.3) at 1-10-2014-19:30 UTC with active retrogressing breach and turbidity current (see also Fig. 25.5). Inset differential plot with 15′ interval (*blue* = erosion, *yellow/white* = deposition)

bathymetry map about every 15 min (see Fig. 24.4). Near-real time differential bathymetry plots and cross-sections clearly showed the evolution of the profile (see Fig. 25.5). Since the dredger itself partly blocked the full view on the seabed, the dredged area could be surveyed in detail during the periods that the dredger disposed of the sand in two dedicated areas 300 m up- and downstream of the test site. These dump sites were also surveyed in detail (see Fig. 24.3). Moving sand ripples and dunes could be observed clearly. A third larger vessel served as the test control centre and moved slowly alongside the dredger. This third vessel was equipped with three Acoustic Doppler Current Profilers (ADCP) and three mutually differently oriented 2D imaging multibeam sonars to image the flow slide and monitor the resulting turbidity currents. The pore water pressure meters were registered with a 10 Hz sampling rate during the total test period and could be read on-line on the survey vessel and on a land-based control centre. In this way, the very beginning of the event could be detected. As soon as any flow slide activity

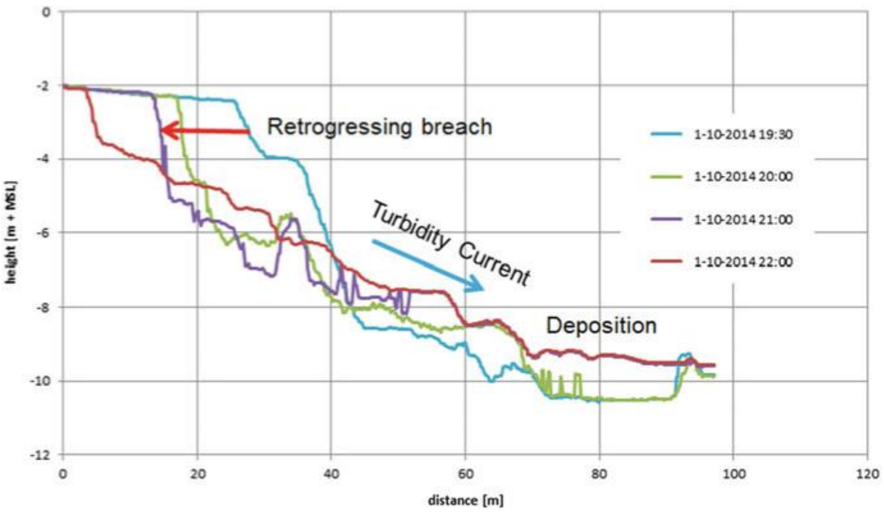

Fig. 25.5 Cross-section flow slide of Fig. 24.4. Breach retrogression speed about 20 m in 2 h. Active breach height 6–8 m. Flow length 60–100 m

was observed, the dredger was moved off the location, only to resume if any activity ceased.

At low tides the subaerial part of the flat was surveyed by a laser-altimeter installed on the survey vessel operating in the shallow water zone. On two survey vessels a low-frequency echo-sounder (sub-bottom profiler) was running, to be able to penetrate into the turbidity current and to image changes in subsurface conditions.

The larger survey vessel was equipped with three ADCP's of different frequencies (300, 600, 1200 kHz) to primarily measure the flow velocity of turbidity currents that could be triggered by a flow slide. The advantage of having three different frequencies is that it gives the possibility to not only measure the flow velocity, but also grain size and sediment concentration of the turbidity current, as these different frequencies respond differently to variation in grain sizes and concentrations (Kostaschuk et al. 2005). Three 2D imaging multibeam sonars were also installed on the other side of the survey vessel. These imaging sonars have the advantage of giving much higher resolution images of the turbidity currents in both plan and cross-section view, as demonstrated in (Hughes Clark et al. 2012).

24.4 Results and Conclusions

The test took place from 23rd of September until 2nd of October 2014 in generally calm weather conditions. After about 5 days the development of several steep, amphitheatre-shaped breaches started (see Fig. 24.4). These breaches retrogressed upslope above the dredged zone and generated turbidity currents that depleted quickly downslope (see Fig. 25.5). A number of these small flow slides retrogressed into the shallow water zone of the tidal flat, north to the dredging area. However, the flow slides did not retrogress far enough to appear on the sand flat above the low water zone, as was predicted and was seen a few months before, only a few hundred metres to the west. Nevertheless, in total seven flow slide events were observed in detail during the test, including a steep active breach of up to 6 m height and 30 m width, which retrogressed over a couple of hours and generated a turbidity current that ran out over about 100 m (Van den Ham et al. 2015). The autonomous retrogression speed of the active breaches was between 10 and 20 m/h. These observations are well in line with a breaching flow slide as defined in (Van den Ham et al. 2014) and explain the historical observations in the Netherlands (Van Duinen et al. 2014), but also fit with recently published field observations in Australia, where retrogressing breach events occur in sand beaches in the coastal area of Queensland (Beinssen et al. 2014). No positive or negative excess pore water pressures, that could be an indication of static liquefaction or breaching respectively, were measured, but since the flow slides did not get close to the sensors (over 200 m), it is still not clear if any excess pore water pressures occurred near the flow slide. Water levels and even ship waves were monitored accurately however.

It is still uncertain what condition is responsible for the upslope breaching process to continue or to stop, but it may be related to the downslope turbidity current. Since the slope of the dredged area was quite gentle (see Fig. 25.5), the sand may have settled quickly and blocked the flow downslope, resulting in a decrease of the breach height and halting of the flow. This will be further analysed by means of simulation of the observed flow slides with numerical models (Van den Ham et al. 2015) and more detailed data analysis.

It is likely that the flow slide of 22nd of July 2014 started in a similar way, with a small retrogressing breach, but it continued retrogressing for many hours into the subaerial zone of the tidal flat, finally resulting in the observed large amphitheatre shaped bay and depositing the eroded sand in the shipping channel. Seemingly, the turbidity current extended over a much longer distance (over 750 m). It may have been catalysed by the effects of draining of pore water at low tide in combination with flushing of fresh rain water in gullies (see Fig. 24.2), since, unlike our test, this natural flow slide was preceded by heavy rainfall.

The test has resulted in a large quantity of data that still has to be analysed in detail and will be published in subsequent papers, especially the data of pore water pressure meters, ADCP and multibeam imaging sonar, detailed soil investigations, future developments of the site and numerical analyses.

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