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Letter

Discoveries on coastal retrogressive breach failures inspired by failure of an underwater fixed platform

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ABSTRACT

Retrogressive breach failures (RBF) are submarine landslides that result in a nearly vertical sand wall above and below the water surface. Previous studies suggest a four-phase mechanism of RBFs, including triggering, propagation, termination, and recovery phases. There have been both laboratory and field studies on the later three phases, while the triggering mechanism of RBFs remain unknown given the event occurrence is unpredictable both spatially and temporally.

Amity Point on North Stradbroke Island, 37 km Northeast from Brisbane, Australia is a valuable coastal flow slide study site with frequent occurrence of approximately every two weeks (Beinssen et al., 2014) of them at a fixed location. Aiming at revealing the triggering mechanism of flow slides, an eight-meter-tall underwater tripod was manufactured and anchored on the seabed. The tripod location was designed to be fixed at a point with minimum bathymetry change during flow slide events referring to existing studies (Beinssen et al., 2014) with between 1.5 m and 2 m deep helical anchors. The tripod collapsed overnight by the undermining of two of the three helical anchors, including the 2 m deep anchor, by a significant underwater flow slide while there was minimal flow slide evidence on the beach.

The short lifespan of the tripod presents the complexity of RBFs (especially underwater) and the limitations of existing research. Underwater RBF events that do not propagate to the shore (or slightly erode the shore) occur more frequently than previous research reported (Beinssen et al., 2014). While it does not propagate to the shore, the event still erodes a significant amount of sand underwater. It indicates the triggering occurs at 10 m underwater or even deeper.

1. Introduction

‘Flow slides’ refer to slope failures where sediment-fluid mixture rather than solid sediment fails from slopes (Nédélec et al., 2022). Flow slides can be completely submerged or partly above water surface. Retrogressive breach failures (RBF) are a special type of flow slides which present nearly vertical retreating sand wall above and below water, generally referred to as the breach. RBF usually occur in coastal areas close to deep tidal channels (Nédélec et al., 2022), but they also occur at riverbanks or in lakes, associated with sand dredging (Mastbergen et al., 2019).

Since the 19th century, the term ‘ breaching flow slides’ tend to be the synonym of RBF (Alhaddad et al., 2020; Beinssen et al., 2014; Mastbergen et al., 2019) in relevant research literatures, while flow slides refer to both RBF and liquefaction flow slides. In this study, the term RBF will be adopted rather than flow slides to avoid confusion and ambiguity.

RBFs had been reported in the 19th century in the Netherlands (Koppejan et al., 1948) and the 20th century in U.S. (Mastbergen et al., 2019). These reports were in various languages and RBF involves multi-discipline knowledge (e.g., geotechnical engineering, coastal engineering, fluid mechanics, geomorphology). The difficulties filling the language and discipline gaps hindered the research progress of RBF (Mastbergen et al., 2019). One reported event in Dutch (Mastbergen et al., 2019) was characterized as liquefaction, a phenomenon, that occurs in loosely packed sand. The characterization was suggested by Karl Terzaghi, ‘the father of modern geotechnical engineering’. Liquefaction was described in Terzaghi’s, 1925 handbook (Terzaghi, 1925) as one type of land slide mechanism associated with saturation, excess pore water pressure, loosely packed sand and sudden collapse.

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Based on Terzaghi's hypothesis, possible RBF events studied by Müller (1898) in Noord-Beveland, Netherland were caused by liquefaction. Until late 20th century, Padfield (Padfield, 1979) provided a new explanation for bank failures in the Mississippi River that occurred in densely packed sand based on dredging research in Delft (van Os, 1977). This is beyond modern geotechnical engineering theory, where a prompt submerged sand slope failure that erodes a significant amount of sand is wrongly linked to either liquefaction in saturated loose sand or sinkholes in Karst landscapes.

With the capability of sharing photos online since 1993 and the satellite imaging technology becomes widely available since early 21st century, many RBF events have been recorded worldwide (Mastbergen et al., 2019). At the same time, with the progressing of slope failure research, several slope failures occurred in densely packed sand that were misidentified as 'sinkhole' or 'liquefaction', have been identified as RBFs and a four-phase hypothesis has been raised (Beinssen et al., 2014) to describe the mechanism of RBF.

Referring to existing studies and reports (Mastbergen et al., 2019), the preconditions of RBF occurrences include fine, saturated sand near a steep submerged slope (e.g. tidal channels) with the average slope from the beach/toe of the seawall to the deepest point in the approaching tidal channel is more than 1.15 referring to Flood Defence Act (2017). The fine sand should be densely packed to sustain negative pore water pressure when the sand skeleton dilates under shear stress (Iverson, 2005; den Burg, 2002).

The RBF event is divided into four phases as the triggering phase, the propagating phase, the termination phase and the recovery phase. In the four-phase hypothesis, several possible triggering mechanisms are listed, for example, low tide, rise of groundwater table, high rainfall. van Rhee and Bezuijen (1998) suggests that RBF triggers for breaching include suction-induced steep slopes, which propagate as sand-water mixtures flow down. Alhaddad et al. (2020, 2023, 2024) states that the exact triggers for breaching remain complex and under-researched, though factors like sand properties, slope geometry, and sediment-water interactions play a role. Observation of the start of RBF events has never been achieved due to the difficulty in real-time continuous monitoring seabed topography. The field sites of frequent RBF events have extremely dynamic seabeds and any platform attempt to be fixed on the seabeds would have been undercut and failed.

After the RBF event is triggered, a retrogressive breach is formed and propagates upslope (Fig. 2(A)) The breach can reach the shoreline and then propagate onto the beach if not interrupted by sand characterization change or unsustained density current (Fig. 2(B)). Fig. 1(A) is a photo of RBF at the propagating phase at Amity Point, Queensland, Australia, where large blocks of sand fell into water. The propagating phase remained for approximately 30 min in the photographed event and the peak retreating velocity was of the order 5 mm/s. The event had an underwater breach of 7 m high measured by a fishing line by Beinssen et al. (2014).

Unknown trigger of RBF leads to another question about the timing when the nearly vertical breach faces are formed. One possibility is the breach becomes vertical once the event is triggered, while the other possibility is that the breach becomes vertical when the event presents above water due to surface tension in wet sand exposed in air. The 7 m tall vertical wall presented in Beinssen et al. (2014) study does not rule out the hypothesis that the vertical breach forms after breaching reaches water surface. This hypothesis can only be verified or rebutted when triggering is observed in situ and the observed RBF is not triggered by sand dredging, given that sand dredging will create a vertical face.

When the density current is not sustained anymore by erosion and the breach that is reducing in height, the RBF event terminates (Fig. 1(B) and Fig. 2(C)). After the termination phase, the beach eroded by the RBF

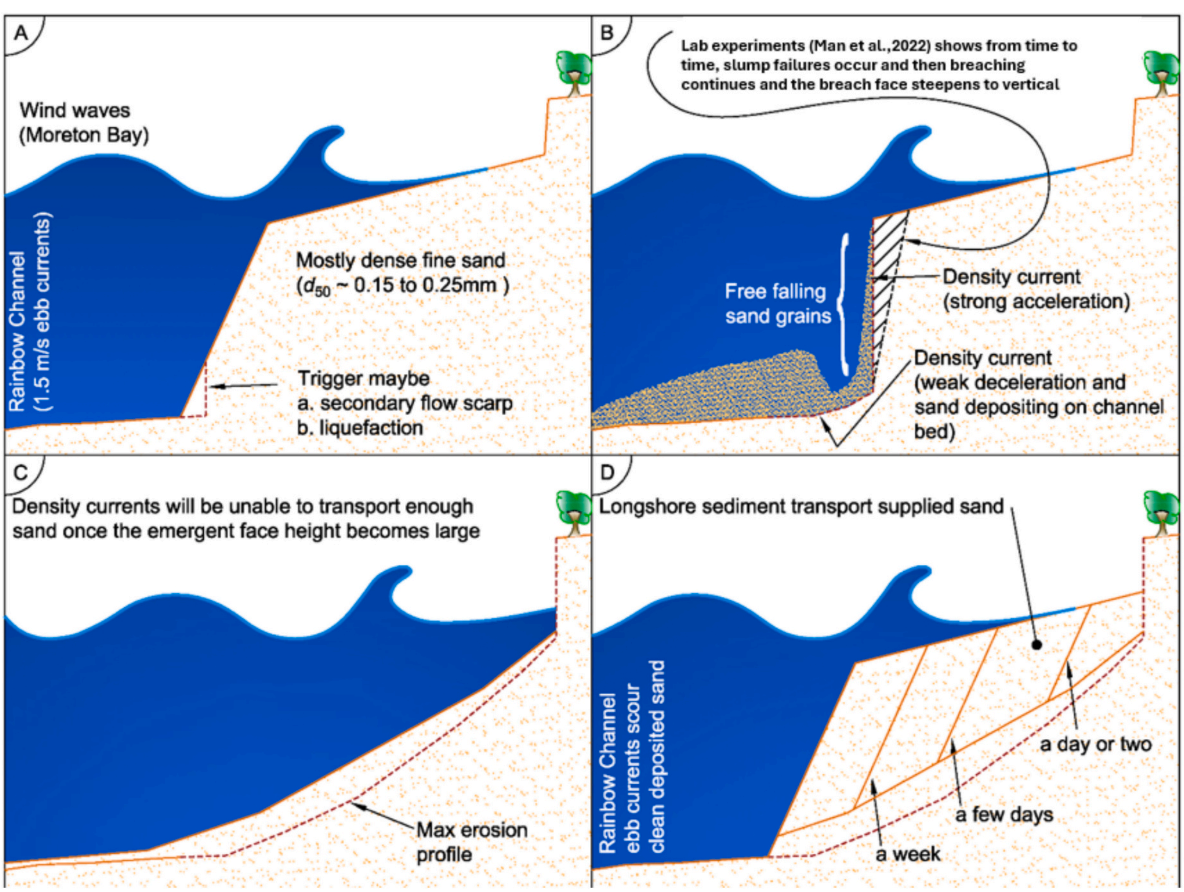

Fig. 1. Conceptual sketch of a breaching flow slide involving a triggering (A), retrogressive breach failure (Man et al., 2022) (B), termination (C), and recovery (D).

(A)
(B)
(C)

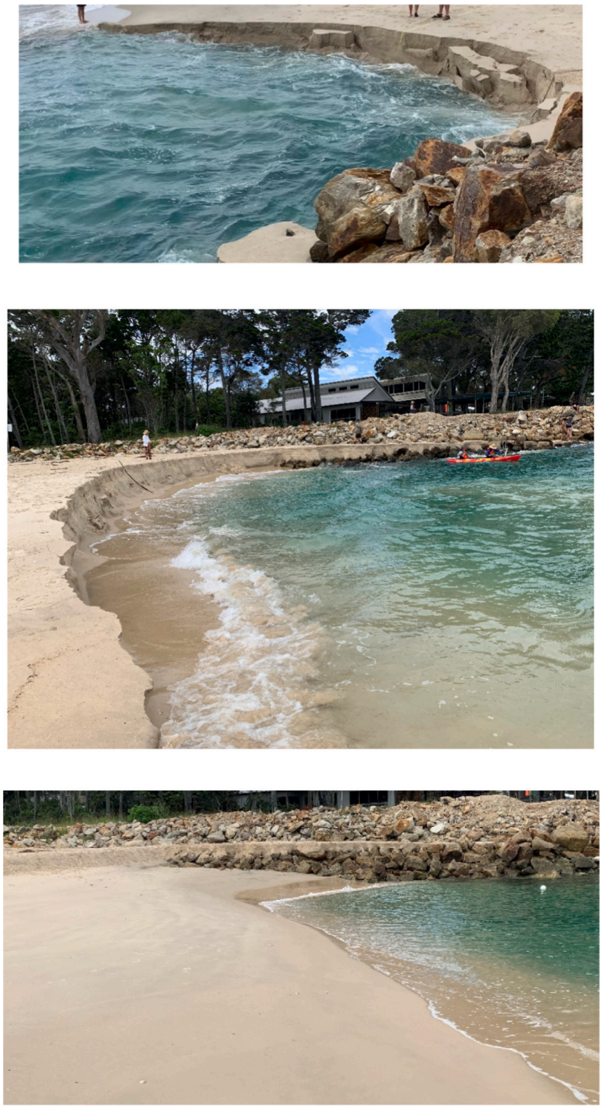

Fig. 2. (A) Propagating phase (B) termination phase (C) the recovery phase in a flow slide event recorded on 14/01/2023 at Amity Point field site.

event gradually recovers with the waves and the longshore current transporting sand from offshore. In the recorded event, the breaches were replaced by normal beach slopes after 24 h (Fig. 1(C) and Fig. 2 (D)). In several days, the beach grew into the original shape but with much less sand compared to the beach profile before event; in ~12 days, the beach fully recovers and the sand is compacted by waves, which preconditions next RBF event. The recovery time varies at different sites. In Westerschelde estuary (Mastbergen et al., 2016), the recovery takes 6 months. Another example with measured bathymetry and recovery is Inskip Point (Shipway, 2015).

Apart from the unknown triggering mechanism, local knowledge regarding the propagation, termination and recovery phases is necessary for managing authorities and residents to manage the emerging threats to properties and the flow slide barrier from RBFs (Beinssen et al., 2014).

The field site in the current study, Amity Point is a flow slide study site that has regular (approximately every two weeks (Beinssen et al., 2014)), spatially predictable events at a fixed point (the end of the rock wall on Fig. 3). Coastal erosion has been a pressing threat for Amity Point for more than a century, where residents have been observing the coastline retreating since 1871. The retreating coastline has drowned a sand horse racetrack at Amity Point to the bottom of the Rainbow Channel where Races were run in the 1920s. There has been belief (Eberhardt, 1978) that the coastal erosion has worsened due to the natural process of Rainbow Channel migration between Moreton Island and North Stradbroke Island from south to south-east direction. The realignment has moved the channel banks inland and the over-steepened banks subject to strong tidal currents eroded Amity Point foreshore with frequent RBF events.

The continuing threat of RBF events at Amity Point has got attention from both Redland City Council and residents. The rock wall on Fig. 3 is a flow slide barrier built and managed by Redland City Council to protect foreshore properties. Both Redland City Council and residents desire knowledge regarding RBF event triggers to improve the flow slide management protocol. There have been speculations on a high groundwater table being the trigger among the residents based on their gardening experience. Beinssen et al. (2014) have communicated with Redland City Council regarding the importance of periodical monitoring the seabed and the Dutch Safety Assessment rules for levees (Flood Defence Act, 2017) where damage is expected if the average slope from the beach/toe of the seawall to the deepest point in the approaching tidal channel is more than 1.15.

This study aims to measure the underwater data for Amity Point flow slides using a fixed platform for discovery of the triggering mechanism. The fixed platform failed, but the failure reveals new knowledge on flow slides presented in the next section. It is emphasized here the fixed platform is an important attempt for RBF in situ triggering study. After the failure of the fixed platform, a floating platform is in testing progress at Amity Point. The floating platform design is to great extent inspired by the knowledge obtained from the fixed platform study. The floating platform consists of two anchors on the seabed and a hobie cat. The platform managed to survive a significant RBF event in early 2024, which was the largest erosion recorded in the past 5 years (Fig. 4).

2. Fixed platform design and field work

The fixed platform was an 8.0 m tall, 8.0 m wide tripod structure made of aluminium pipes. Three cross-sections were bolted in the middle of each tripod leg as a support frame for acoustic sonars. Fig. 5 (A) presents a photo of the upper half of the tripod; Fig. 4(B) is the drawing of the tripod and Fig. 5(C) is a photo of the tripod navigation light after installation.

Two Tritech Super Seaking Dual Frequency Profilers are designed to be bolted onto the cross-sections, with one profiler measuring a high frequency (600 kHz) cross-shore seabed profile and the other measuring an along-shore seabed profile. The high frequency monitoring of cross-shore and along-shore seabeds profiles will reveal the triggering process of RBF events. The along-shore seabed profile and cross-shore seabed profile are presented as two red lines in Fig. 4. The profilers have been tested in laboratory wave tanks and are able to record profile change in accuracy of centimetres with high sediment concentration.

Three square helical anchors were installed (1.5 m × 40 mm × 40 mm) as anchors for the fixed platform. The tripod legs were connected to the helical anchors by box connectors. The fixed platform was installed in ~8 m bathymetry referring to mean sea level. The installation position was designed to be a balance point at Amity Point event site where sand is neither eroded nor accreted referring to previous study (Beinssen et al., 2014). The tripod was designed to endure the maximum turbidity current which occurs at the balance point where the bathymetry change is minimal according to Beinssen et al. (2014). The drag force of a density flow (assume which has a 5 m/s velocity and 1500 kg/m^3 density) is ~225 kN. The pressure from the force onto the tripod (~22.5 MPa) is much less than strength of aluminium (276 MPa).

Besides the installation and retrieval of the tripod, beach-based and kayak-based measurements were conducted in January and May 2023 to enhance understanding of Amity Point RBF events. Beach profiles were surveyed daily between January 14th – 24th after an RBF event (more frequent immediately after the event) to record beach recovery. The beach profile measurements were obtained by a measurement tape and a

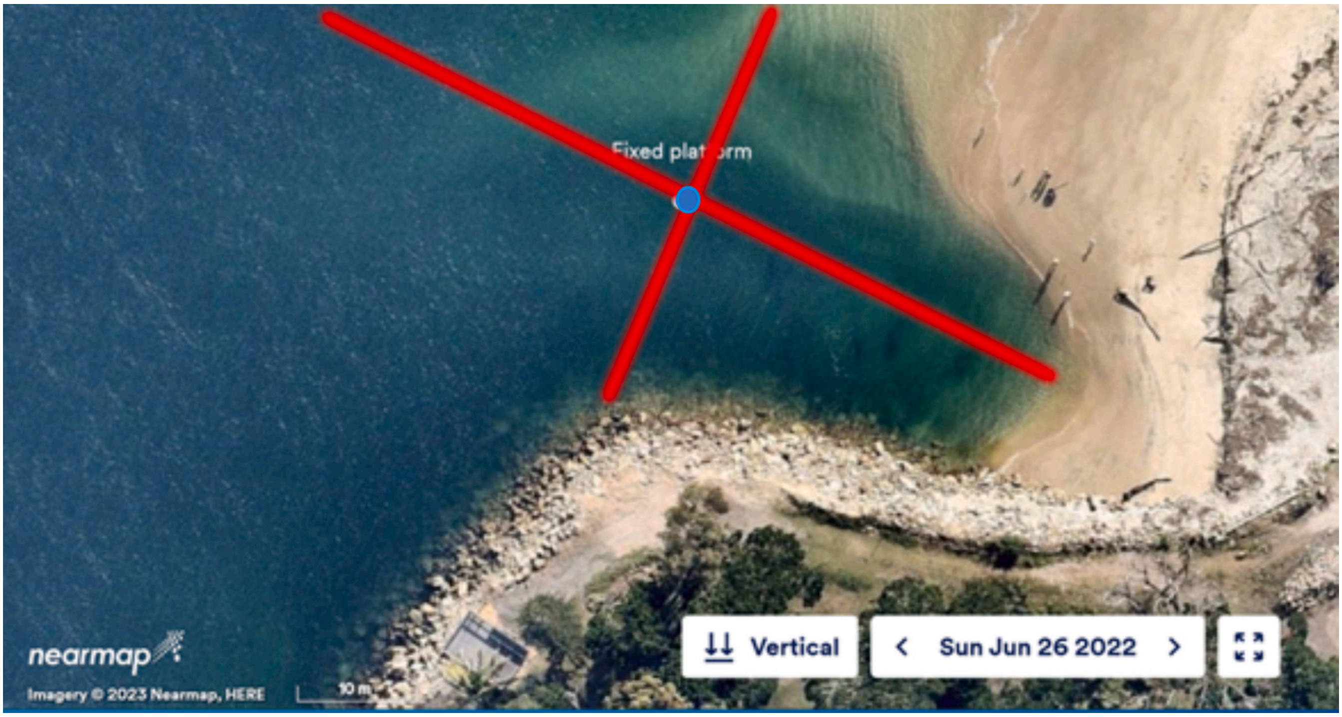

Fig. 3. Nearmap image of Amity Point field site shortly after a flow slide event. The blue dot indicates the location of the fixed (and the floating) platform installed in this study. Image date June 26th, 2022 (Nearmap, 2014). The two red lines represent the cross-shore and along-shore profiles the profilers will record. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 4. The significant RBF event 05/01/2024, which is the largest erosion recorded in the past 5 years. The floating platform survives the event and stays safe on the water surface 50 m away from the beach.

graduated staff. Kayak-based bathymetry survey was conducted on January 23rd and May 5th, 2023, using a Garmin GT20 Transducer to obtain bathymetry in different stages of RBF events. The bathymetry maps are presented in Fig. 8.

3. Platform installation timeline and field work results

The fixed platform was installed by commercial divers on May 3rd, 2023, at mean sea level bathymetry of ~8 m. The West-North-West

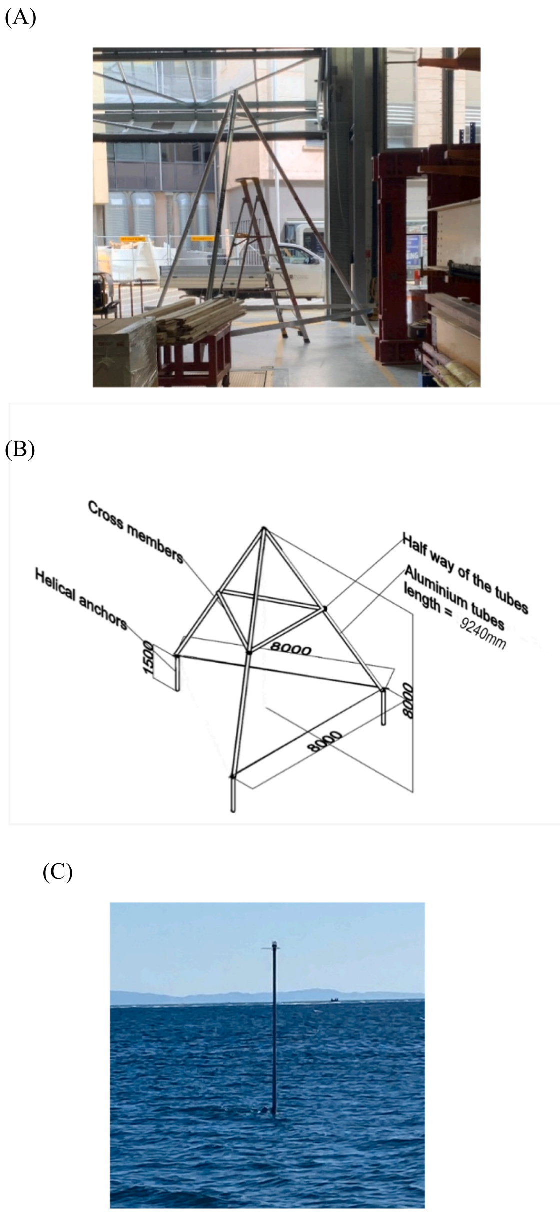

Fig. 5. (A) Photo of half of the fixed platform (i.e. three 4-m legs and three cross members.) (B) Drawing of the fixed platform including the legs, cross-members and helical anchors. (C) Photo of the installed submerged platform with a navigation light ~2 m above mean sea level.

anchor had a 2 m extension due to water depth differences from the other two anchors. The initial position of the tripod was 27^{O} 23.566′ S 153^{O} 26.375′ E. The orientation of the fixed platform was 35 degrees from true north.

The crew went to site on May 4th, 2023, and the tripod navigation light disappeared. At the shoreline, a small, negligible RBF event was observed (Fig. 6). A large sand movement in comparison with the negligible RBF event onshore, was observed by a snorkeler underwater. Referring to the fact that the tripod fails, it can be deduced that the sand erosion at the bathymetry of 8 m is more than 1.5 m. It also suggests the trigger of RBF events is further than 20 m offshore, where the bathymetry is 8 m.

There are three possible causes of the tripod failure: (1) an RBF event propagating from the deep channel towards the beach eroded the foundation; (2) the foundation is eroded by the density current resulting from an RBF event propagating from the shoreline. (3) The structure of the tripod was damaged by the impact of the turbidity current. The

Fig. 6. Small above water RBF event photo (04/05/2023) correspond to significant erosion underwater. The onshore vertical sand wall height is only several centimetres.

second can be ruled out given that ~1.5 m height of sand was eroded. Turbidity current erosion leads to a continuous surface rather than an underwater 1.5 m tall breach. Furthermore, one anchor was more buried while another was completely exposed. The height difference indicates an RBF event with at least 1.5 m breach height, rather than erosion.

The photo of the collapsed tripod and the description from the commercial divers also proves that the tripod is not damaged by the turbidity current but due to foundation failure. The tripod legs were intact, only three cross members were bent, possibly by the gravity of the tripod.

The commercial divers found the tripod wreckage after 15 min of searching at ebb current headed towards low tide. The diver stated that the entire area of tripod installation was considerably deeper (~10 m) than the time of installation (~8 m). The South-South-West (SSW) anchor was completely exposed and flapping in the forcing of waves and current (Fig. 7(A)). The WNW (offshore) anchor which had a ~ 1 m extension was still imbedded but the shaft was more exposed (Fig. 7(B)). The North-North-East (NNE) anchor and its shaft was completely buried (Fig. 7(C)). The diver reported significant differences in both sand color and compaction. The sand was much softer (i.e., uncompacted) on the day of tripod retrieval than the day of installation. At the current field site, soft sand is an indication of recent RBF occurrence, while dense sand is a sign of recovery/reposition for the next event. Regarding sand color, the diver observed a difference between the original sand bed and recently deposited sand. The original sand bed has a deeper color than the recently deposited sand that possesses a fluffy look. The tripod legs survived without bending while all three cross-members were severely bent. The apex bracket couplers were all bent in the same direction, indicating strong torque around the vertical axis of the tripod.

Besides the tripod collapse, kayak and boat-based bathymetry also proves the occurrences of underwater RBF events. Fig. 8(A) is the boat-based bathymetry contour surveyed in 04/2022 as the seabed level at the recovery phase. The tripod is placed between 9 m and 10 m contour line where the seabed is relatively flat. RBF events can be observed in both Fig. 8(B) and Fig. 8(C), adopting the bathymetry contours in Fig. 8 (A) as a baseline for comparison. Interestingly, the two RBF events present different characteristics regarding propagating directions, vertical sand wall heights and spatial ranges. In Fig. 8(B), a steep slope (where the bathymetry drops from − 2 m MSL to − 7 m MSL) presents close to the shoreline. This RBF event was also captured by beach profile surveys and beach volume calculation in Fig. 9. While in Fig. 8(C), the bathymetry contour lines shift directions where the tripod was deployed, indicating an RBF event not propagating cross-shore and it

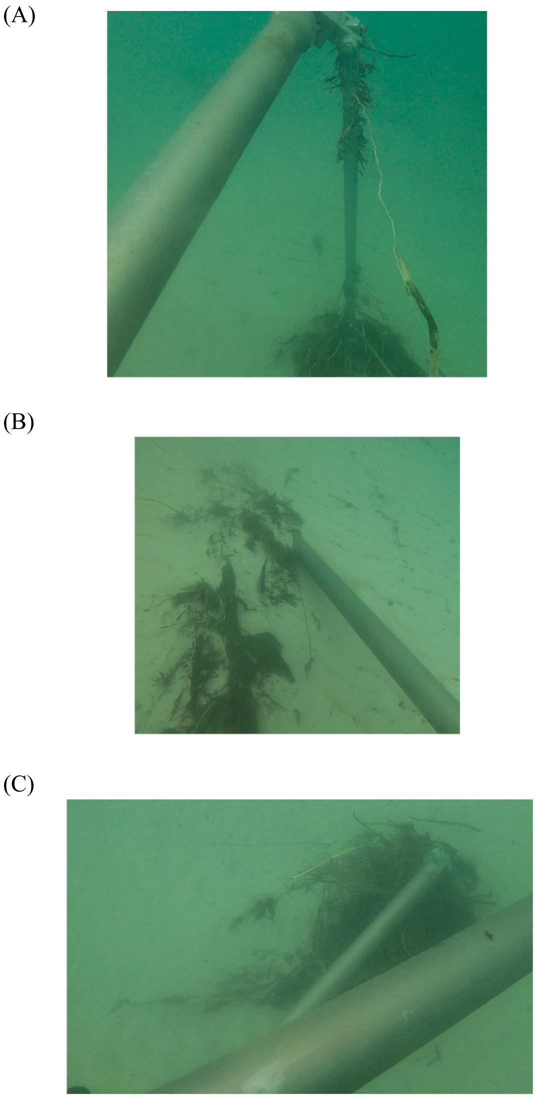

Fig. 7. Photos of tripod wreckage on 09/05/2023. (A) The SSW anchor that is completely exposed. (B) The NNE anchor that is more buried than the installation day. (C) The WNW (offshore) anchor, whose extension is still buried but more exposed than the installation day.

eroded ~3 m sand comparing to the recovery phase seabed level in Fig. 8 (A). The slight shift in contour line directions may indicate there have been two RBF events in different directions. It should be noted that the kayak-survey date (05/05/2024) is earlier than the tripod retrieval date (09/05/2024). Referring to the tripod retrieval photos (Fig. 7), there possibly was an along-shore RBF event between 05/05/2024–09/05/2024, that deposited sand at the NNW anchor while eroding more sand at the WNW and the offshore anchor.

Fig. 9(A) and (B) present the beach profiles and beach volume after the RBF events on 14/01/2023, respectively. The beach profile 124 h after the RBF event was fuller than the beach profile 170 h after the event, which indicates an underwater RBF event. The beach volume suggests the same as it decreased at 124 h after the RBF event. Fig. 10 presents a beach photo after 124 h after the RBF event: there was a vertical, short wall of several centimetres on the beach. The photo presents a minor RBF event extremely similar to that in Fig. 6, indicating that major underwater slides without eroding the beach occur frequently at the field site. The minor RBF occurs between 124 h – 170 h after the previous RBF event and eroded approximately 15 m^3 beach volume for each meter width, which is before the beach completely recovered. This is another new observation on RBF events given the

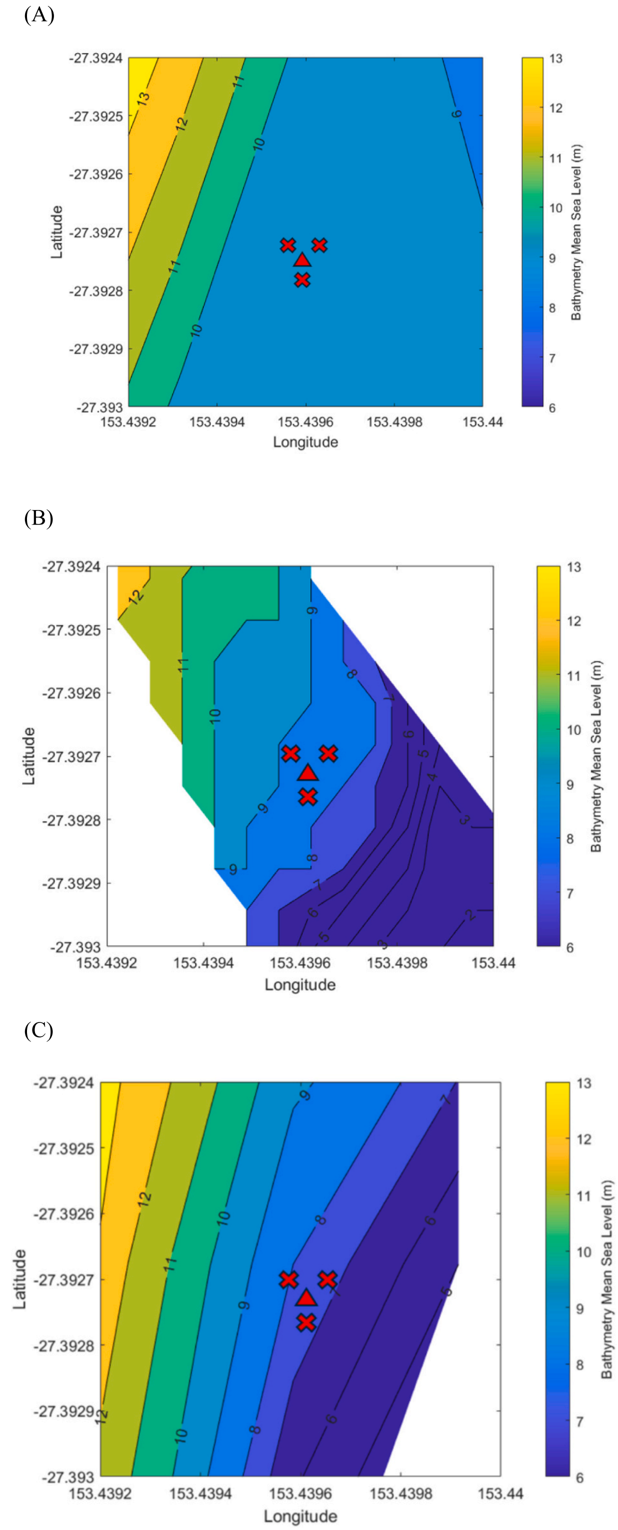

Fig. 8. Bathymetry survey results on 22/04/2022 (A) and 23/01/2023 (B) and 05/05/2022 (C) with tripod location (the red triangle) and tripod anchors location (the red crosses). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

current theory assumes that an RBF is only triggered after the conditions (steepness, height) for a new event are present. Referring to Beinssen et al. (2014) and Mastbergen et al. (2019), the conditions of RBF triggering is a fully recovered beach, compacted fine sand and a slope angle steeper than the repose angle. These conditions, however, does not

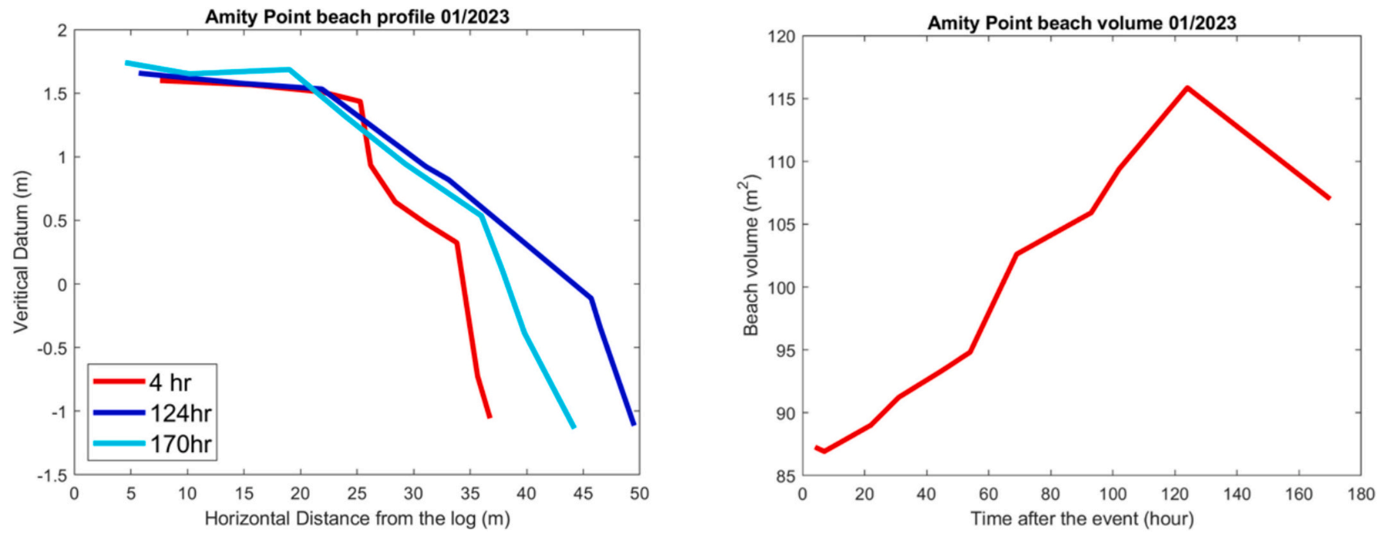

Fig. 9. (A) Beach profiles 4–170 h after the RBF event on 14/01/2023. (B) Beach volume after the RBF event.

Fig. 10. Small above water RBF event photo (19/01/2023) correspond to significant erosion underwater.

comprehensively describe the triggering conditions at the current study site. In Fig. 6, a short, vertical sand wall (whose slope steeper than the repose angle) stands for days without triggering a larger RBF event. In Fig. 9, the 4 h profile does not trigger an RBF event despite its steepness. The RBF event occurred between 124 and 170 h after the previous RBF event indicates that RBF event triggering does not require a fully recovered beach. More reports on different study sites and events are required to determine a comprehensive RBF triggering conditions that applicable to worldwide. Both in laboratory and in situ.

4. Findings and future research

This study reveals several innovative findings regarding underwater RBF events. Underwater RBF events that do not propagate to the shore (or slightly erode the shore) occur more frequently than previous research reported (Beinssen et al., 2014). A record of visible RBF events from the residents is provided in supplementary information, which leads to a frequency of approximately two weeks. The actual frequency should be higher than two weeks because the record neglects underwater RBF events. When it does not propagate to the shore, the event still erodes a significant amount of sand underwater. The direction of propagation can be along-shore rather than cross-shore, the RBF events are fundamentally a 3-D process, which has been proved by the amphitheatre-shaped scars left on the beaches after the events (Mastbergen et al., 2019; Alhaddad et al., 2020).

Finding the underwater RBF event supports the finding of Alhaddad et al. (2020, 2023, 2024) in laboratory that breaching can be categorized as stabilizing and destabilizing, where stabilizing breaching terminate before reaching water surface. Referring to laboratory observation by Alhaddad et al. (2024) confirms that specific geometric and hydraulic conditions determine whether breaching stabilizes or escalates.

Meanwhile, the current study provides new insights into in situ underwater RBF events: the in situ underwater RBF events can propagate in various directions including the along-shore direction, which contrasts with the cross-shore breaching failure which propagates to the shoreline. In laboratory observation of Alhaddad et al. (2024), stabilizing breaching's breach height decreases over time, while in the current in situ observation, underwater RBF events can be as significant as breaching that propagates to the shoreline, with under water breach of ~2 m and ~ 5 m observed in two different RBF events.

The finding indicates that RBF events, either propagate to the shore or submerged, are a significant mechanism of coastal erosion. The mechanism is not directly related to tidal or storm conditions, which is not aware of by many coastal engineers (van Dijk et al., 2018). The record provided in supplementary information proves that occurrence of RBF events does not correlate high, low tide or storm at Amity Point over 2 years.

The study also inspires future in situ RBF research. A fixed platform is ideal to obtain continuous bathymetry measurements at field site. However, given the extremely dynamic seabed, there is only one way to prevent the fixed platform to be washed away by underwater RBF. Long anchors (much longer than the 1.5 m length adopted in this study) should be adopted and the anchors should be placed in after a large RBF event. Considering an RBF cycle is less than a fortnight and other factors (weather and marine contractor availability, etc), the installation opportunity is limited. Another option is to conduct continuous bathymetry survey with a survey vessel or submarine drone continuously scanning the area as soon as some activity is detected, when triggering an artificial RBF event like the flood control test in Netherlands in 2014 (Mastbergen et al., 2016).

In this case, a floating platform is preferred because it is not affected by seabed level changes. On the other hand, a floating platform is affected by wave, wind and tidal currents so adequate engineering design is necessary to stabilize the platform and obtain reliable measurements.

Besides attempts at installing a platform, frequent boat-based or remote-operating-vehicle (ROV) based, spatially and temporally extensive bathymetry survey is another option to gain knowledge on the scope of the bed level changes during RBF events. These bathymetry survey results are also useful on designing any permanent or semi-permanent instrument deployment platforms.

Author contribution

X.M., D.P·C, W.R.D designed the tripod and supervised the installation. X.M., D.P.C., W.R.D. collected bathymetry and beach profile data. X.M. processed these data and wrote the manuscript. All co-authors proofread and edited the manuscript.

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CRediT authorship contribution statement

Xiamei Man: Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation. **William R. Dally:** Supervision, Resources, Methodology, Investigation. **David P. Callaghan:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Peter Nielsen:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.margeo.2025.107530.

Data availability

All relevant data used in this study has been published in the Github repository:

https://github.com/xman2403/Amity-Tripod-Paper

The repository can be cited as doi.org/10.5281/zenodo.13298967.

References

Alhaddad, S., Labeur, R.J., Uijttewaal, W., 2020. Large-scale experiments on breaching flow slides and the associated turbidity current. J. Geophys. Res. Earth 125 (10). https://doi.org/10.1029/2020JF005582 e2020JF005582.

Alhaddad, S., Weij, D., van Rhee, C., Keetels, G., 2023. Stabilizing and destabilizing breaching flow slides. J. Marine Sci. Eng. 11 (3), 560.

Alhaddad, S., Keetels, G., Mastbergen, D., van Rhee, C., Lee, C.H., Montellà, E.P., Chauchat, J., 2024. Subaqueous dilative slope failure (breaching): current understanding and future prospects. Adv. Water Resour. 188, 104708.

Beinssen, K., Neil, D.T., Mastbergen, D., 2014. Field observations of retrogressive breach failures at two tidal inlets in Queensland, Australia. Aust. Geomech. J. 49, 55–63.

den Burg, Van, 2002. The importance of breaching as a mechanism of subaqueous slope failure in sand. Sedimentology 49 (1), 81–95.

Eberhardt, J., 1978. Erosion at Amity Point-an Example of Shoreline Recession in a Tidal Inlet. University of Queensland Press, Brisbane.

Flood Defence Act, 2017. Wet op de Waterkering [Flood Defense Act]. Government of the Netherlands.

Iverson, R.M., 2005. Regulation of landslide motion by dilatancy and pore pressure feedback. J. Geophys. Res. Earth 110 (F2). https://doi.org/10.1029/2004JF000268.

Koppejan, A., Van Wamelen, B., Weinberg, L., 1948. Coastal flow slides in the Dutch province of Zeeland. In: Proceedings of the 2nd International Conference on Soil Mechanics and Foundation.

Man, X., Callaghan, D.P., Nielsen, P., 2022. Laboratory and Field Investigation on Vertical Retreating Sand Wall Observed in Coastal Flow Slides, International Coastal Engineering Conference, Sydney, Australia.

Mastbergen, D., van den Ham, G., Cartigny, M.J.B., Koelewijn, A., de Kleine, M., Clare, M., Hizzett, J., Azpiroz, M., Vellinga, A., 2016. Multiple flow slide experiment in the Westerschelde Estuary, the Netherlands. Submar. Mass Movem. Their Conseq. 41, 241–249. https://doi.org/10.1007/978-3-319-20979-1_24.

Mastbergen, D.R., Beinssen, K., Nédélec, Y., 2019. Watching the beach steadily disappearing: the evolution of understanding of retrogressive breach failures. J. Marine Sci. Eng. 7 (10). https://doi.org/10.3390/jmse7100368.

Müller, F., 1898. Das Wasserwesen der Niederländischen Provinz Zeeland; with Atlas Containing 10 Tafeln (maps) with detailed illustrations, Berlin, W. Ernst Verlag. Kessinger Legacy Reprints, Whitefish, MT, USA, p. 2010.

Nearmap, 2014. Aerial Map of Hoddle Grid, Melbourne. http://www.nearmap.com.

Nédélec, Y., Fouine, P., Gayer, C., Collin, F., 2022. Time-lapse camera monitoring and study of recurrent breaching flow slides in Cap Ferret, France. Coasts 2 (2), 70–92. https://doi.org/10.3390/coasts2020005.

Padfield, C.J., 1979. Stability of river banks and flood embankments: a centrifugal model study of the influence of the interaction of two deforming layers in the analysis of river bank stability problems. https://doi.org/10.17863/CAM.14114.

Shipway, 2015. Risks Associated with Nearshore Instability Inskip Point, QLD. EDG Consulting.

Terzaghi, K., 1925. Erdbaumechanik auf Bodenphysikalischer Grundlage. F. Duetick., Liepzig-Vienna.

van Dijk, W.M., Mastbergen, D.R., van den Ham, G.A., Leuven, J.R.F.W., Kleinhans, M. G., 2018. Location and probability of shoal margin collapses in a sandy estuary. Earth Surf. Process. Landf. 43, 2342–2357. https://doi.org/10.1002/esp.4395.

van Os, A.G., 1977, June. Behaviour of soil when excavated underwater. In: International Course Modern Dredging. The Hague, The Netherlands.

van Rhee, C., Bezuijen, A., 1998. The breaching of sand investigated in large-scale model tests. In Proceedings of the 26th International Conference on Coastal Engineering, pp. 2509–2519.