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Article

Watching the Beach Steadily Disappearing – the Evolution of Understanding of Retrogressive Breach Failures

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Abstract: Retrogressive breach failures or coastal flow slides occur naturally in the shoreface in fine sands near dynamic tidal channels or rivers. They sometimes retrogress into beaches, shoal margins and river banks where they can threaten infrastructure and cause severe coastal erosion and flood risk. Ever since the first reports were published in the Netherlands over a century ago, attempts have been made to understand the geo-mechanical mechanism of flow slides. In this paper we have established that events, observed during the active phase, are characterized by a slow and steady retrogression into the shoreline, often continuing for many hours. This can be explained by the breaching mechanism, as elaborated in this paper. Recently, further evidence has become available in the form of video footage of active events in Australia and elsewhere, often publicly posted on the internet. All these observations justify the new term 'retrogressive breach failure' (RBF event). The mechanism has been confirmed in small-scale flume tests and in a large-scale field experiment. With a better understanding of the geo-mechanical mechanism, current protection methods can be better understood and new defense strategies can be envisaged. In writing this paper, we hope that the coastal science and engineering communities will better recognize and understand these intriguing natural events.

Keywords: coastal erosion; beach morphodynamics; beach erosion; flow slide; slope instability; bank erosion; bank collapse; flood risk; breaching; dredging; liquefaction; submarine landslide; turbidity current; dilatancy.

1. Introduction

Retrogressive breach failures (RBF events), often more loosely named 'coastal flow slides' or just 'flow slides', are a type of underwater slope failure with a final very gentle run-out angle. This type of geohazard occurs naturally in fine sandy or silty subaqueous and water-saturated sediments on river and tidal channel banks, beaches and tidal flats. When they retrogress into the foreshore above water, their progress can be directly observed (Figure 1).

Figure 1. A large post-event RBF scar at Inskip Point, Australia, 24 September 2018. ABC News.

The failure mechanism itself, powered by gravity, is complex and involves a geo-mechanical component within the water-saturated sand skeleton and an associated hydrodynamic component which carries suspended sand grains away before they resettle [1, 2]. Sediment is released steadily over hours from the surface of an almost vertical, retrogressing submerged sand wall and mixes completely with ambient water to generate a sustained turbulent density current flowing downslope. As this current encounters more gentle slopes it loses momentum and grains of sand settle in layers on the seabed.

Flow slide events are seldom witnessed directly, since the active phase is short lived, they do not occur frequently and often remain completely submerged. They only sometimes retrogress into the beach or bank. Above the water table, in the generally moist unsaturated sand, blocks tear off and fall into the water as they are undermined by the retrogressing sand wall (Figure 2). This extra sand further boosts the density current. At termination, a characteristic amphitheater shaped head scar and a fan or tongue of newly deposited sand remains.

Figure 2. An active RBF even at Inskip Point, Queensland, Australia, 2011. Gympie Times / Jim Wyers / Youtube.

A diagnostic feature of an RBF event is the high, near vertical subaqueous sand wall which retrogresses steadily upslope during the active phase. This wall is called a 'breach' and the process 'breaching'. Negative pore pressure within the sand skeleton behind the breach causes suction which stiffens the deposit (strain hardening) and so resists a wall collapse.

Many historical descriptions of RBF events are available from the Netherlands. The term 'coastal flow slide' was introduced by Koppejan et al [3]; 'flow' in a hydrodynamic sense, as a sustained sediment current and 'slide' in a geotechnical sense, as a type of slope failure or instability in coastal settings. More recently events have been recognized and recorded on video during their active phase in Australia, France and again in the Netherlands. Events are not triggered by storms, waves or earth quakes; they are a category of geohazard which is associated more with coastal tidal channel or river bend erosion. They can also be associated with human activities in the submarine environment such as sand mining, dredging or sand deposition at sea. They occur at many locations worldwide.

RBF events are still poorly recognized and understood by the coastal science and engineering communities, even though they can pose considerable risks to coastal and submerged infrastructure and sometimes to public safety. Often, they are misdiagnosed as shear slides, liquefaction failures or simply as 'severe erosion'. Popular names given by the press are 'sinkhole', 'beach collapse', 'underwater landslide' or 'channel slump'. Larger events are newsworthy because of their spectacular nature and hence are often reported in the media. In recent decades, active events have been opportunistically videoed and posted on the internet and these have become a valuable source of new information.

Research into these events is on the crossroads of several scientific specialties (geology, geotechnical engineering, geomorphology and hydrodynamics), which has led to confusion and isolated research lines. In addition, reports over many years have been written in three languages (Dutch, German and English) so information sharing has been difficult.

In this paper we use the terms 'retrogressive breach failure' (RBF event) and 'coastal flow slide' as synonyms. This is not strictly true as the more general term 'flow slide' is sometimes used to describe any mass wasting and slope failure process other than shear or slip failures, such as (retrogressive) slumping, bank or beach collapses, earth and debris flows, earth quake induced liquefaction and landslides in sub-aerial muddy and water saturated sediments like tailings dam failures. Our preferred name is 'retrogressive breach failure' (RBF event) because it uniquely and unambiguously describes the failure mechanism.

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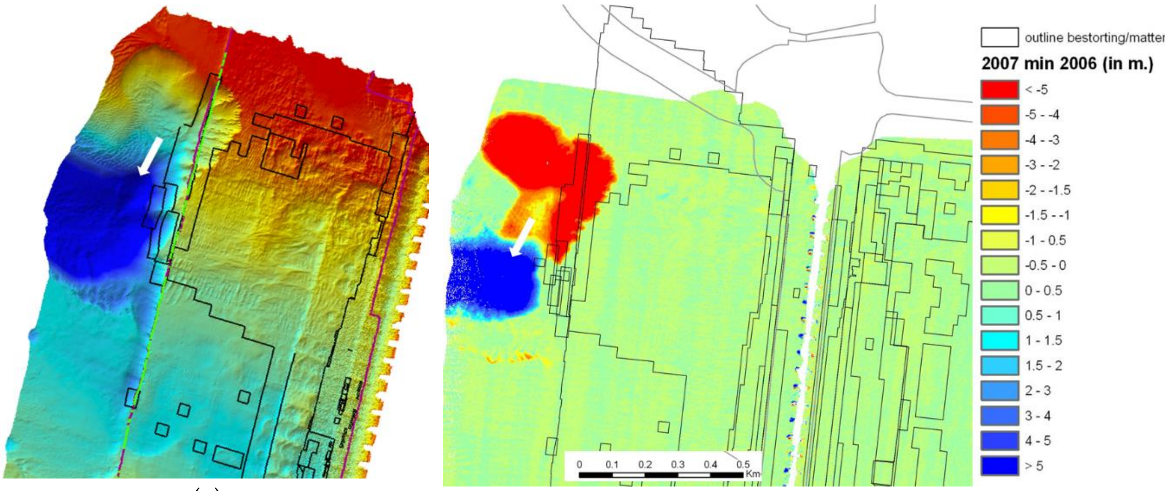
2. Historical Overview of the RBF phenomenon

2.1. History of the flow slide threat in the Netherlands

Zeeland, the southwestern delta region of the Netherlands, has suffered from the threat of flooding for centuries. Here, the loss of land and lives due to flow slides destroying dikes and flood protection works has been high. Many mitigation measures have been trialed but it is only since the completion of the Delta Works program in 1987 that dike collapses have been substantially overcome [4].

Post event flow slide damage profiles have been measured for almost two centuries [5]. The occurrence of flow slides can be easily recognized today in the typical hourglass shaped differential pre- and post-event bathymetry in ocean floor and coastal zone surveys. Figure 3 shows the erosion and deposition pattern of a completely subaqueous flow slide event in a steep channel bank eroded by tidal currents near the Eastern Scheldt Barrier [6, 7]. Van Dijk [8] assessed a large number of previously unnoticed subaqueous shoal margin collapses from historical bathymetry data of the Western Scheldt.



(**a**) (**b**)

Figure 3. (a) Large subaqueous flow slide near Eastern Scheldt Storm Surge Barrier, Netherlands (Roompot channel (in 3D bathymetry), 2007; (b) Differential bathymetry 2007-2006 with scale and color scheme. Red = erosion (<-5 m), blue = deposition (> 5 m). distance 500 m. Black lines indicate contours of bed protection, white arrows indicate flow slide direction. From [7].

De Bruin and Wilderom [9] collated historical information on the fate of polders related to dike failures and the struggle with the sea. We expand on this history since it supports present day observations and the modern understanding of flow slides. In the 18th and 19th centuries many polders in Zeeland, reclaimed in previous centuries from slowly aggrading marshlands, were lost again due to the gradually advancing tidal channels and flow slides attacking embankments and dikes. Adequate protection became harder and more expensive and often retreat (building a new sea dike behind an existing one, called 'inlaagdijk' in Dutch) was the only option. In those days heavily protected groynes ('fixed points') were built to redirect currents away from the shore, a strategy which failed since flow slides occurred in the unprotected areas between them (see Figure 4).

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Figure 4. Partial dike collapse following a flow slide event at Hoofdplaatpolder, Western Scheldt, Netherlands, 1964. Photo: Beeldbank Zeeland Zeeuwse Bibliotheek.

A hot spot for flow slides was the northern shore of the island Noord-Beveland where the strong tidal currents of the Eastern Scheldt approach the coast. Here, more than one kilometer of marshland was eroded within a century and finally the polder dikes came under direct threat [10]. A contemporary eye witness report documents the nature of the process of a dike collapse in 1864 [11] (translated from Dutch): *'At 5:30 in the morning of the 10th of March 1864 the headman of the polder laborers noticed that already 4.5 ha of the bank area was taken into the deep and the water level already penetrated 15 m into the toe of the dike. The slide extended in both eastern and western directions. Blocks of soil of 2 to 8 m^3 were torn off and tumbled down twisting into the emerging depth. The progression of this process diminished gradually and became less significant after 9 o'clock. Catastrophes like this usually happen at low tide. At 9.15 in the evening of 9th of March 1864 it was low tide and it should not remain unnoticed that one of the roommates of the headman started to hear from this time on and the whole night further, the sound of big blocks of soil falling into the water. Apparently, the event took place in the time between two successive ebb tides.'*

While various 19th century authors described flow slides in detail in Dutch, the phenomenon remained unknown to the mostly German and English speaking international scientific communities in those days. Koppejan [3] explains the 'Luctor et Emergo' (I struggle and emerge) history of Zeeland and introduced the English term 'coastal flow slide' for the first time. They describe a typical Zeeland flow slide of that time: *'A Zeeland flow slide is a gradual process where at intervals of a few minutes soil masses slide downward and flow out. Observation however is only possible after the disturbance has progressed to above the waterline and a steep wall has been formed here. Then at a place one or more meters landwards cracks appear about 10 m long, after which the soil mass in front starts to slide. In this way the slides go on, progressing about 50 m per hour. On the landward end of the slide the soil above and a little below the waterline may keep a very steep slope. The duration of the complete process varies from a few hours to a day.'*

This report again clearly describes the slow retrogressive nature of events, all very similar to present-day observations elsewhere in the world. Van Rummelen [12] calls the phenomenon 'coast' or 'dike falls' and indicates that they, not storm surges such as the disastrous 1953 flood event, are the major cause of the immense loss of land in the province of Zeeland over the past two centuries. The poor condition of many dikes due to the lack of maintenance during and after WWII also contributed to the problem.

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2.2. Terzaghi and the origin of the term 'zettingsvloeiing'

The concept of the flow slide mechanism as a slope instability dates back to the origins of modern geotechnical engineering. Friedrich Müller, a German engineer, studied the coastal engineering works in Zeeland in the late 19th century, in order to later apply this knowledge in the German province of Schleswig-Holstein. In his report, published in 1898 [13], he described the phenomenon of coastal bank failures, especially observed at the northern coast of the island of Noord-Beveland adjacent to the large Roompot channel of the Eastern Scheldt, referring to detailed descriptions written in Dutch. He named this type of bank failure in German 'Fälle' or 'Uferfälle' (bank falls), a translation of the original Dutch concept 'vallen' or 'oevervallen'. He distinguished this type of failure, characterized by a very gentle post event run-out slope and a typical amphitheater shaped head scar, from 'Abschiebungen' or ordinary shear failures.

Karl Terzaghi, known as the 'father' of modern science-based geotechnical engineering, studied the work of Müller, available to him in his native German. He categorized the described 'Sandfälle' (sand falls) in Zeeland as an example of a type of instability that he called 'Setzungsfließung' or subsidence induced liquefaction in his famous 1925 handbook 'Erdbaumechanik' [14]. In a classification of land slide mechanisms Terzaghi considered liquefaction as a type of slope failure in granular material, associated with subsidence, densification and saturation and hence reduction of effective stress, as in quick sand. In German, Setzungsfließung is still used in the context of a subaerial landslide (Rutschung) related to subsidence in unsaturated soil, for example after heavy rainwater infiltration resulting in saturation, excess pore water pressure (liquefaction) and associated sudden collapse, as recently described by Gudehus et al [15].

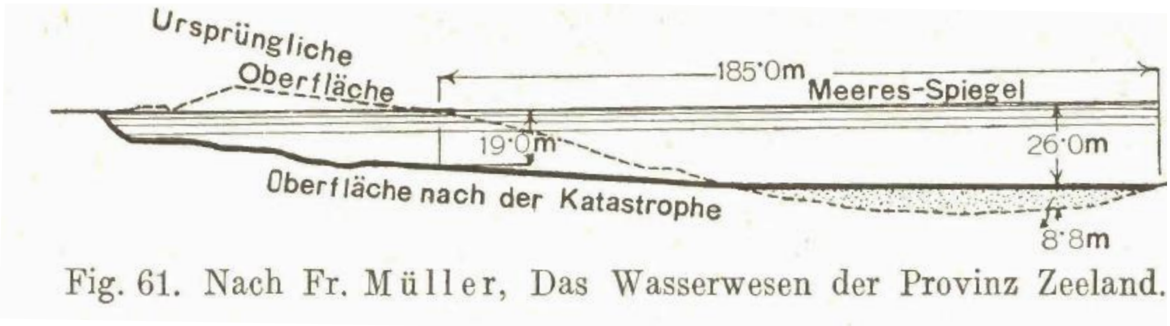

Figure 5. Cross section of a flow slide from Terzaghi [14]; later published in English [16], referring to Fr. Müller [13].

Terzaghi included a typical profile of what he considered to be a liquefaction flow slide (Figure 5) referring to Müller [13]. According to his description it was located at Noord-Beveland, a former island in Zeeland, but he did not specify the exact location or date of the event. Examining more closely Müller's original diagrams ('Tafeln', which are not included in recent reprints of the book) in the Middelburg library we noticed that Terzaghi's Figure 5 actually shows the cross section of a large flow slide and dike collapse event that took place on 11th August 1881 at the Oud Noord-Bevelandse Polder, on the northern coast of the island, see Figure 6.

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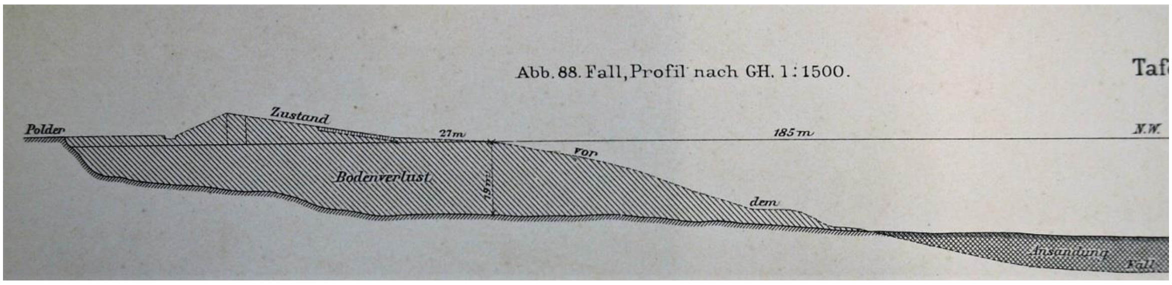

Figure 6. Cross section of 1881 flow slide at Oud Noord-Beveland Polder, Zeeland. Original figure of Fr. Müller [13]. Compare Figure 5. For location see maps in Figure 7.

In Figure 6 and Figure 7(a) the original figures of Müller are shown. Figure 7(b) shows the reconstructed location of this event on a recent Google Earth image. As can be seen in Figure 7 the shape of the northern coastline of Noord-Beveland today still shows the remains of lost dikes. The dikes were never repaired and the former polders ('inlagen') have been permanently lost, leaving here a wetland with salt marshes, today called the Oesterput. The encroachment of the Eastern Scheldt has been arrested only after the completion of the Delta works in 1987.

(**a**) (**b**)

Figure 7. (a) Left: Map of 1881 flow slide (Uferfall) at Oud Noord-Beveland Polder, Zeeland. Original figure of Müller [13]. For cross section G-H see Figure 6. (b) Present day image of 1881 flow slide site with remains of dikes and a salt marsh, now called the Oesterput. Photo Google Earth, 2018.

Terzaghi cites a geological report which may have stated that the event took place with '*catastrophic speed*' and was announced by a '*muffled, thunder like roar*'. The description in Müller may have given Terzaghi the impression of a rapid landslide event like a rock- or mud avalanche ('Bergsturz' or 'Erdrutschung' in German), common in mountainous landscapes. The short time and high speed reported by Terzaghi for this flow slide event however was definitely not reported in the original eye witness descriptions. In the English version of his handbook 'Soil Mechanics in Engineering Practice' [16], Terzaghi writes: '*Slides can occur only in loose saturated sands. They are caused by spontaneous liquefaction. The disturbance required to release a sand slide can be produced either by a shock or by a rapid change in the position of the water table. Once the movement has started, the sand flows as if it were a liquid and does not stop until the slope angle becomes smaller than 10° (about 1:6). The sand slides along the coast of the island of Zeeland in Holland belong in this category. The coast is located on a thick stratum of fine quartz sand that consists of rounded grains. The slope of the beach is only 15° (about 1:4). Yet, once every*

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few decades after exceptionally high spring tides, the structure of the sand breaks down beneath a short section of the coastal belt. The sand flows out and spreads with great speed in a fan-shaped sheet over the bottom of the adjacent body of water.‘ (refers to Figure 5).

The 1864 eye witness report [11] states that the event took place over about 12 hours and was characterized by slow retrogression. The sound that could be heard all night came from blocks of sand falling into the water after the event arrived at the shoreline. A ‘catastrophic’ or ‘great speed’ is not mentioned by Müller, nor in the older original Dutch publications.

We conclude that the process was not like a landslide or an avalanche taking place in only minutes and the sound was not related to the speed of the process. Terzaghi had never read the original publications in Dutch and never personally witnessed the phenomenon in Zeeland, so he incorrectly diagnosed the flow slides or ‘Sandfälle’ in Zeeland to be a type of rapid liquefaction landslide he called ‘Setzungsfließung’. His hypothesis is not supported by the original publication of Müller to which he refers. Terzaghi’s explanation was adopted in 1940 by Keverling Buisman, the founder of the Soil Mechanics Laboratory in the Netherlands in his handbook [17]. He introduced the Dutch term ‘zettingsvloeiing’ as a translation of the German word ‘Setzungsfließung’. Following Terzaghi, he supported the hypothesis of the liquefaction mechanism as applied to the flow slides in Zeeland but did not further elaborate on this concept in his book.

2.3. Liquefaction or breaching?

In the Dutch water management magazine OTAR in 1943, Barentsen [18], after having read Keverling Buisman’s book disputed the mechanism of liquefaction for the observed coastal bank failures, since it was not in agreement with the observed slow retrogression. Several very large flow slides occurred during WWII. He proposed that a flow slide would be better described by ‘a number of successive seepage slides’ (‘kwelafschuivingen’ in Dutch), coming close to the concept of RBF events. A long debate in OTAR followed.

After the 1953 floods, the Delta program was started and in the 1970’s and 1980’s research by the Department of Public Works and Water Management in the Netherlands focused on ways to prevent flow slides on the bank protection works of the sea dikes in Zeeland and the Storm Surge Barrier foundations in the Eastern Scheldt mouth. At that time, the flow slide mechanism was generally believed to be static liquefaction and despite Barentsen’s arguments the term ‘zettingsvloeiing’ came into use as a synonym for coastal flow slides [19, 21]. Research for the Delta works in large scale flume tests in the 1970’s and later, focused on rapid liquefaction failures and prevention measures in loosely packed sands [21, 22, 23]. Flow slides like those observed in Zeeland however, have never been demonstrated in flume tests.

In the early 1970’s a research program was initiated in the Netherlands on dredging processes [24, 25]. One of the first observations with suction in fine, densely packed saturated sand in small scale flume tests was the slow retrogressive erosion of a steep, often vertical sand wall or ‘breach’ which continued autonomously even after suction was discontinued (see Figure 14). Van Os described the effect of sand dilatancy on slope behaviour that explains breaching [26, 27]. Boehmer conducted a field experiment to define the effect of flow slide and sediment gravity flow on dredged under water slopes [28]. Van den Berg applied breaching on geological deposits [29] and De Groot introduced the distinction between a liquefaction flow slide (‘verwekingsvloeiing’ in Dutch) and a breach flow slide (‘bresvloeiing’) for dike safety assessment [30]. He used ‘zettingsvloeiing’ as a more general term for both types of flow slide. In the Netherlands, flow slide risk research today is part of dike safety assessment required by law. Flow slides are presently assumed to be either breaching or liquefaction failures [31]. However, post-event bathymetry measurements do not reveal conclusive information on the geo-mechanical failure mechanism involved. Only ‘live’ observations of active events can prove if the process is slow (breaching continuing for hours) or fast (slides or liquefaction failures taking place in only minutes).

Terzaghi’s 1925 hypothesis and successive Dutch research also influenced thinking in other parts of the world. Failures in the Mississippi river banks, USA, the Fraser River near Vancouver, Canada [32] and Jamuna River, India [33] were attributed to static liquefaction, as were many events which

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occurred during dredging, sand mining and sand placement [34, 35]. Sands in which flow slides have been observed are generally not very densely packed but often still exhibit dilative behavior. Wanatowski [36] indicates that several well documented slope failure events like Fort Peck Dam, Mississippi river banks and the Canadian arctic sand berms previously diagnosed as liquefaction occurred in dilative sands. The 'bowl-shaped crests' in the Nerlerk sand berm failures as described by Sladen et al [34] may equally have resulted from RBF events.

2.4. Retrogressive bank failures in the Mississippi River, USA

After a disastrous flood in 1927 in the Lower Mississippi River area, the US Army Corps of Engineers Waterways Experiment Station (WES) was assigned responsibility for research into river bank failures (called 'bank cavings') that led to levee damage and flooding. Many river bank instabilities or 'flow failures' had been noticed here although again, very few were directly witnessed during the active phase. In the 1950's much effort was spent on determining an empirical method to assess 'liquefaction flow failure' susceptibility, based on geotechnical investigations and data of previously observed river bank failures [37].

In 1985 in the Lower Mississippi, New Orleans, a large flow slide known as the Celotex failure occurred. It resulted in damage to the levee [38] and extensive flooding. Dunbar et al [39] present an overview of the research on river embankments and levee safety and risk prediction of flow slides in the USA. Typical post-event morphology was the 'hour glass' shape in plan-view and the gentle runout gradient of about 8° (about 1:7). The Celotex flow slide occurred during low water, opposite to previously observed flow slides in river point bar deposits. The initiation was attributed to scouring near the toe, which occurs mainly during high water. It was noted that the retrogression length of failure related to the thickness of the various sand layers and overburden of clay layers. Torrey et al [38] reported the dense (dilative) nature of sand deposits in the lower Mississippi from CPT tests, which Dutch geotechnical engineers involved in the research found remarkable since it excluded static liquefaction as the failure mechanism.

Padfield, a PhD student from Cambridge University studying bank failures in the Thames and Mississippi River, supervised by USACE, presented a new understanding for the Mississippi flow slides applicable to dense (dilative) sands [40]. He concluded that rather than liquefaction in loose sands, flow slides may be characterized by retrogressive erosion in dense sands, generating a sustained suspended sand flow. Witness reports of active failures at Montz in 1973 and Free Negro Point in 1949 [41], say that the retrogression process lasted over twenty hours, which is a clear indication of retrogressive breaching in dilatant sand. During a visit of members of USACE to Van Os and Delft Hydraulics, Padfield was acquainted with some results of Dutch dredging research related to the dilatant behavior of sands [27, 26]. He applied this theory to retrogressive bank failures as observed in the USA. Later, small-scale flume tests as shown in Delft were performed by students at Cambridge University to show the stable retrogression of a steep face. Padfield also described the flow of sand along a gentle run-out angle but assumed a viscous Bagnold-type of partially liquefied flow rather than a turbulent density current. Torrey confirmed the slow retrogressive nature of Mississippi failure events [38], with the 'over-steepened face' of a submerged sand wall (the 'breach'), where negative pore pressures develop due to dilatancy of the sand skeleton. We conclude now that the Mississippi bank failures can be accurately interpreted and classified as RBF events.

3. Recent case studies of RBF events from around the world

The three authors of this paper have each experienced and reported on coastal flow slides in their respective countries. Examples are discussed below. In addition, recent examples of active events from other parts of the world as reported in the media and on the internet, will be described. Table 1 at the end of this section gives a summary of RBF events worldwide, assessed in this study, showing date, location coordinates and internet address of video footage if available.

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3.1. RBF events in Queensland, Australia

Rapid beach collapse events have been observed at several locations on Australia's east coast for over a century. In recent decades many have been recorded on video and some subsequently posted on the internet (Figure 1, Figure 2). Big events receive wide media publicity and are often referred to in the popular press as 'sinkholes' or 'underwater landslides'.

All Australian events observed during the active phase have been characterized by a breaching sand wall up to 7 m high (measured with a weighted line) retrogressing upslope slowly onto the beach at between 0.3 to 0.8 meters per minute (5-13 mm/s). At the shore above the water table moist sand shearing off in large blocks is a common feature and generates a characteristic 'slapping' sound. While not all events are witnessed during their active phase, post-event morphology always displays a typical amphitheater shaped head scar. If post-event bathymetric images are available [1, 42], a tongue or fan of sand deposited offshore can usually be identified.

(**a**) (**b**)

Figure 8. (a) Satellite image of an RBF crater at Amity Point captured on 18th August 2014 (Google Earth) (b) Image of this active event reaching the beach on 17th August 2014 viewed to the South, from [1].

Prior to 2014, the geo-mechanical mechanisms driving these erosion events remained unclear to local coastal scientists and engineers. They were usually misdiagnosed as shear failures of an over-steep channel margin. Following a recent concerted awareness campaign, most local professionals now recognize these events as 'retrogressive breach failures' (RBF events) after Beinssen [1], (Figure 8(b). Several 'hotspots' can be identified, including Amity Point on the NW point of North Stradbroke Island, Figure 8(a), which is a low spit of Holocene deposited fine silica sand. A deep (-22m) tidal channel runs close to the shoreline. Frequent RBF events have been occurring here for over a century and often collapse the beach and sometimes penetrate into vegetation further inland (Figure 9).

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Figure 9. Damage after an RBF event at Amity Point (2017), including slumping of the 'flow slide barrier'. Note that heavy foam is a common feature of events at this site. Photo: Beinssen.

Local historian Thomas Welsby wrote in 1913 [43] of his observations made many years earlier; '*I have known large slips at Amity carry away tons of sand and many a tea-tree familiar to my boating companions has toppled and fallen into the waters of the Bay*'.

Events still occur frequently here. One specific site was monitored for 26 months during which 52 events were recorded [2], so on average an event reached the shoreline every two weeks. After each event, a crater is left which is subsequently filled with sand transported to the site in the littoral drift to set conditions for the next event. Since the water is usually very clear at Amity Point, the shear failure of wedges of sand under the water table has also been clearly observed in natural RBF events as they reach the shoreline. This is known as 'dual mode failure' [44, 45].

The trigger which starts these events is not known and will be the subject of further research in Australia. One event in January 2011 coincided exactly with the arrival of a silt laden flood plume from the Brisbane River with substantially increased local tidal velocity and so suggests that the initial breach was started on this occasion by current scour. Another event coincided with the draining of a lake after heavy rain indicating that submarine groundwater discharge may have been the trigger.

3.2. Plaat van Walsoorden Flood Control Test, Netherlands

In 2014, the development of a flow slide was extensively monitored in a large-scale field experiment in the Netherlands, which tracked the progress of an artificially triggered breach [46,47]. A very large flow slide or shoal margin collapse occurred in a sand shoal in the Western Scheldt 22nd July 2014 [48, 49, 50], just weeks before a field experiment was scheduled at the site to assess flow slide risk, proving the vulnerability of the site to flow slides. Consequently, the test site was relocated a few hundred meters to the east where conditions were almost identical.

Extensive pre- and post-geotechnical and bathymetric investigations were performed. Breach failures were initiated by dredging and multiple flow slides with over 6-meter-high breaches and associated density currents were detected for a few hours on multibeam images (Figure 10). On this occasion, retrogression stopped near the low tide mark and the volume of displaced sand remained small. The test conclusively demonstrated that these flow slides were characterized by slow

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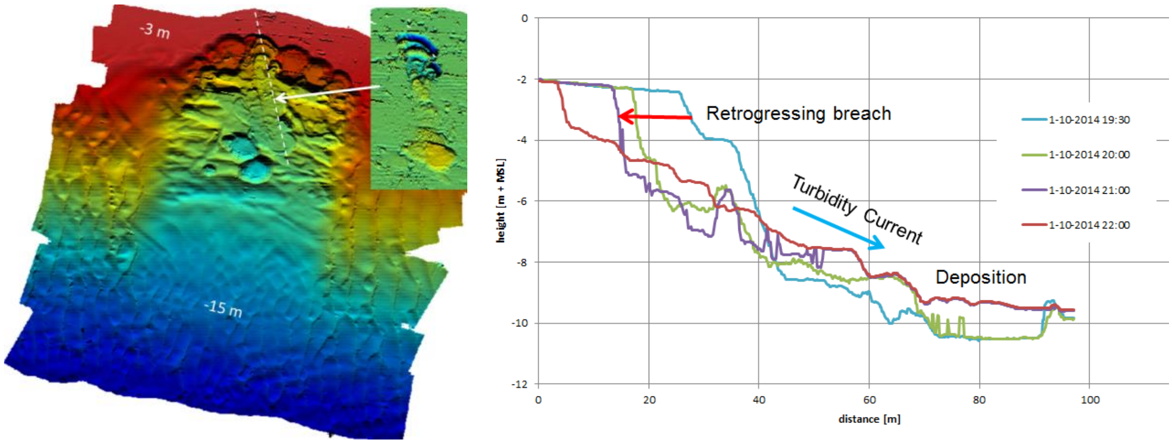
retrogressive breaching (indicating that the sand exhibited dilatant behavior despite its young marine origin) and that the sand was conveyed away from the breach for some distance. However, why these breaches did not retrogress further and grow as large as the earlier natural event remains unclear.



(a) (b)

Figure 10. Flood Control flow slide test in 2014. (a) Bathymetry of dredging area (100x100 m) with small flow slide scars (below low-water line). Inserted: Differential bathymetry (blue=erosion, yellow=deposition). (b) Cross section along dashed line in (a) showing breach retrogression for 2.5 hours, sand deposition and breach height of about 6 m [46].

3.3. Ameland Southwest beach, Netherlands

The Wadden Sea in the north of the Netherlands is characterized by tidal inlets between barrier islands. The Borndiep tidal inlet approaches the southwest coast of Ameland island. It consists of sand and steep, firm clay layers to a depth of -20 m. The coast is defended by revetments and groynes. At one specific site (Figure 11), adjacent to a groyne, the revetment turned out to be damaged and here periodical beach collapse events ('strandvallen' in Dutch) have occurred [51].

In 1979 a tragic accident took place at this site when a rescue boat was launched for an emergency and all ten horses pulling the trailer over the beach to the seafront suddenly fell into deep water and drowned, probably due to an RBF event. In 2017 and 2019 beach collapse events again occurred at this site and were captured on video for the first time in the Netherlands. This footage displays the slow retrogressive nature of the collapses and the steep wall with sliding blocks, typical for RBF events.

(**a**) (**b**)

Figure 11. Beach collapse or RBF event at Ameland Island Southwest, Netherlands, near coastal protection groyne, 2017. Photo (a): J. Kanger-Wijnberg (b): Staatsbosbeheer.

3.4. Coastal erosion and associated RBF events at Cap Ferret, France

The Bassin d'Arcachon is a triangular-shaped lagoon, about 174 km² in area. This area is completely submerged during high tides and about 65% emerges at lowest tides only. Inside the bay, deeper channels convey high tide water towards an entrance which is about 4km wide and about 10 m deep, oriented north-south. Strong tidal currents flow through the entrance. Cap Ferret is a natural sand spit dividing the outlet of the Bassin d'Arcachon from the Atlantic Ocean in France. It is constituted of fine silica sand (150 – 200 µm) and its surface is largely covered by woods, municipal facilities and residential houses [52].

The highest flow velocities are observed along the south-eastern side of Cap Ferret. This shoreline has faced recurrent and hazardous slumping associated with ongoing coastal erosion. The coast on the inner part of the lagoon is partly protected from oceanic swell but several locations along the spit have been damaged in the past by sudden beach or rip-rap collapse events. In particular, the southernmost beach is subject to beach collapses. Figure 12 shows a recent example of an active medium sized event (about 10 m in diameter). The coastal morphodynamical process is characterized by a cycle of RBF events followed by rapid infilling of sand carried to the site by the littoral drift. The site is analogous to Amity Point and Ameland described in the previous sections in its geographical setting, frequency and size of RBF events and the presence of a nearby riprap protection construction.

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Figure 12. Active flow slide or RBF event at Cap Ferret, 8th February 2018. For safety, the beach was closed for bathers. Photo: Denis Salle, France 3 Nouvelle-Aquitaine, 2019.

Considering the potential danger to the public of a beach collapse, a program to monitor the beach using time lapse photography was carried out over a 17-month period in 2015 and 2016. Many RBF events were recorded, and the beach dynamics of this site was described. The diameters of RBF scars range from 1-5 m to about 25-30 m. It was found that the events that emerged above water are part of a larger number of partly or entirely subaqueous events.

Time intervals between events also cover a large range of values, from one day to several weeks. Beach recovery can be very rapid here, nourished with sand brought by littoral drift. It generally comes along with a redistribution of sand on a large coastal area surrounding the scar and induces a significant modification of the beach shape, showing that a larger area is influenced by morphodynamical processes here than just within the RBF scar itself.

Figure 13 shows another event at Cap Ferret, seen over a timestamped sequence of static views. It shows a regression speed of about 10 meters over half an hour or about 5 mm/s.

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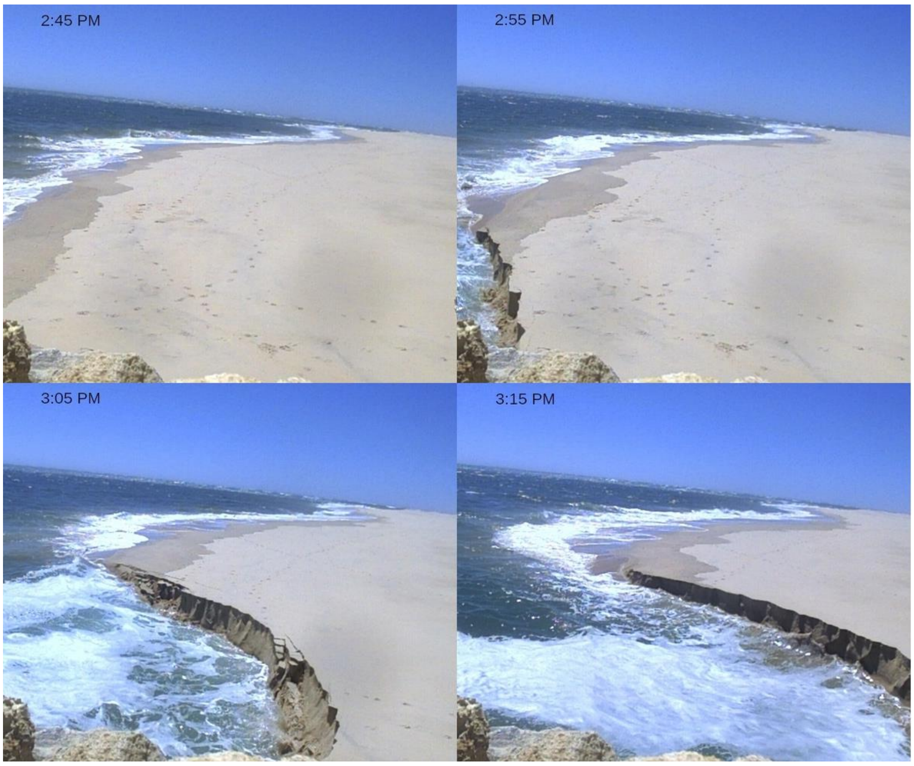

Figure 13. Beach collapse at Cap Ferret, dated June 2016. Time stamps 2:45, 2:55, 3:05 and 3:15 PM. Photo: Nédélec.

3.5. Internet video search results

Very few coastal experts have actually witnessed and reported an active flow slide process. Van den Berg [29] for the first time described a typical RBF event with sequential photographs that took place on a sandy shoal in the Dutch Wadden Sea in 1983.

More recently new direct observational field evidence including videos of RBF events in beaches or banks has become available. Today with cell phone cameras and social media, rare events can be captured and shared, although observers are usually not aware of the geo-mechanical processes they are witnessing. Video evidence is particularly useful since it provides an understanding of the time scales. Using key words such as ‘sinkhole’, ‘beach liquefaction’, ‘beach collapse’, ‘sand collapse’, ‘disappearing beach’ or simply ‘beach erosion’, descriptions and video footage can be found on the internet, usually with related information such as location, timing and local engineering interpretations. Searching in other languages also often reveals events which can be interpreted as RBF events; in Dutch ‘strandval’, in French ‘effondrement de plage’ and in German ‘Einsturz’ or ’Uferrutschung’.

The first video of a large beach collapse that we now identify as an RBF event, was recorded with a cell phone at Inskip Point, Australia in 2011 and posted on the internet (Figure 2). This event was also reported by the TEN NEWS network. Large events at this location again took place and were recorded and posted in 2015 (with some damage to a camping area) and most recently 2018 (Figure 1). We found more examples of internet published footage of active events. In the USA, an event at Fort Popham, MN was recorded in 2011 and another at North Wildwood, NJ, in 2012 where on a previous occasion, reported by NBC10 Philadelphia, three bathers fell into the water and where dragged into the tidal current and drowned. Another event occurred in the Philippines at Candelaria, Zambales in 2013, reported by ANC news. Videos clearly reveal the slow retrogressive nature of the above RBF events, the sliding of blocks of sand and the steep scar. Typical RBF ‘foot prints’ often can be identified on Google Earth satellite images, Figure 8(a).

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443 **Table 1.** Overview of RBF events with date, characteristic dimensions, location and video internet URL.

Location	Year / date	Volume	Channel depth	Retrogression length	Latitude	Longitude	Video internet URL
		1000 m³	m + MSL	m	°	°	
Amity Point, QL, Australia	17-8-2014		-14	210	27° 23′35″ S	153° 26′23″E	
Amity Point, QL, Australia	2017				27° 23′35″ S	153° 26′23″E	
Inskip Point, QL, Australia	2005				25° 48′31″S	153° 03′38″E	https://www.youtube.com/watch?v=ILptlF7P6LI
Inskip Point, QL, Australia	26-6-2011				25° 48′31″S	153° 03′38″E	https://www.youtube.com/watch?v=I9ieYvYdvdw
Inskip Point, QL, Australia	26-9-2015		-22	330	25°48'32.96"S	153° 3'39.93"E	https://www.brisbanetimes.com.au/national/queensland/car-and-caravan-in-sinkhole-at-qld-beach-20150927-gjvq44.html
Inskip Point, QL, Australia	2-4-2016			300	25° 48′31″S	153° 03′38″E	https://www.youtube.com/watch?time_continue=12&v=cqGi2S69XLs
Inskip Point, QL, Australia	24-9-2018				25°48'31.11"S	153° 3'4.90"E	https://www.abc.net.au/news/2018-09-24/inskip-point-beach-collapses-into-the-ocean/10297840
Jumpinpin, NSW, Australia	24-11-2016		-20	300	27°43'43.50"S	153°26'57.52"E	https://globalnews.ca/video/2363621/sinkhole-as-big-as-a-football-field-opens-up-on-australian-beach/
Pelican, NSW, Australia	8-2-2016		-6	90	33° 04′ 06″S	151° 38′ 30″E	
Cap Ferret, Bassin d'Arcachon, France	8-2-2018		-22	330	44°37'17.32"N	1°14'44.49"W	https://france3-regions.francetvinfo.fr/nouvelle-aquitaine/gironde/arcachon/video-cap-ferret-littoral-interdit-face-au-risque-effondrement-1621487.html
Ameland SW, Netherlands	10-3-2017	12	-14	210	53°25'56.63"N	5°37'34.32"E	
Ameland SW, Netherlands	3-11-2017				53°25'56.63"N	5°37'34.32"E	https://www.youtube.com/watch?v=zKKvYitUsj8
Ameland SW, Netherlands	11-11-2017				53°25'56.63"N	5°37'34.32"E	https://www.youtube.com/watch?v=ZQfbTkmJg8s
Ameland SW, Netherlands	16-11-2017				53°25'56.63"N	5°37'34.32"E	https://www.youtube.com/watch?v=rD6tAmoxyeE
Ameland SW, Netherlands	27-1-2019				53°25'48.20"N	5°37'47.82"E	https://www.youtube.com/watch?v=vubgtLRbkho

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Ameland SW, Netherlands	8-3-2019				53°25'56.63"N	5°37'34.32"E	https://www.youtube.com/watch?v=vZERSlpQpdg
Oost-Vlieland, Netherlands	1-2-2006	18	-20	300	53°17'43.05"N	5° 5'34.83"E	
Eastern Scheldt Barrier, Netherlands	2007	850	-30	450	51°36'59.26"N	3°40'31.26"E	
Hoofdplaatpolder, Netherlands	10-6-1964		-30	208	51°22'51.39"N	3°37'3.32"E	
Oud Noord-Bevelandse Polder, Neth.	11-8-1881		-34	185	51°36'18.30"N	3°47'53.01"E	
Plaat van Ossenisse, Netherlands	2018	1100	-37	555	51°25'34.42"N	4°0'12.74"E	
Plaat van Walsoorden, Netherlands	1-10-2014	60	-6	90	51°22'38.02"N	4° 4'5.45"E	
Plaat van Walsoorden, Netherlands	22-7-2014	850	-25	375	51°22'42.10"N	4° 4'1.70"E	
Vlietepolder, Netherlands	10-3-1864	195	-24	320	51°36'2.03"N	3°45'27.86"E	
Vlietepolder, Netherlands	28-10-1886	540	-40	380	51°35'55.53"N	3°44'57.32"E	
Candelaria, Zambales, Philippines	23-6-2013				15°38'31.99"N	119°55'27.54"E	https://www.youtube.com/watch?v=k736TXjVij0
Celotex, LA, USA	30-7-1985	230	-36	540	29°54'14.99"N	90°7'0.59"W	
Free Negro Point, LA, USA	24-3-1949				30°30'48.98"N	91°12'43.24"W	
Montz, LA, USA	1973				30° 0'13.48"N	90°27'57.58"W	
Fort Popham, MN, USA	18-3-2011				43°45'11.44"N	69°47'0.23"W	https://www.youtube.com/watch?v=BEN5SR0yXfU
North Wildwood, NJ, USA	19-9-2012				39° 0'39.02"N	74°47'29.92"W	https://www.nbcphiladelphia.com/news/local/Severe-Beach-Erosion-in-North-Wildwood-170430206.html
Seabrook Island, SC, USA	15-7-2016				32°33'34.99"N	80°10'41.30"W	
Nerlerk Berm, Canada	1983				70° 6'26.09"N	134°51'3.54"W	

Jamuna river, India	1999				24°23'50.41"N	89°45'46.24"E	
Fraser river, Canada	1985				49° 7'28.42"N	123°12'37.87"W	

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4. The modern understanding of Retrogressive Breach Failures (RBF)

4.1. The breaching mechanism

Retrogressive breaching requires sand to be relatively tightly packed, so that it will dilate when subjected to shear, as discovered in Dutch dredging research [24, 26, 27]. The 'shear dilatancy effect' requires sand grains to lever themselves apart thus increasing the void ratio and causing a lowering of pore water pressure relative to ambient pressure. It is this 'underpressure' which causes suction and stiffens the deposit (strain hardening), allowing a steep, almost vertical sand slope to temporarily exist. Figure 14 (lower layer) shows a breach face in a small-scale suction test [46]. Shear dilatancy cannot occur in loosely packed sand; instead the sand grains slide along the natural friction angle (Figure 14, upper layer). Retrogressing sand walls were also observed in the field during suction dredging and were named 'Aktive Bresche' [53], active banks [54] or breaches [25, 55]. In sand mining pits the process can unintentionally result in bank collapses (RBF events).

Van den Berg [29] introduced breaching of sand as a natural slope failure mechanism in deep sea sediments, generating supercritical turbidity currents in submarine canyons , to explain fine-layered geological deposits (turbidites). Van Rhee and Weij [56, 57] suggested 'unstable breaching' to be distinguished from stable breaching as is used in dredging practice.

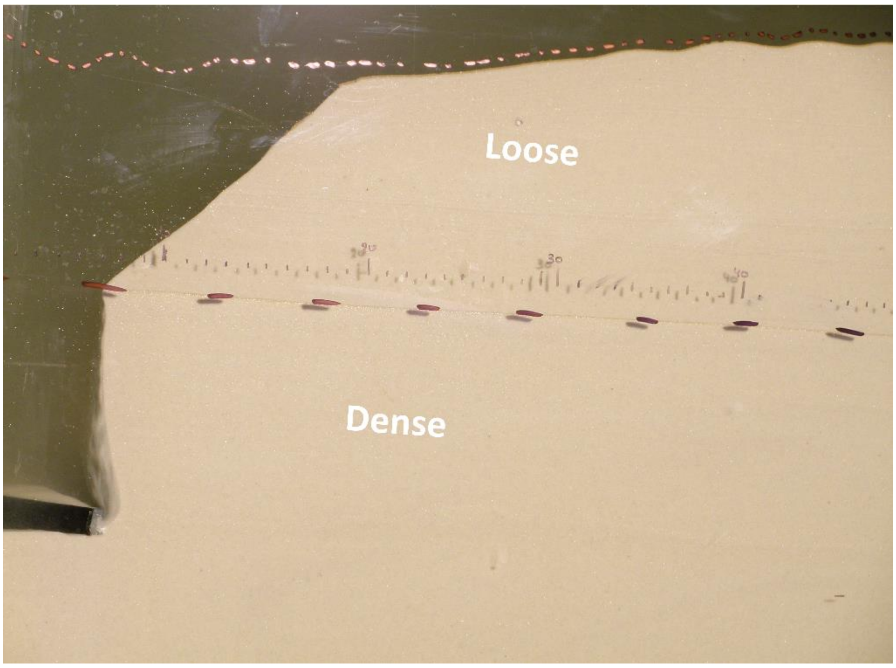

Figure 14. Small-scale breaching test in fine sand. Upper layer loosely packed, lower layer densely packed fine sand (d_{50} = 120 μm, slope height 40 cm). Retrogression velocity 1-2 mm/s. The sand produced by the breach is removed by suction (left) [46]. Photo: M. Busink.

Although porewater underpressures generated by the dilatant shearing of sand stabilizes the sand wall, it may still fail by shearing from time to time. Wedges of sand shear off the breach and fall, mixing with water and boosting the density current. A new breach surface is then exposed which again sheds sand grains individually so that the mechanism switches back and forth between the two failure modes. Van Rhee and Bezuijen [55] reported this from flume tank tests and You et al [44, 45] applied the name 'dual mode failure'.

4.2. The density current

Another prerequisite for sustained active breaching is that the sand raining or sliding from the sand wall is transported away from the base of the sand wall. If the breach is sufficiently high and the sand sufficiently fine the suspended sand can gain enough momentum to initiate a turbulent

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density current. With supercritical flow conditions, enough sand will be removed from the base of the wall to permit breaching to continue.

As the density current flows downslope, it can generate enough momentum to erode the seafloor at the base of the breach and further downslope, entraining more sand in suspended load and increasing its density. This self-accelerating nature (sometimes called ignitive growth) of turbidity currents depends on slope geometry and seabed sediment properties and has been modelled in various ways [58, 59, 60]. Retrogressive breaching can maintain sustained turbidity currents for hours in a quasi-steady mode, flushing sediment filled submarine canyons on a large scale [59, 61, 62]. As the density current encounters more gentle slopes, it will gradually lose momentum, slow and dissipate so that sand deposition prevails.

4.3. Anatomy of an RBF event

In common with all landslides, RBF events are powered by gravitational potential energy. However, the mechanism is more complex than most other types of (submarine) landslides. RBF events require two elements working in tandem:

1) a geotechnical element: the 'shear dilatancy or breaching effect' taking place within the sand skeleton itself, causing suction which stabilizes the retrogressing breach, at slopes much steeper than the natural angle of internal friction. This requires the sand to be sufficiently densely packed (dilatant) and water saturated. The breach sheds a constant supply of 'raining' sand particles into the water that produce a dense mixture of sand and water,

2) a hydrodynamic element: this is characterized by the generation of a turbulent density current mixing and carrying suspended sand grains downslope and is governed by slope geometry and sand characteristics. The sand must be fine grained (low fall velocity) so that the density current can carry the grains some distance away before they again settle out of suspension. The breach must be high enough to provide enough sand and energy for turbulent mixing of the sand grains with the ambient water to generate a homogeneous, denser than water suspension. Figure 15 gives a schematic diagram of an RBF-event.

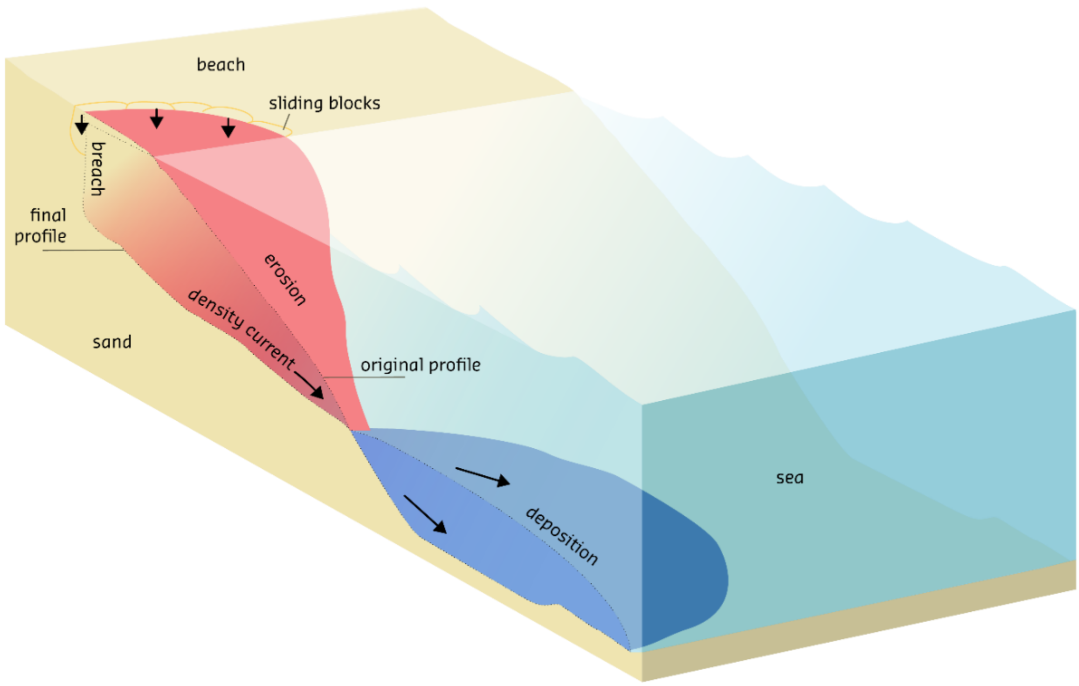

Figure 15. Schematic diagram of a flow slide or RBF event in the coastal shoreface retrogressing into the foreshore and beach during low water (Left: cross section. Right: 3D view. Red = erosion, blue = deposition). Graphics: R. Savert.

The following processes and stages of an RBF event can be distinguished:

Preconditions: Fine grained dilatant and water-saturated sand on a sufficiently steep and high subaqueous shoreface or channel slope. The 'rule of thumb' to assess flow slide vulnerability is a gradient of 18° (1:3) or more over a height of 5 meters or more and a total slope height over 10 m [5]. The sand needs to be sufficiently fine grained (about 100-200 μm), freshly deposited (in general young uncemented Holocene marine sands) and not containing too much clay which could make the sediments more cohesive and less prone to breaching. More advanced methods to assess flow slide occurrence and flood risk have been developed in the Netherlands [20, 31].

Triggering: The start of a natural event has never been directly observed so it is not known how small the initial breach is or how it is formed. Possible mechanisms are a small shear failure, liquefaction or fluidization caused by submarine groundwater discharge, in turn caused by an exceptionally low tide or after high rainfall, conditions which are often mentioned in the literature. However, it can be assumed that if unstable preconditions exist, some form of triggering mechanism is likely to ultimately occur to set off an RBF event.

Breaching: Once started, a breach tracks autonomously upslope, powered by gravitational potential energy only. The only condition required for the breaching process to continue is that enough sand is conveyed away from the base of the sand wall so that its height is maintained or can grow.

The density current: If the sand wall is high enough, the sand grains being shed from the breach will mix with ambient water to generate a homogeneous denser than water, turbulent suspension that flows rapidly downslope as a density current and behaves like a deep-sea turbidity current. If the underwater slope is high and steep enough, the density current will entrain sea bed sand and increase its density, resulting in a self-accelerating avalanche-like flow. This will lead to further slope degradation and increase the size and volume of the event.

Reaching the shoreline (beach, bank or defense structure): Events always track upslope along the maximum seafloor gradient and if breaching does not terminate underwater (for example by a change in the geology or sand properties or slope causing deposition of sand at the base of the breach etc.), the sand wall can reach the shoreline and continue into the beach or shore, where it can be observed and videoed. Moist unsaturated sand (where grains are held together by surface tension resulting in cohesive behavior) is undermined and topples off in blocks.

Termination: RBF events terminate naturally when sand settles at the base of the breach, reducing the sand wall height to the point where breaching can no longer shed enough sand to sustain the density current. The distance which events can penetrate landward is limited because the runout angle is usually small (about 3-4° or 1:15 to 20, [5]) and the breach height is limited at the top by the level of the water table. Therefore, as an event penetrates landward, the height of the breach progressively reduces. Events terminate abruptly as the almost vertical under water breach reduces its steepness and porewater under-pressures decrease until the slope reaches the natural angle of internal friction of the sand.

5. Modern flow slide protection and coastal defense strategies

Since a better understanding of the RBF mechanism is now available, new opportunities for prediction, prevention and mitigation measures and even completely new and innovative solutions for coastal defense are possible.

Most experience in defense against coastal flow slides still resides in the Netherlands. Here, coastal construction work to protect newly reclaimed polders in Zeeland, started in the late 18th century. These early engineering works often remained ineffective since only 'defended points' or groynes were built at that time. Between these points the tidal channel kept approaching the shoreline, so the embankments remained vulnerable to sequential RBF events. Recession often continued until the dike finally collapsed (Figure 4, Figure 6). The oldest and largest sea defense construction in the Netherlands, the Helderse Zeewering (Den Helder seawall), originally built in 1750, finally stopped the ongoing loss of land in the North of Holland and still survives today due to continuous monitoring and maintenance by Dutch authorities [63].

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During the Delta works program, started after the 1953 floods and completed in 1987, closure dams and storm surge barriers were built, and sea dikes were extensively reinforced. Since then no further damage by flow slides has occurred. Note that in Figure 3 a flow slide is detected that penetrated into the unprotected channel slope and partly under the scour protection (black lines) of the Eastern Scheldt Storm Surge Barrier. This event remained completely submerged and only minimal damage occurred, [7]. Here, protection consists of connected stone mattresses which can be undermined by breaching. Loose stone protection may have quenched this event earlier. The stability of the barrier itself was not affected and additional maintenance measures have since been taken.

How stone protection against RBF events actually works has been demonstrated in a small-scale flume test with a 1:2 (26°) protected slope in fine sand (see Figure 16 and compare this with Figure 14). Two types of protection were used, a) a filter construction of fine and coarse gravel laid directly on the sand and b), the same protection layer but on top of a permeable geotextile membrane. In the test with the geotextile, undermining by breaching continued until finally the complete slope was degraded and the natural angle of repose was reached. In the test with loose gravel protection, the retrogression of the breach was immediately smothered by the loose rocks covering the breach. In both cases the retrogressing breach did not develop into a full RBF event, since in small scale experimental conditions a sufficiently strong density current cannot develop.

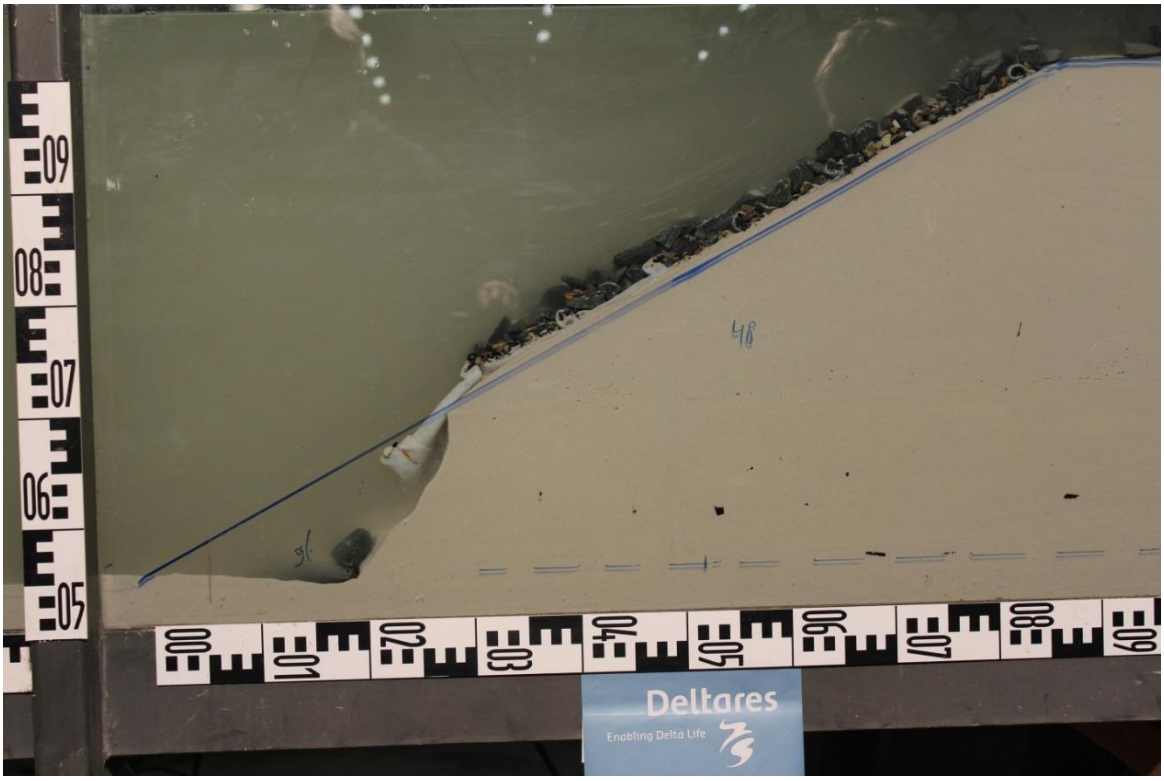

Figure 16. Model test of breaching under a slowly collapsing rock slope protection consisting of a filter layer of fine and coarse gravel on a permeable geotextile membrane [64]. Photo: M. Busink.

Today, for protection of the mildly sloping coastal zones along the North Sea where erosion only occurs during storm events, sand nourishment is generally used as the best erosion prevention strategy. Vegetation can also protect the berms of sea dikes from wave attack. However, along the deep tidal channels in Zeeland and the Wadden Sea where tidal channels run close to the embankment, currents are often too strong for these strategies.

Risk for protected embankments along tidal channels and rivers still exists in the case of scouring of the channel bed near the toe of the underwater slope. Generally, the toe is protected also with rock armor or mattresses but where ongoing scour exists, a breach can develop that retrogresses and undermines the complete revetment [64]. If consisting of a sufficiently thick layer of loose rock, the

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breach will be quickly covered and smothered, preventing further retrogression, as shown in flume tests, Figure 16.

Recurrent RBF events over many years at Amity Point in Australia have caused significant coastal recession into both publicly and privately-owned land in a small coastal village [1, 2]. Several erosion defense strategies have been trialed ranging from wooden and rock groins and placement of car bodies. All proved to be ineffective until finally a continuous rock wall was progressively built, funded by both private landowners and Government. This has proven to be successful in stopping further loss of land. Deep RBF events sometimes still penetrate under this barrier but this causes rocks to slump into the breach, quenching further retrogression. Where slumping has occurred, as in Figure 17, the sea wall was repaired by adding rocks from above, so the wall foundation moved deeper after each event. In this way the structure has become more stable over time. The protective riprap wall is now called a 'flow slide barrier' and its effectiveness is acknowledged by local coastal engineers. A 'Shoreline Erosion Management Plan' has recently been adopted which formalizes this understanding [65].

Figure 17. Damage to the 'Barrier' at Amity Point (2016) after an RBF event has partly undermined it. Repairs by adding new rock have started. Photo: Beinssen.

Beinssen and Neil [2] describe how a collapsing riprap works to quench an active event. If an event encounters a rock wall defense and the base of the breach is higher than the rock wall foundations, the event terminates because it runs out of sand (Figure 8). If the base of the breach is lower than the rock wall foundations, the breach will undermine the rocks and the wall will slump or collapse (Figure 17).

At Cap Ferret in France local authorities are concerned about the hazardous character and frequency of RBF events and consequently have restricted access to unstable beach areas for public safety. Though RBF events occur most frequently on the beach immediately adjacent to the riprap protection wall, no causal link has been established between the seawall and beach collapses. In the past, seawall extensions moved the most frequent events southward, but recently several massive collapses of riprap material have also occurred along the protected shoreline. Falling rocks appear to be the most superficial ones and the core of the seawall remains stable.

6. Conclusions

Coastal flow slides are slope failures which occur naturally in subaqueous slopes of fine, water saturated sands in the coastal shoreface. Events go mostly unnoticed but sometimes they emerge onto

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beaches, shoals, tidal flats or river banks. Events are powered by gravity and not by the kinetic energy of storms, waves or currents. The phenomenon is generally not well recognized or understood by coastal engineers although flow slides can threaten coastal infrastructure and embankments and cause significant coastal recession and flood risk. We have documented the history of coastal flow slides in the Netherlands and the immense impact on land loss, finally overcome with the completion of the Delta Works in 1987.

Ever since the first eye witness reports of these events were published in the Netherlands over a century ago, attempts have been made to understand the geo-mechanical mechanism. For many years it was thought that the failure mechanism was liquefaction induced sliding, as proposed by Terzaghi, the 'father of modern geotechnical engineering' in 1925. We have established that early events, observed during the active phase, were characterized by a slow, steadily retrogressing sand wall as they arrived at the shoreline, going on for many hours to a day as described in now forgotten eye witness reports which is not consistent with Terzaghi's analysis.

Dredging research in the Netherlands in the 1970's revealed slow retrogressive breaching in dilative sands as an alternative explanation for the flow slide failure mechanism. Breaching occurs when medium to tightly packed sand is subjected to shear and consequently dilates internally (shear dilatancy effect) so that a temporary 'under-pressure' or suction occurs in the pore water. The sand wall or breach is temporally stabilized by this internal suction (strain hardening) which reduces as water flows into the deposit. The breach sheds sand grains which generate an associated density current. The only requirement for breaching to continue is that enough sand is conveyed away from the base of the breach by the density current so that its height is maintained. In order to maintain a sustained breaching event, the sand must be fine enough to be entrained and conveyed away from the breach before again settling out of suspension.

Recently, further evidence on the flow slide mechanism has become available in the form of video footage posted on the internet of active events in Australia, France, the Netherlands and in coastal areas elsewhere in the world. This footage clearly confirms the slow retrogressive nature of the events and the near vertical breach. These observations exclude liquefaction failure as the mechanism and justify the term 'retrogressive breach failure' (RBF event).

Flow slides present difficult problems to researchers; their timing and location can be predicted only in terms of probability and they occur largely underwater where they are hidden from view. We have described how flow slides can pose risks to infrastructure and lead to undermining of shore and bank defenses, leading in turn to loss of land and to flooding risk. By understanding the mechanism however, better defense strategies can be envisaged. Shore and levee protection using stone protection and riprap now can be understood, since rocks slump and smother the breach, disrupting the progress of events. This has been observed in the field in Australia and France and confirmed in recent small-scale flume tests.

We explained that the lack of a consistent name for these events has confused thinking over many years. We propose the name 'retrogressive breach failure' (RBF event) because it accurately describes the process. In writing this paper, we hope that the coastal science and engineering communities will better recognize and understand these intriguing natural events.

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