



Flow Slides: Understanding their geo-mechanical mechanisms, the threats they pose and how these threats can be managed

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Abstract

Australian coastal engineers are very familiar with the kinetic energy of waves and currents which transport sand. However, gravitational potential energy is also an important force that can rapidly move large volumes of sand offshore in certain river and coastal settings, a fact that is often not recognised. Subaqueous slope failures, which occur frequently in some dynamic coastal environments, (although seldom observed directly) are complex gravity driven events. Since the sand, once detached from the slope, flows as a mixture rather than as a mass, this type of failure is called a 'flow slide'.

Two types of flow slides are recognised, based on the geo-mechanical failure mechanism. Liquefaction flow slides can occur in loosely packed sand when the pore water pressure increases (relative to ambient pressure) to the extent where the weight of sand is borne by the pore fluid itself and liquefaction occurs. The pressure increase is caused by contraction of the sand skeleton. If unconfined, the liquefied sand mass flows rapidly down-slope in a very short lived event, lasting only a few minutes.

By contrast, breach flow slides occur in densely packed sand when the pore water pressure decreases in relation to ambient pressure. The pressure decrease is caused by dilation of the sand skeleton. Suction (strain hardening) stabilises the deposit so that slowly retrogressing vertical subaqueous sand walls, known as breaches, can exist. Such events can last several hours. Sand grains cascading down the face of the submerged breach generate a turbulent density current which carries the sand away down-slope before it resettles.

Flow slides can cause significant damage to built defence structures and submerged infrastructure. When they reach the shoreline they can cause the beach or bank to collapse. A number of strategies to prevent damage or mitigate risk can be employed.

This paper will address the current state of knowledge of flow slides using examples from around the world. All coastal engineers would benefit from a basic understanding of the mechanisms that drive these complex events.

1. INTRODUCTION

A key element of coastal engineering is an understanding (both qualitative and quantitative) of coastal processes including in particular sediment transport processes. For example, the role of littoral sand drift in sediment transport and the kinetic energy of waves and currents that power it are well understood by coastal engineers. However, flow slides and the complex mechanisms that drive them are less well recognised, in particular in relation to coastal erosion.

Wherever natural, often dramatic, beach collapse events occur, the engineering community is asked to explain them. In popular media, they are often referred to as 'sink holes', which implies that sand disappears into an underground cavity such as a limestone cave, which generally do not exist on

sandy coasts. Sometimes the general terms 'channel slump' or 'underwater landslide' are used implying shear failure. Explanations given are frequently incorrect.

Retrogressive breach failures (RBF events) are gravity driven but are not primarily shear failures. They are a complex failure mechanism which relies on both the mechanical properties of sand itself and the behaviour of associated density currents which carry the suspended grains away. They can initiate and propagate on quite gentle subaqueous slopes where shear failures could not occur. Natural events are not rare. At one study site at Amity Point in Queensland, Beinssen and Neil (2015) report that events emerge onto the beach on average every 14 days. They have been recorded at many coastal and river settings worldwide.

In general, flow slides occur in dynamic coastal environments when sufficiently steep and high subaqueous slopes of fine, often freshly deposited, sand exist and following a triggering event such as toe erosion by tidal scour, a low tide or submarine groundwater discharge after rain.

This paper provides a broad overview of current knowledge of flow slides to inform coastal professionals attending this conference.



Figure 1. This image shows an active retrogressive breach failure (RBF) event at Amity Point, advancing at about 0.8 metres per minute. The spectator is standing on top of a 7 metre high, near vertical subaqueous wall of sand (the breach) which is sustained by a temporary strain hardening of the sand skeleton immediately behind the breach (under the observer's feet).

2. GEOMECHANICAL MECHANISMS

The term 'flow slide' can be found in the technical literature in a number of contexts. In this paper the term is specifically used to describe two failure mechanisms of subaqueous (saturated) sand slopes. Such slopes can be unstable and vulnerable to failure even if the slope angle is much less than the maximum angle of repose of sand (about 30° to 35°) where avalanching and shear failure might be expected.

In theory two forms of flow slides can be distinguished depending upon the degree of packing (the void ratio) of the sand.

2.1. Liquefaction flow slides

Where saturated sand is very loosely packed, in situations where no energy is applied as grains settle onto the seabed (Yao You, 2013), the sand skeleton is likely to contract under shear. Contraction (reduction in the void ratio) will cause an elevation in the pore water pressure so that water will

progressively carry more weight of the deposit until liquefaction occurs. This process occurring within the sand deposit causes progressive 'strain softening'. If unconfined at liquefaction, the sediment behaves as a liquid and flows rapidly down-slope in a flow slide event that is very short lived (just a few minutes). The elevated pore pressure is dissipated rapidly during the event.

Static liquefaction has been observed in flume tanks (De Groot et al 2012, Bezuijen and Mastbergen, 1988) but has not yet been positively identified as the cause of flow slides in nature or during dredging. Early analysis of historical flow slides in Zeeland in the Netherlands, provided much insight into pre and post-event geometry and associated geological conditions (Koppejan et al 1948, Silvis and de Groot, 1995, Stoutjesdijk et al 1994). However, few eyewitness reports were recorded so the actual slope failure mechanism, generally assumed to be liquefaction of loosely packed sand, remained unclear.

2.2. Breach flow slides

Where energy is applied during sedimentation (for example wave energy) settling sand becomes more tightly packed and it is likely to dilate under shear. Dilation increases the void ratio and hence causes a temporary 'under pressure' in the pore water. The grains are held together by a temporary suction which causes a 'strain hardening' of the deposit. As water flows into the deposit the pore pressure will return to ambient pressure. The rate of water inflow is governed by the hydraulic conductivity of the sand.

Strain hardening sustains dynamic underwater sand walls termed 'breaches' which retrogress up-slope relatively slowly. Sand grains released from the surface of the breach cascade down its face, generating a density (turbidity) current which transports large volumes of sand down-slope and offshore before it again settles onto the seabed. Van den Berg, van Gelder and Mastbergen (2002) name this form of flow slide 'breach failure' and Beinssen, Neil and Mastbergen (2014), apply the name 'retrogressive breach failure' (RBF).

RBF events start offshore and small, growing larger by bed-erosion as they retrogress up-slope. The sand wall (breach) can continue to propagate up-slope for hours, sometimes reaching the shore where it can be observed and may cause damage. At Amity Point, the height of the breach when it reaches the beach (Fig. 1) has been measured at 6 to 7 metres on several occasions, as reported by Beinssen, Neil and Mastbergen (2014).

Events terminate when the supply of sand feeding the density current diminishes and the current loses momentum so sand settles progressively more at the base of the breach. The breach height is rapidly reduced. Morphology at termination is typically an amphitheatre shaped bowl with sides inclined at near the maximum angle of repose of about 30° to 35° (Figure 2). A tongue or fan of deposited sand can usually be identified on bathymetric images.

The mechanism that triggers these instabilities is still not well understood and requires further research. Silvis and de Groot (1995) state that, *'there will always be a initiation mechanism: a sudden, local change in water pressure due to waves from a passing ship or a wind wave, an increase in outflowing groundwater during an extreme low tide, a quickly changing soil pressure due to a local shear failure or due to dredging activities, vibrations caused by pile driving, and so on'*. They suggest there may be multiple trigger mechanisms. While the start of an RBF event in nature has never been directly observed, it is possible that many are triggered by a small liquefaction event, which generates an initial subaqueous sand scarp which then migrates up-slope by breaching, growing in height as it does so.

2.3. Comparing liquefaction and breach flow slides

Flow slides are difficult to study in nature because they initiate and propagate where they cannot be directly observed, are short lived and their timing is unpredictable. They do not always emerge onto the shore where their active phase can be seen or where their post event morphology is displayed.

Much insight comes from flume tank experiments (Bezuijen and Mastbergen, 1988, de Groot et al, 2012 and Yao You, 2013). Breaching has also been reported from small and large scale flume tank experiments (Breusers, 1974, van Rhee and Bezuijen, 1998) as part of dredging research in the Netherlands, in particular suction dredging of fine sands. Research into levee bank failures in the

lower Mississippi River caused by flow slides has also been important for a better understanding of the mechanism. Torrey (1995) describes the retrogressive nature of these failures.

Extensive research has been conducted in the Netherlands on liquefaction in relation to the stability of estuary shores and dikes (Koppejan et al 1948, Stoutjesdijk et al, 1994, Silvis and de Groot, 1995).

Both Dutch and US researchers have now come to understand that breaching, not liquefaction, is the main driver of observed flow slides in nature, since this is in agreement with their high and near vertical, breaching sand walls and the slow retrogression speeds. Torrey (1995) wrote that he '*has wondered whether or not other cases of flow slides reported in the literature believed to have been the result of spontaneous liquefaction might not actually have been by retrogression in denser sands*'. Similarly, Van den Berg et al (2002) speculate that '*many slope instabilities that have been reported as liquefaction slope failures might be interpreted as breach failures or combinations of both failure types*'.

Mastbergen et al (2015) report the results of an innovative field experiment during which a flow slide was artificially triggered and its progress tracked. After dredging the toe of a sand slope to initiate the failure, several steep walls over 6 m high developed and slowly retrogressed upslope towards the shore of a emergent sand bank. These breaches finally decreased in height and the event stopped before it reached the bank. Nevertheless the retrogressive breaching nature of these flow slides was clearly identified on bathymetric images. Van den Berg et al (2017) describe a large natural flow slide which occurred close to the above experiment's location. They argue that breach flow slides result in thinly layered sand deposits, in contrast to liquefaction flow slides which produce mass deposits.

Two associated shear failure mechanisms which feed sand to the flow slide density current are important.

First, van Rhee and Bezuijen (1998) reported that 'lumps' of sand were released from breaching 2.5m high sand walls in flume tank tests. Yao You (2013) also noted this and called it 'sliding'. Wedges of saturated sand shear off the breach and sink vertically to augment the density current. He describes 'dual mode failure' where the mechanism switches back and forth between breaching and sliding. Dual mode greatly increases the rate of sediment release and so boosts the density current. Yao You (2013) notes that sliding is more likely to occur in sand which is loosely packed (but still dilatant) than in more tightly packed sand.

Second, as events advance up a beach, moist sand above the water table (where grains are held together by surface tension) fails in blocks as it is undermined. These blocks fall down the face of the breach and mix with water, again adding to the momentum of the density current.

Both of the above shear failures have been clearly observed in natural RBF events at Amity Point (Beinssen and Neil, 2015).

In nature, we can assume that sand in any large deposit is not uniformly packed. Sand feeding the density current can be attributed to four mechanisms;

- Grains being released from the surface of the breaching sand wall,
- Liquefaction within the sand wall as loosely packed pockets of sand are encountered,
- Sliding wedges of sand breaking off the face of the subaqueous sand wall as shear failures,
- Sub-aerial sand blocks toppling and sinking down the face if/as the event encounters a beach.

We can conclude that flow slide failure mechanisms in nature are complex hybrids of all the above but which depend ultimately upon the phenomenon of breaching in medium to densely packed fine sand. So they can appropriately be named 'retrogressive breach failures' (RBF) but are most often referred to in the literature as 'flow slides'.

3. EXAMPLES OF THREATS POSED BY FLOW SLIDES

World wide, the threats posed by flow slides are considerable. Some examples are given below.

In the US, flow slides along the lower Mississippi River threaten the stability of mud levee banks built on top of fine sandy deposits, which can sustain retrogressive breaching. They pose a major flooding risk. Torrey (1995) states '*contemplation of high population densities, many heavy petro-chemical*

industries and even a nuclear power plant (in the lower Mississippi) totally dependent upon a thin thread of earthen embankment is frightening enough. The additional realisation that the thin protective thread is itself vulnerable to sudden breach during the worst of high water periods elevates the flow slide problem to the status of national importance'.

In the Netherlands, flow slides over many years have damaged dikes and caused flooding. Hundreds of events have been recorded (Koppejan et al, 1948). An ongoing risk which flow slides present is damage to the bed protection and foundations of the Oosterschelde storm surge barrier (De Groot and Mastbergen, 2006). Flow slides here do not emerge onto the bank so are monitored using bathymetric images which display the characteristic post-event morphologies.

Nairn et al (2015) report that density currents generated from flow slides threaten infrastructure and ships at the Vale iron ore loading facility in Brazil. This facility is located in a sandy estuary with steep sides but flow slides here never reach the bank where they can be directly observed.

In Bangladesh, the Padma multipurpose bridge foundations risk being undermined by both scouring and flow slides (Neill et al 2010 and Ishihara 2008). In Canada, flow slides in the Fraser River delta pose a major threat to infrastructure (Chillarige et al 1997).

Examples from Australia are described below.

At Inskip Point in Queensland, a large RBF event occurred on 26/9/2015 and impacted a camping area at about midnight (Figure 2). Many similar events have occurred along this stretch of beach, posing a risk to campers and beach traffic, particularly at night. Shipway (2015) describes the problem and recommends risk management measures.



Figure 2. This image shows the amphitheatre shaped crater left after a large RBF event at Inskip Point, Queensland which took place at night on 26th September 2015. This event retrogressed into a camping area behind the beach and undermined a car and caravan. Many similar events have occurred on this beach.

At Amity Point in Queensland (Figure 3), many RBF events have occurred dating back over a century. Coastal recession here has been consistent and significant over many years but its RBF mechanism has only recently been recognised (Beinssen, Neil and Mastbergen 2014).

At Pelican in NSW, a building unexpectedly and suddenly collapsed during calm conditions at 9.45am on 8/2/2016 (Figure 4). The building was built partly over the water and supported on its seaward side by piles driven into fine subaqueous sand. The sudden nature of the collapse of this building (which

had been recently declared structurally sound) fits with the hypothesis that the outer piles were undermined by an RBF event.

4. MANAGEMENT AND MITIGATION METHODS

A number of techniques to mitigate the affects of flow slides have been trialled and employed.

In the lower Mississippi River systematic monitoring of bathymetry and scour hole evolution is carried out in an attempt to identify problem areas where levee banks may need 'beefing up' or where a secondary levee may need to be built. Torrey (1995) states *'The record proves that the articulated concrete revetment mattress placed as a typical single layer will not prevent flow slides'*. Flow slides can propagate under such mattresses.



Figure 3. These images show a slump in the riprap 'flow slide barrier' at Amity Point in Queensland after it had been undermined by an RBF event. Repairs by adding new rock have started. The amphitheatre shaped crater in the beach left after the termination of this event can be seen in the background.

In the Netherlands, vulnerable estuary and river shorelines have now largely been protected with rock armour. Nevertheless, the capacity of dikes and foreshores to resist failure due to flow slides is regularly assessed. The Dutch engineering 'rule of thumb' is that slopes in excess of 18° and over 5M in height are considered 'at risk'. Silvis and de Groot (1995) report that a technique called the 'fixed point method' of groyne was tried in Holland around 1880. They write that *'history has shown that this was not a good solution'* and that *'Groynes were eventually connected in 1965 providing a continuous foreshore protection'*.

Flow slides are still a concern at the Oosterschelde Storm Surge Barrier where entirely subaqueous events threaten the bed protection and ultimately the foundations of its caissons. A 600mm filter layer of gravel and stone over the sand ensures that events cannot retrogress to the foundations. The areas of sand which need to be covered were carefully calculated and regular bathymetric monitoring is carried out. How best to apply rock protection here is still under question.

In Brazil, Nairn et al (2015) report the technique used to protect Vale's iron ore loading facility is to conduct frequent bathymetric surveys to identify potential problem slopes which are then dredged to mitigate risk.

In Bangladesh, Neill et al (2010) describe the extensive underwater slope protection works carried out using rock riprap and geobags to mitigate the effects of flow slides and scour. They stress the need for ongoing monitoring and maintenance.

At Inskip Point in Australia, camping has been prohibited in vulnerable areas close to the beach and beach driving has been restricted in areas known to be flow slide prone (Shipway 2015). The building of hard structures at this site cannot be justified.

At Amity Point, the village is protected by a progressively built rock wall recently named a 'flow slide barrier' (Figure 3). This structure has proven to be successful in arresting coastal recession. Whilst it has been undermined on many occasions by RBF events which penetrate under its foundations, it is repaired by adding rock to the top and in this way has become progressively more stable over time (Beinssen and Neil 2015). The Dutch experience of groynes being ineffective has been mirrored at Amity Point where an earlier built groyne field did not provide a solution to the flow slide threat.

Finally, if the building collapse at Pelican in NSW was caused by an RBF event that undermined its outer piles, then these piles driven deeper and preferably to bed rock, would have saved the building (Figure 4).



Figure 4 This building at Pelican on the mid north coast of NSW collapsed at 9.45am on 8/2/2016 during calm conditions. It was supported by piles driven into the subaqueous sand at the building's seaward side. Undermining of these piles by an RBF event could explain this sudden collapse.

5. CONCLUSIONS

Retrogressive breach failures (RBF) commonly named 'flow slides' are not uncommon events in nature and can present significant risk management challenges to coastal engineers. The record shows that they are still poorly understood and are often misdiagnosed as shear or liquefaction failures or simply as a common erosion process. They are a complex failure mechanism, which

depends upon two elements; the geo-mechanical properties of saturated sand and the behaviour of associated turbulent density currents, which rapidly carry large quantities of suspended sand down-slope.

All coastal engineers would benefit from a basic understanding of the mechanisms that drive flow slides, the environmental settings in which they may be expected to occur, the risks they pose and successful countermeasures employed around the world.

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