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Field Observations of Retrogressive Breach Failures at two Tidal Inlets in Queensland, Australia

K. Beinssen[1], D.T. Neil[1] and D.R. Mastbergen[2]

[1] School of Geography, Planning and Environmental Management, The University of Queensland, St. Lucia, Qld. 4067, Australia.

[2] Department of Marine and Coastal Systems, Deltares, P.O. Box 177, 2600 MH Delft, The Netherlands.

ABSTRACT

This paper describes observations of rapid beach erosion events which occur regularly adjacent to deep sandy tidal channels at Amity Point and Inskip Point on Australia's east coast. The characteristics of these events are consistent with others which have been extensively studied and described in the scientific literature and which occur at several river and coastal locations elsewhere in the world. This connection has not previously been made. The geomorphological mechanism of retrogressive breach failure (RBF) events reported in the literature matches the study site observations well. It is concluded that the described Australian events are caused by breaching of fine, subaqueous, dilatant sand. This understanding will help coastal planning including the design of coastal defences.

1. INTRODUCTION

'Retrogressive breach failures' (RBFs), known in the United States as 'retrogressive flow slides', are natural events which occur in sandy deposits at many river and coastal locations throughout the world. To date they have not been reported in the scientific literature to occur in Australia

At some sites, RBF events play a very important role in the stability of river banks and coastal foreshores. In the lower Mississippi River they are responsible for levee collapses causing flooding and damage to infrastructure. Consequently, the US Army Corps of Engineers has applied considerable research effort to understanding the geomorphological mechanisms underlying RBF initiation and behaviour (Torrey, 1995). In the Netherlands, RBFs threaten the stability of dikes and the foundations of the Oosterschelde Storm Surge Barrier, so here too a large research effort has been and is still being applied (Silvis et al, 1995, Stoutjesdijk et al, 1994). Insight also comes from the behaviour of sand observed in dredging research carried out in the Netherlands (Van Rhee and Bezuijen, 1998 and Breusers, 1974).

Active natural RBF events have seldom been witnessed by researchers because they initiate underwater, only become visible when and if they reach the subaerial bank, start unpredictably and remain active for only a few hours at most. Scientific knowledge comes mostly from flume experiments (de Groot et al, 2012, Yao You, 2013) and from the analysis of sites after events have occurred (Torrey, 1995).

A unique opportunity to observe active natural RBF events exists at Amity Point on Australia's east coast. Daily monitoring of a beach adjacent to a tidal channel enabled the recording of every event which affected the beach at the study location over a twenty month period. Many events were witnessed, videoed and measured during their active phase which typically lasts less than 100 minutes after they reach the channel bank.

At the second site at Inskip Point, RBF events were photographed or videoed by others who subsequently reported their observations to the first author or posted them on the internet.

The objectives of this paper are to briefly outline the geomorphological processes which drive RBF events, to describe some field observations of such events in eastern Australia and to provide a detailed description of one event as a typical example.

2. THE MECHANISM OF RBF EVENTS

The geomorphological mechanisms which characterise RBF events are described here to contextualise the field observations to be described later.

When a mass of densely packed fine sand exists on a subaqueous slope such as the edge of a tidal channel it is susceptible to failure. This failure can be initiated by a small triggering event, which forms an initial scarp and then may transform into a retrogressing, amphitheatre shaped, near vertical wall of sand termed a breach. On some occasions, the retrogressing wall reaches the shore where it becomes observable as it collapses the subaerial bank or beach.

The three pre-conditions for RBF events are first, relatively tightly packed (dilatant) fine sand which, second, exists on a subaqueous slope (which together cause an unstable situation) and third, a 'trigger' mechanism which initiates the breach. Each of these three preconditions is described below.

Pre-condition 1. The sand is usually fine with a median grain size in the 150 to 250 micron range and with the grains relatively tightly packed to give a low void ratio, generally less than 50%. When a shear force is applied, the sand grains move apart so that the void ratio increases (dilation). This shear force comes from the tendency of the retrogressing sand wall to collapse under gravity, with the sand fabric near the vertical face of the wall dilating. This causes a decrease in the pore water pressure in the sediment close to the sand wall, relative to the adjacent hydrostatic pressure. The hydraulic conductivity of the fine sand limits the rate at which this pressure differential can equalize and the grains are 'sucked' together for a short time, so that the wall resists collapse. However, the unconfined grains on the edge of the wall detach and fall down its face, generating a density current which carries the falling sand away into deeper water. By this dynamic mechanism, near vertical retrogressing walls of sand (breaches) can exist without collapsing.

It is important that most sand is removed from the base of the retrogressing wall so that the breaching process is not choked and can continue. This is achieved by the density current generated as described above but may also be assisted by tidal or river currents, according to the setting. Fine sand implies a low settling velocity, so the grains remain suspended and the density current is sustained over hundreds of metres.

Pre-condition 2. The initial slope characteristics of the channel bank are an important precondition for RBF events. Stoutjesdijk, de Groot and Lindenberg (1994) conclude that the average slope angle is not the best measure of RBF susceptibility; the inclination of the steepest part may be a better measure. An empirical approach taken by Dutch engineers in Zeeland (Silvis and de Groot 1995) proposes that a subaqueous sandy slope is only susceptible to failure if the steepest section over a height of 5 metres is steeper than 18.4 degrees.

Pre-condition 3. The 'trigger' which initiates RBF events can be almost any small change in soil stresses (Stoutjesdijk, de Groot and Lindenberg, 1994). It may be man made, such as pile driving operations or waves generated by a passing ship, or natural, such as erosion by tidal flow or a tidal vortex, sudden changes in local water pressure caused by waves, submarine groundwater discharge causing a small local liquefaction event or some combination of these factors.

In the case of a loosely packed sand layer (void ratio over about 100%) the grain stress decreases when a shear force is applied and sudden liquefaction with shear failure can occur instead of steady breaching. If more densely packed sand layers are present on top of such a loosely packed layer, a sudden small liquefaction event can trigger a subsequent breach event. Note that a sandy channel may have pre-conditions one and two but not be subject to a trigger event (pre-condition three). In such circumstances the sandy slope will remain stable, sometimes indefinitely (Silvis and de Groot, 1995).

Mass failure events in subaqueous sand deposits were long thought to be caused by liquefaction in loosely packed sands (Silvis and de Groot, 1995) rather than by breaching in tightly packed ones. Many of the conclusions in earlier accounts can now be reinterpreted in the light of recent research findings (Van den Berg, van Gelder and Mastbergen, 2002). Breaching is now recognised as a common feature in subaqueous densely packed fine sands.

A further insight comes from flume tank experiments. Van Rhee and Bezuijen (1998) first noted 'lumps' of sand could be released from a breaching wall. Yao You (2013) describes 'dual-mode' slope failures where the mechanism switches back and forth between breaching and sliding (shear) modes. During breaching, sand is released from the subaqueous retrogressing wall, grain by grain. During sliding, wedges of sand at the breaching front calve off and slide vertically, eventually breaking up as they mix with water to augment the density current. Dilation in the sand wall immediately behind the calving wedge stiffens the wall again and breaching restarts. Yao You (2013) argues that within dilatant deposits, those with larger porosity are more likely to generate dual-mode slope failure than those composed of the same sediment with smaller porosity (greater dilation potential).

3. DESCRIPTION OF THE STUDY SITES

RBF events occur commonly at two locations in southeast Queensland, Australia. The primary site for observations was at Amity Point (27 23'35" S, 153 26'23"E). Here a tidal channel passes close to a sandy beach at the southern edge of a tidal inlet (South Passage; Figure 1). An 800 metre long rubble mound rock wall has been built immediately south of this site, to protect the coastal village of Amity Point from erosion.

Longshore drift largely driven by residual ocean swell crossing the ebb tide delta of the South Passage Entrance, transports fine sand along the beach (Figure 1) and delivers it to the upper bank of a tidal channel, causing the channel slope to steepen. Scouring by tidal currents at the base of the slope may also act to increase the slope angle. As the channel edge steepens, it becomes increasingly vulnerable to breaching if subjected to a trigger.

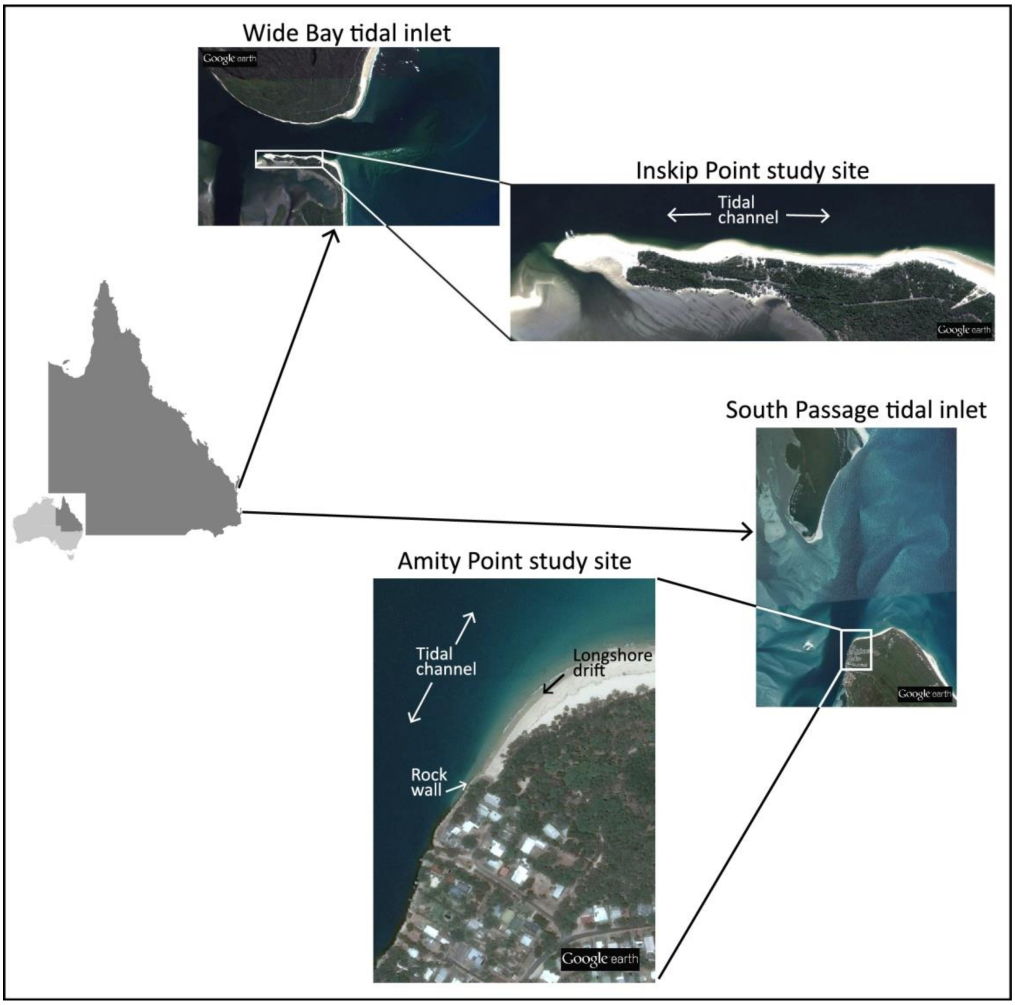


Figure 1. Locations of Amity Point and Inskip Point study sites from Google earth.

A second site (Figure 1) where RBF events commonly occur is located at Inskip Point (25 48'31"S, 153 03'38"E). This site is similar to the Amity Point site in having a deep tidal channel with a sloping margin of fine sand. However, there are no man made structures at or adjacent to this site.

4. OBSERVED CHARACTERISTICS OF RBF EVENTS AT AMITY POINT AND INSKIP POINT

4.1 Historical observations

At Amity Point, acute erosion events have been observed for well over 100 years. Local historian Thomas Welsby wrote in 1913 (Thomson 1967) of his observations made many years earlier; 'I have known large slips at Amity carry away tons of sand, and many a ti-tree familiar to my boating companions has toppled and fallen into the waters of the Bay'.

Since that time, numerous rapid, catastrophic events have been observed. Two longstanding Amity Point residents (G. Litherland, 2013 pers. comm., E. Jarvis, 2013 pers. comm.) recall witnessing a rapid and deep event in 1947 which undermined a local beachside tavern, tipping it into the sea. Many later events have been 'fought' by local residents with car bodies and other materials until rock from a local quarry became available and construction of a seawall commenced. Descriptions and photographs of these events are consistent with RBFs.

Since the early 1970's 'channel slumping' has been recognised by coastal scientists as an important mechanism of erosion at Amity Point (Eberhardt, 1978). The Queensland Beach Protection Authority (BPA), the government body responsible for erosion management from 1968 to 2003, wrote in 1997 of the erosion events at Amity Point that 'the cause of the slumps are the tidal currents which undermine the steep nearshore batter of the adjacent Rainbow Channel' (correspondence from BPA to Redland Shire Council). In other words, the frequent events were diagnosed as shear failures of an over-steepened bank, a view which is still widely held today.

4.2 Research methods.

A section of beach at Amity Point (Figure 1) where RBF events frequently emerge from the channel onto the bank was the subject of a systematic monitoring program for a 20 month period from July 2011 to February 2014. The outline of the beach was measured and videoed almost daily. The researcher was called to the site by local residents whenever an active event was observed. In this way, many active events could be videoed and measured as they occurred. Each observed active event left behind a characteristic 'amphitheatre' shaped scar. Using this observation, events that had emerged onto the beach undetected (at night for example) could be identified. The area of each event was measured. Additional opportunistic observations were made including the sand wall height measured with a weighted line, retrogression speed by timing over a measured distance and surface water movement using dye tracking.

The study site included the northern end of a rubble mound rock wall (Figure 1) built to protect the village of Amity Point from erosion. The stability of this structure through successive RBF events, was monitored by measuring the level of eight points on the crest of the wall relative to a fixed point further inland using a GeoMax ZDL700 digital level. Periodic bathymetric scans were made adjacent to the site using a Lowrance HDS 10 plotter/sounder and the computer package 'DrDepth' to draw the maps. Sites of RBF events which did not emerge onto the bank could be identified on these maps by their characteristic shape. Sand particle size analysis on samples taken about 12 hours after a large RBF event (described below) was carried out. Four sand samples were obtained from the beach face adjacent to the event and one sample from the seafloor at the site of the event. Particle size analysis (dry sieving, nested 0.5 phi interval sieves) was carried out on these samples (two replicates per sample) using a Retsch Analytical Sieve Shaker (modal As 200 Basic) set at amplitude 70 for 10 minutes.

The Inskip Point observations reported herein were made by phone interviews with local residents who had witnessed the events and who also provided photos and video footage. Video footage posted on the internet was also used.

4.3 Field observations at Amity Point

During the 20 month study period, 44 RBF events emerged onto the subaerial beach at the study site. Of these, 40 reached the rock wall but little change in the level of the wall was detected on any of these occasions. The mean subsidence for the eight reference points over the 17 month period from September 2012 was 40.5mm.

On no occasion was the approach of a subaqueous RBF event evident on the surface of the water. Events only became visible when they reached the beach.

The speed of retrogression was always close to 0.8 meters per minute on the lower beach but on at least one occasion (detailed description below) slowed to 0.3 meters per minute on the upper beach. The height of the almost vertical subaqueous retrogressing wall of sand was measured on six occasions at between 6 and 7 metres.

The morphology of each RBF was always amphitheatre shaped as it progressed up the beach. On each occasion, sand could be seen 'raining' off the wall below the water line. Periodically, wedges of sand about 0.4 metres thick by 4 to 10 metres wide sheared off the sand wall and sank vertically downwards (see photograph 2e). Above the water level where the sand was moist it broke away in slabs, consistent with grains here being held together by capillary forces. A dye release 15 metres from an active breach during one event clearly showed that surface water was being drawn towards the breach and then down the sand wall with the density current.

The surface area of beach affected was measured at between 20 m^2 and almost 3000 m^2. On 29 occasions (about 66% of events) the surface area of the beach eroded was less than 500 m^2 and the rest were between 500 and 2980 m^2. The largest observed event (described below in detail) penetrated 54 metres up the beach, with a final width of 105 metres.

After arrival on the beach events remained active for between just 10 minutes to a maximum of 107 minutes. Each event ended abruptly with a collapse of the breaching wall. The subaqueous sand slope assumed its natural maximum angle of repose (angle of internal friction) of about 30 to 35 degrees.

At Amity Point RBF events appear to initiate on slopes of about 5 degrees (Figure 4). However, small areas of steeper slopes beyond the resolution of this study's bathymetric scans may exist and may be the trigger sites. The maximum subaqueous slope angle for sand at the study site (angle of internal friction) was measured at about 30 to 35 degrees.

After each of the RBF events finished, sand transported southwest along the adjacent beach in the longshore current always replaced the eroded sand quickly. The beach took as little as 24 hours to rebuild after small events, while it took about four weeks to replace sand lost in the largest event.

Finally, at Amity Point many RBF events go unnoticed because they do not emerge onto the bank where they can be observed. Such events can be identified on bathymetric scans by their characteristic morphology (Figure 2).

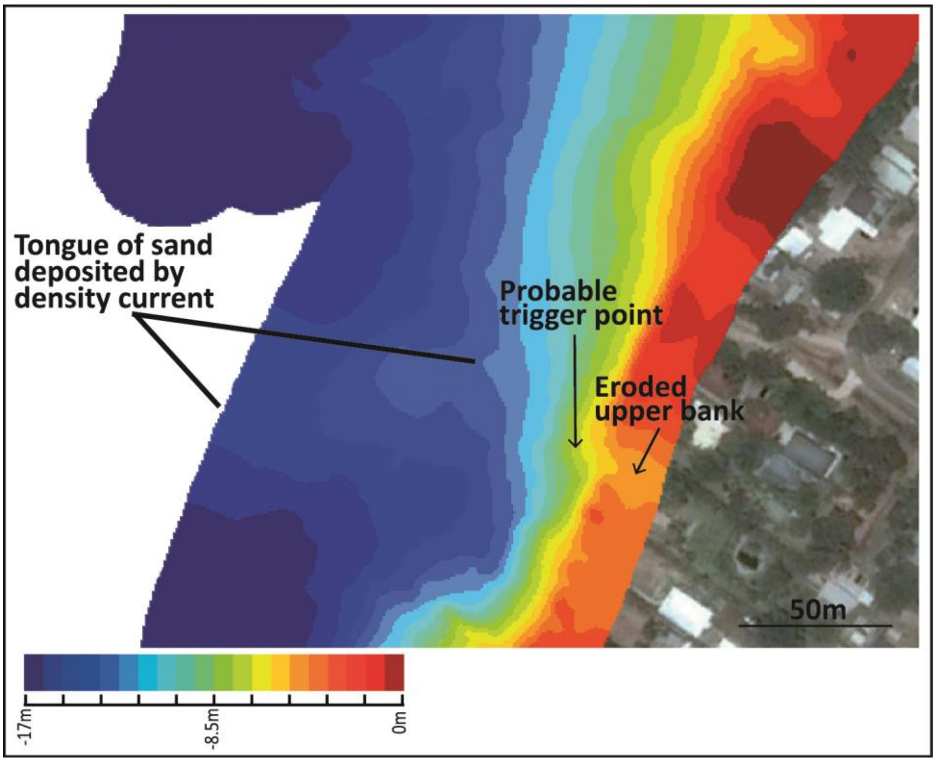


Figure 2. Bathymetric scan taken on 13.02.2014 of an RBF event adjacent to the Amity Point rock wall. This event did not erode the foreshore or destabilise the rock wall, so went undetected at the time.

4.4 Field observations at Inskip Point.

RBF events regularly occur along a section of beach adjacent to Inskip Point (Figure 1). Very large events were recorded in May 2006, June 2011 and August 2013. Each was estimated at over 150 metres in diameter and six metres deep, progressed up the beach and into the vegetated area and was active for about 3 hours. Photograph 1 shows an aerial view of the June 2011 event. Note the thick surface foam which is a feature of large RBF events when they retrogress into sand which has not been disturbed for some time.

Photograph 1. Aerial view of a large RBF event at Inskip Point in June 2011, taken from a helicopter. (Source: Channel 10 television news).

An additional observation at both study sites is significant. The amphitheatre shaped scars left by RBF events are evident on satellite images at both sites. Given how rapidly sand movement obliterates RBF sites, it is further evidence that these events occur frequently at these locations.

4.5 Description of an RBF event

The progress of one RBF event which took place on 21.1.2014 at the Amity Point study site is described in this section. A video recording was made covering the event from its unexpected arrival at the beach to its conclusion. From this video and observations made at the time, the progress of the evolving event has been reconstructed.

The event reached the beach at 4.55pm (t=0 min) and finished at 6.42pm (t=107 min) having remained active for 107 minutes and eroded an area of 2980 m^2 in plan. The event's progress is shown in Figure 3 and Photographs 2a to 2f. The height of the subaqueous sand wall when it arrived at the beach was estimated by eye at between 6 and 7 metres and its initial wall velocity in clean sand was about 0.8 metres per minute.

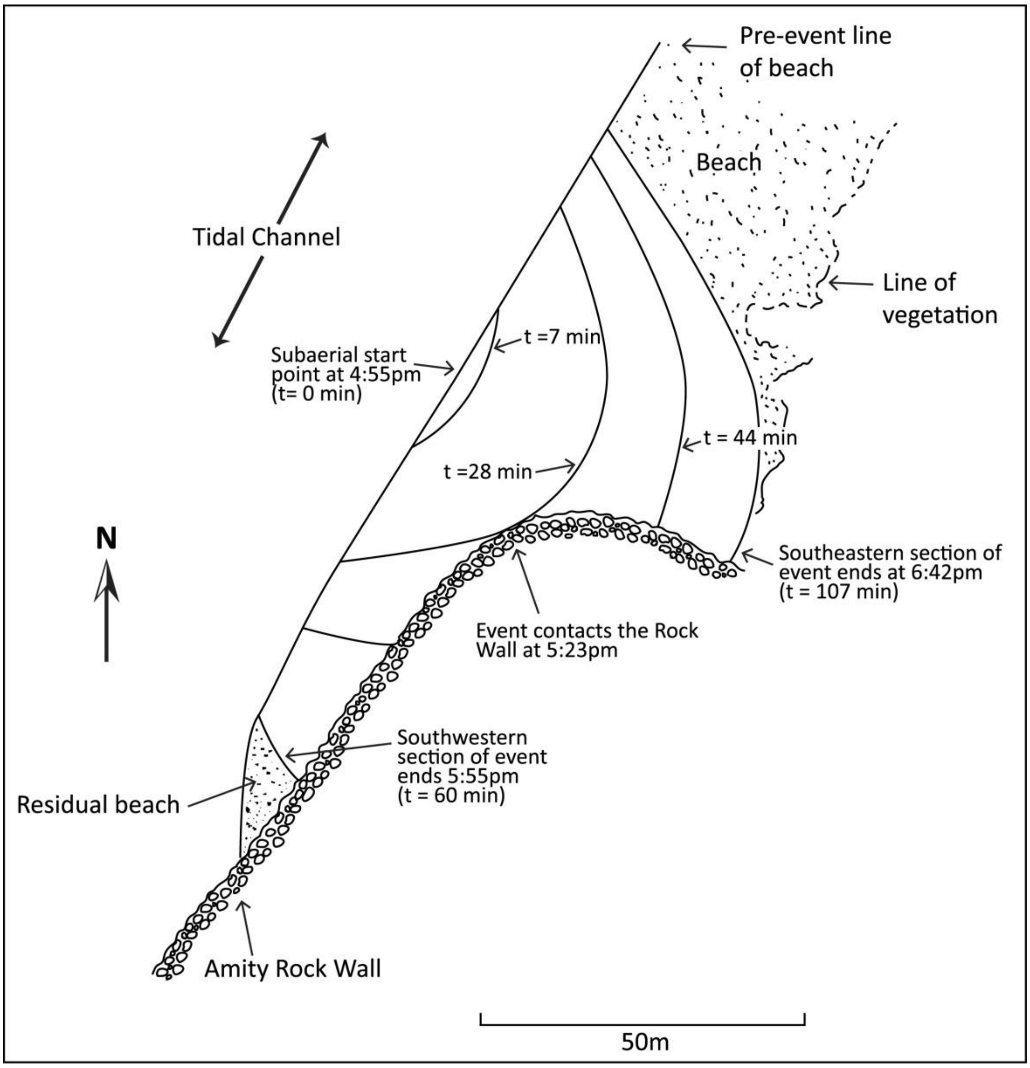
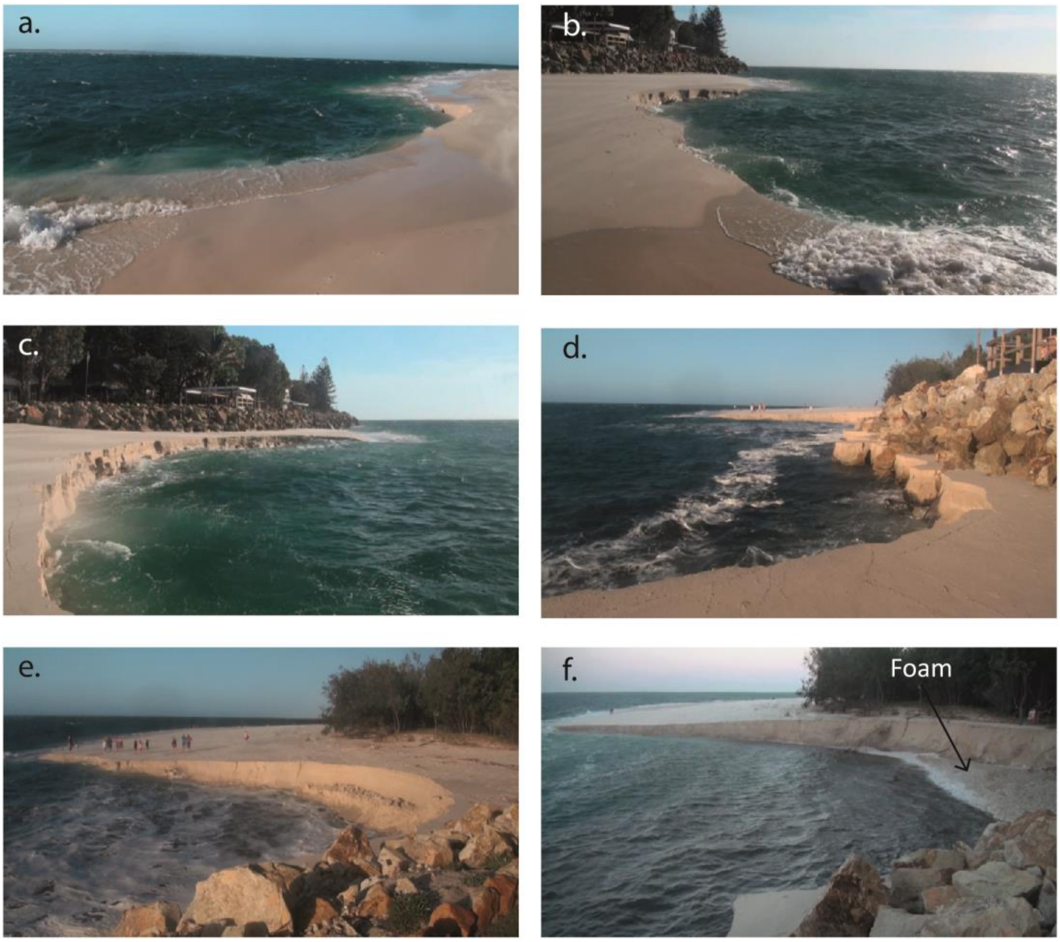


Figure 3. Evolution of the described RBF event which took place at the Amity Point study site on 21.1.2014.

When the event reached the rock wall at t=28 min., it bifurcated and continued in two directions, one southwest and one southeast (Figure 3). The southwestern section continued to move at about 0.8 metres per minute, with a sand wall height of about 6 metres and finished at t=60 min., leaving a small residual beach (Figure 3). The southeastern section remained active until 6.42pm (t=107 min.). For the last hour, its wall velocity slowed to less than 0.3 metres per minute. Over this period, a thick layer of foam was produced (Photograph 2f). The pore water here was fresh. It is possible that the slowing rate and foam production are related. Organic matter in the pore spaces between sand grains could be expected to reduce hydraulic conductivity and/or increase fluid viscosity, thereby slowing the pore pressure dissipation rate and consequently the retrogression velocity of the wall.



Photographs 2 (a to f). Evolution of the RBF event of 21.1.2014. a. t=12min and view to NE. b. t=20min and view to SW. c. t=25 min and view to SW. d. t=45 min and view to NE. e. t=45 min and view to NE. f. t=100 min and view to NE.

A bathymetric scan taken 14 hours after the event indicates that triggering probably occurred at about 6 or 7 metres depth and about 50 metres offshore (Figure 4). If so, the event was active and retrogressing towards the beach for about an hour before it became visible. There was no sign of the approaching event evident on the sea surface before it arrived at the beach.

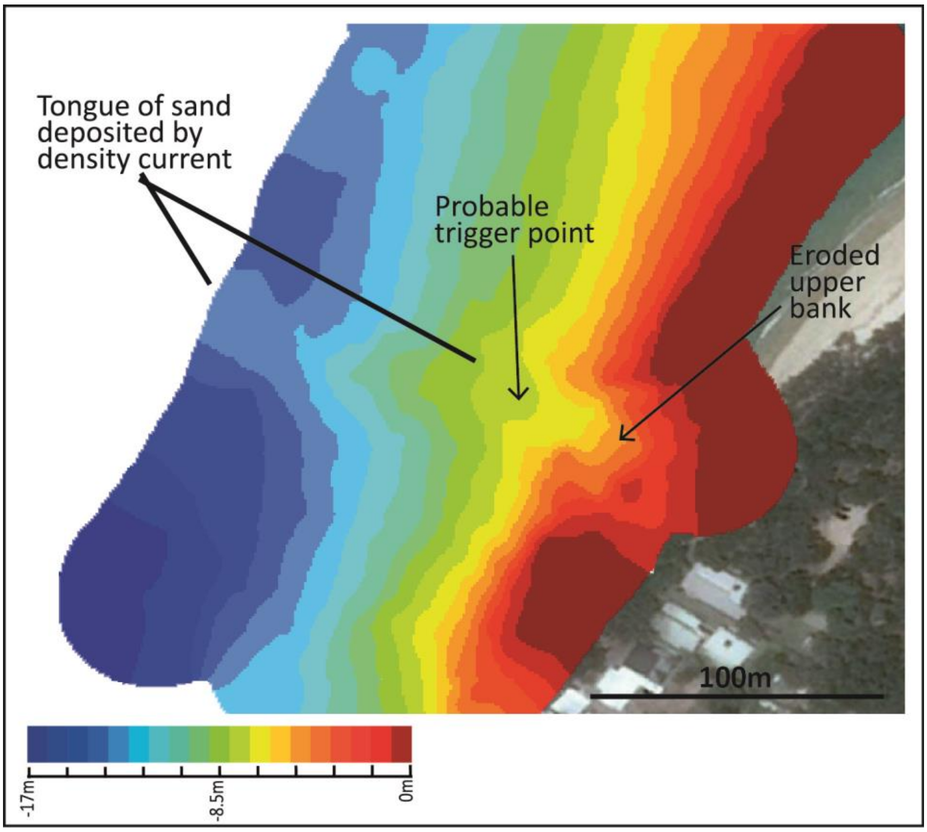


Figure 4. Bathymetric scan taken 14 hours after the described RBF event. Note the probable starting point, the eroded upper bank and the deposited tongue of sand.

The bathymetric scan also shows that the density current extended offshore for well over 200 metres, depositing a tongue of sand 10 metres wide and about 1 metre high (Figure 4). Note that this eroded sand was transported further into the channel than the area covered by the post-event bathymetric scan.

Figure 5 shows the bathymetric profiles before and after the event. The pre-event profile is derived from a bathymetric scan taken one week prior to the event and is probably very similar to the starting profile on the day of the event. The post-event profile is derived from a bathymetric scan taken about 14 hours after the event (Figure 4) and after considerable sand infilling on the upper beach had already occurred. The volume of sand eroded from the upper beach is not consistent with that deposited in the channel probably because the area of deposition exceeds the area of erosion and because the bathymetric scan did not extend sufficiently far offshore to capture the entire area of deposition. However, it is possible that a significant quantity of eroded sand did initially settle closer to the event and was subsequently moved by tidal currents in the 14 hours before the bathymetric scan was recorded (Figure 5).

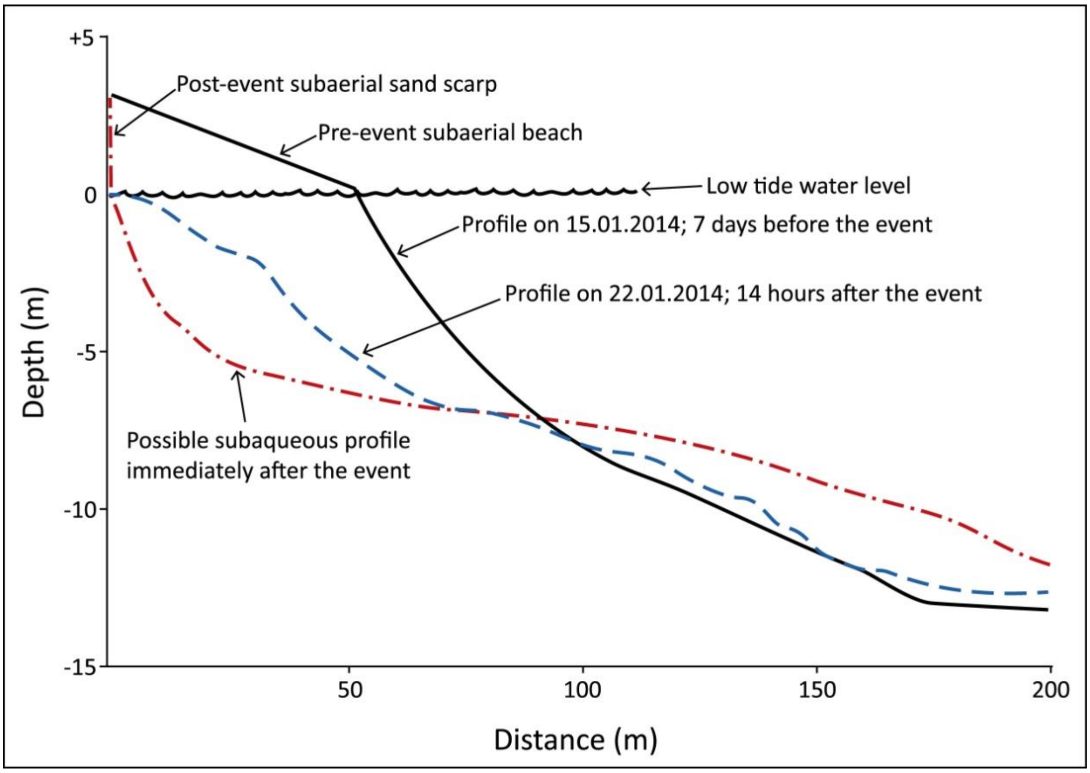


Figure 5. Profile of the described RBF event which took place on 21.1.2014. (Note vertical exaggeration =3).

The tidal cycle on the day of the event was recorded by a pressure logger located 0.3 kilometres from the study site. These data indicate that the event probably started about two hours after maximum ebb flow. By the time the breach arrived at the beach at 4.55pm, there was little tidal current. It is concluded that the sand was carried away primarily by the density current generated by the event itself and that tidal currents did not play a major role in sediment redistribution during this event.

Beach sands sampled had 52.9% by weight in the 125-250 micron range and 45.9% in the 250-500 micron range (mean of 4 samples x two replicates), consistent with the sediment characteristics of RBF sites elsewhere. The sea floor particle size distribution within the RBF site was slightly coarser than the beach face sediments, with 37.8% in the 125-250 micron range and 60.3% in the 250-500 micron range (1 sample x two replicates), consistent with some winnowing of finer particles and their redistribution further offshore.

5 INTERPRETATION OF FIELD OBSERVATIONS

Here we briefly interpret the field observations in the light of other geotechnical knowledge.

The observations can be explained by dilative behaviour of sand which allows breaching to occur. We reason that the observed slowly (0.3 to 0.8 metres per minute) retrogressing, subaqueous, near vertical walls of sand (6-7 metres high) can only occur in sand with dilative potential (relatively tightly packed). Such vertical walls of sand could not exist in non-dilative (loosely packed) sand because rapid flow liquefaction would prevent their development.

Independent measurement of the density profile of an RBF site prior to an event by CPT or SPT testing was not carried out in this observational study. If such information was available, it would help to confirm the above explanation. Two indications that the sand on the upper beach at the Amity Point study site is relatively densely packed are available. First, the intertidal beach supports heavy machinery which is regularly used to maintain the rock wall. Second, it is known that sand with relatively uniform grain size tends to pack tightly, particularly if an external energy source is also available. Yao You (2013) states, ‘long-shore drift and wave re-worked deposits favour the production of dilative deposits’. Sand arriving in the long-shore drift and settling on the upper beach at the study site has been winnowed into a relatively uniform grain size with waves supplying energy during deposition.

In contrast, sand settling at the base of the study site in 5 to 10 metres depth and hence beyond the influence of wave energy could result in loose packing. If loose sand was present at the base of the deposit, flow liquefaction could result which may be the trigger for the subsequent RBF events observed on the upper beach.

Finally, early in the event described in section 4.5 above, both breaching and sliding were observed and the wall velocity was measured at about 0.8 metres per minute. This suggests the dual-mode of failure described from flume tank experiments by Yao You (2013) was operating. Dual-mode failure continued in the south western section of the event until the end. However, late in the south eastern section, no sliding was observed and the wall velocity had slowed to 0.3 metres per minute. This suggests that breaching only was occurring. The evolution of the south eastern section from dual-mode to breaching only can be explained if the event encountered sand with greater dilation potential further up the beach.

5 CONCLUSIONS

While rapid erosion events at Amity Point and Inskip Point on the east coast of Australia have been observed for over a century, previously they have not been systematically recorded and analysed and they have not been recognised as the retrogressive breach failures which have been extensively studied at other sites overseas and in flume tanks. Previously, they have been diagnosed by coastal scientists as shear failures of an over-steepened channel.

Observations made during this study clearly show that these events are caused by breaching of fine relatively densely packed sand at the channel margins at both sites. These events happen commonly at both study sites and are natural phenomena which are triggered offshore and retrogress towards the shoreline, sometimes causing significant erosion and damage to shoreline erosion defences. This new understanding will assist shoreline planning and management including the design of appropriate erosion defences.

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