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Research Article

Retrogressive Breach Failure in a Tropical Sandy Spit: A Case Study in Puntarenitas, Costa Rica

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Abstract: On Thursday, February 8th, 2024, a subaqueous slope failure occurred adjacent to the sand spit terminus at Puntarenitas, Puerto Jiménez, Costa Rica, whereby sediments were mobilized from a nearshore area encompassing approximately 410 m² of beach front. Investigation procedures included salinity, temperature, and density profiling at multiple stations, complemented by underwater videography. Additionally, photogrammetric mosaics were generated through Unmanned Aerial Vehicle (UAV) surveys, and a bathymetric map was constructed using echosounder data. The failure event was characterized by a primary headscarp and three secondary scarps exhibiting a succession of a stepped-like configuration that extended into the subaqueous zone. The submarine failure surface displayed a concave convergent morphology with a proximal sediment accumulation adjacent to the landslide. Morphological and kinematic analysis of the event indicates that it represents a Retrogressive Breach Failure mechanism. These processes are relatively rare yet recurrent at specific locations, as was corroborated through satellite imagery analysis, thereby constituting a natural hazard requiring measures to prevent future risk generations.

Keywords: coastal landslide, breaching, coastal geohazard, slope failures, shoreline instability, flow slides.

Resumo: Na quinta-feira, 8 de fevereiro de 2024, ocorreu um deslizamento subaquoso de talude adjacente ao término do esporão arenoso em Puntarenitas, Puerto Jiménez, Costa Rica, no qual sedimentos foram mobilizados de uma área costeira abrangendo aproximadamente 410 m² de frente praial. Os procedimentos de investigação incluíram perfilagem de salinidade, temperatura e densidade em múltiplas estações, complementados por videografia subaquática. Adicionalmente, mosaicos fotogramétricos foram gerados através de levantamentos com Veículo Aéreo Não Tripulado (VANT), e um mapa batimétrico foi construído utilizando dados de ecossonda. O evento de ruptura foi caracterizado por uma escarpa principal e três escarpas secundárias exibindo uma sucessão em configuração escalonada que se estendia para a zona subaquosa. A superfície de ruptura submarina apresentou uma morfologia côncava convergente com acumulação sedimentar proximal adjacente ao deslizamento. A análise morfológica e cinemática do evento indica que este representa um mecanismo de Ruptura Regressiva por Brecha. Estes processos são relativamente raros, porém recorrentes em localizações específicas, conforme foi corroborado através da análise de imagens de satélite, constituindo-se assim em um perigo natural que requer medidas para prevenir a geração de riscos futuros.

Palavras-chave: deslizamento costeiro, brechamento, perigo geológico costeiro, falhas de talude, instabilidade da linha de costa, deslizamentos de fluxo.

1. Introduction

There are many kinds of landslides, and some of them are submarines. According to Hampton et al. (1996), these processes have two essential features: a rupture surface and a displaced mass of sediment and/or rock. The rupture surface is where failure takes place and where downslope motion originates. The displaced mass commonly rests partly over the surface of rupture, but in others it might move completely beyond it. Moreover, this mass may be slightly or highly deformed, may break up into distinct blocks, and even in some cases all or part of it may completely disintegrate and produce a flow. These authors claim that the surface of rupture is commonly upwardly concave in mechanically homogeneous materials, such as sand. These slides are formally called "rotational slides" or "slumps". However, when the material is not homogeneous or contains bedding planes, the surface of rupture is planar, and the slide is called a "translational slide".

Along the continental offshore slopes, from Guatemala to Costa Rica, researchers have identified submarine slides ranging in width and length from a few hundred meters to tens of kilometers (Harders et al., 2011). In general, these slides are related to the mechanics of the subduction zone (Middle America Trench) in the overriding plate (Harders et al., 2014). Rotational landslides are observed near the Coco seamount chain in Costa Rica, the edge of the continental shelf in Yucatán on the northern coast of Panamá, and the submarine mountain range located east of Tuxpán, México (Carranza, 2010). According to the analysis of historical submarine landslide cases worldwide, the main triggering factors are earthquakes, tectonic steepening, gas and hydrate dissociation, diapirism, rapid sedimentation, sea level fluctuations, anthropogenic activities, volcanism, tidal variations, tsunami, and storm loading (Wang et al., 2025).

However, in marine environments not directly associated with the subduction trench, as in Puntarenitas spit, Puerto Jiménez, rapid sedimentation generates excess pore pressure surpassing dissipation rates (Wang et al., 2025). As highlighted by these authors, this excess pressure plays a significant role in the preconditioning for the occurrence of submarine landslides characterized by high sedimentation rates, such as deltas, continental shelf slopes, margins of deep-sea basins, and submarine canyons. Rapid rates of continental uplift also play a significant role by increasing submarine slope angles and erosion rates inland (Walton et al., 2024).

The primary objective of this work is to characterize the February 8, 2024, event in Puntarenitas, Puerto Jiménez. Based on evidence collected regarding environmental conditions and event development, the findings support the conclusion that the event represents a natural process of retrogressive breach failure (RBF or breaching) triggered by natural conditions.

1.1. Retrogressive Breach Failures or breaching

The event known as Retrogressive Breach Failure (RBF) or subaqueous dilative slope failure (breaching) is a type of gravitational mass movement that is more complex than rotational slides or translational slides. This category of sediment transport occurs in certain river and coastal environments where sand is carried away in turbulent density currents generated by the momentum of sand grains cascading off the face of a retrogressing, near-vertical subaqueous wall called a 'breach' (Beinssen & Neil, 2015). According to these authors, if such events reach the shoreline, they can cause significant damage to beaches and coastal infrastructure. Alhaddad et al. (2024) state that breaching can occur naturally in estuaries, along riverbanks, shoals, beaches, and artificial sand fills. Larger events are newsworthy because of their spectacular nature and, hence, are often reported in the media. Popular names given by the press include 'sinkhole', 'beach collapse', 'underwater landslide', or 'channel slump' (Mastbergen et al., 2019).

The breaching materializes in fine sand deposits ranging from moderate to high compaction (Van Rhee, 2015; Alhaddad et al, 2024). Under shear stress conditions, these sediments exhibit dilative behavior. This dilatancy leads to an expansion of pore volume by compression, resulting in the development of negative pore pressure relative to in situ conditions. This mechanism enhances the material's shear strength by creating a pressure differential that generates an inward-directed hydraulic gradient, facilitating the infiltration of surrounding water into the sand matrix, which subsequently neutralizes the negative pressure conditions (Alhaddad et al, 2019; Alhaddad et al, 2024).

Alhaddad et al. (2024) describe a mechanism controlling the stabilization or destabilization of RBF. During destabilization, the height of the breach face progressively increases over time, leading to a slope-retrogressive failure that advances inland. In contrast, breaching tends to stabilize when the height of the breach face is reduced.

According to these authors, in both cases, failure stops when sediment morphology reaches a lesser angle or approaches the internal friction angle (i.e., shear strength increases). If sediment is deposited by the turbidity current near the face base, the breach height will steadily diminish and consequently motion stops; but if the turbidity current erodes sediment at the face base, the breach height will increase over time, creating positive feedback.

The typical features of an active breaching event are (Alhaddad et al., 2024): slow retrogression celerity, formation of an amphitheater-shaped escarpment, continuous falling of sand lumps into the water when reaching the shore, and an underwater almost-vertical breach face that does not collapse abruptly. Mastbergen et al. (2019) point out that breaching can be triggered by exceptionally low tides and/or heavy rainfall. A gradual increase in steepness of submerged slopes due to erosion processes caused by river or tidal currents in estuaries can potentially trigger breaching events. Similarly, Alhaddad et al. (2024) suggest that when the slope angle surpasses the internal friction angle due to gradual steepening of submerged slopes from river or tidal current erosion, retrogressive erosion occurs, starting at the toe of the slope.

Below the breach, a tongue or fan of sand is deposited downslope and offshore as the density current loses momentum, and its entrained sand settles. This morphology 'signature' can be used to identify RBF sites after the active phase has ended and before sand infilling occurs (Beinssen & Neil, 2015).

To explain the behavior of an RBF event, a four-phase sequential model has been proposed: triggering, propagating, termination, and recovery. Each phase is described below based on Man et al. (2025). For the first phase, multiple potential triggering mechanisms have been identified, including low tide conditions, groundwater table rise, and high rainfall. Nevertheless, no consensus exists regarding its causative factors, as RBF is considered a complex phenomenon encompassing suction-induced slope steepening, the downslope propagation of sand–water mixtures, and the factors like sand properties, slope geometry, and sediment–water interactions.

During the propagating phase, a retrogressive breach develops and advances in an upslope direction. This breach has the potential to extend as far as the shoreline and subsequently progress across the beach surface, provided it is not impeded by variations in sand characterization or by the dissipation of the density current driving it. When either of these conditions occurs, the termination phase is reached: erosion diminishes, and the breach progressively decreases in height until the RBF event ceases entirely. The recovery phase occurs when the beach eroded by the RBF event gradually recovers its profile through the redeposition of sand driven by wave action and longshore current transport.

2. Study Area

Puntarenitas is a coastal sandy spit formed by the combined action of littoral currents and sedimentary contributions from the Platanares River, previously described as a peninsula by Bergoeing (1978). This sandy spit is located on the Osa Peninsula, within the inner basin of the Golfo Dulce, east of Puerto Jiménez, Puntarenas Province, on the southeastern Pacific coast of Costa Rica (Figure 1). The sandbar begins as a narrow path around 30 m wide, separating the Platanares river estuary and Platanares beach. Currently, the bar has a width of 1.15 km from north to south and 0.8 km from west to east. Its western side is exposed to swells from the south or southwest of the Pacific Ocean, while its northern side, where the event occurred, is protected from direct waves.

Golfo Dulce has a tectonic origin with an inner section fringed by two parallel faults along its northern and southern shores, characterized by narrow shorelines that fall almost vertically down to basin depths (Vargas et al., 2021). A sill, located at the southeastern entrance and with a depth of only 60 m, restricts water exchange between the open Pacific Ocean and the deeper waters of the gulf, which reaches depths of 185 to 210 m (Malzer & Fiebig, 2008). Puntarenitas is located near the southern slope of the deep basin (attaining a maximum depth of approximately 180 m in this section of the deep basin) (Rincón & Ballestero, 2015; Vargas et al., 2021), which shows a rapid descent from -20 m to -140 m over just a few tens of meters.

Figure 1. Location of the Puntarenitas peninsula, Puerto Jiménez, in the Pacific coast of Costa Rica, Central America.

3. Materials and Methods

The methodological approach employed in this research integrated multiple observation and measurement techniques to comprehensively characterize the submarine slope failure event (Figure 2). The investigation encompassed three primary observational domains: marine observation, coastal observation, and social media analysis. The following sections describe each methodological component.

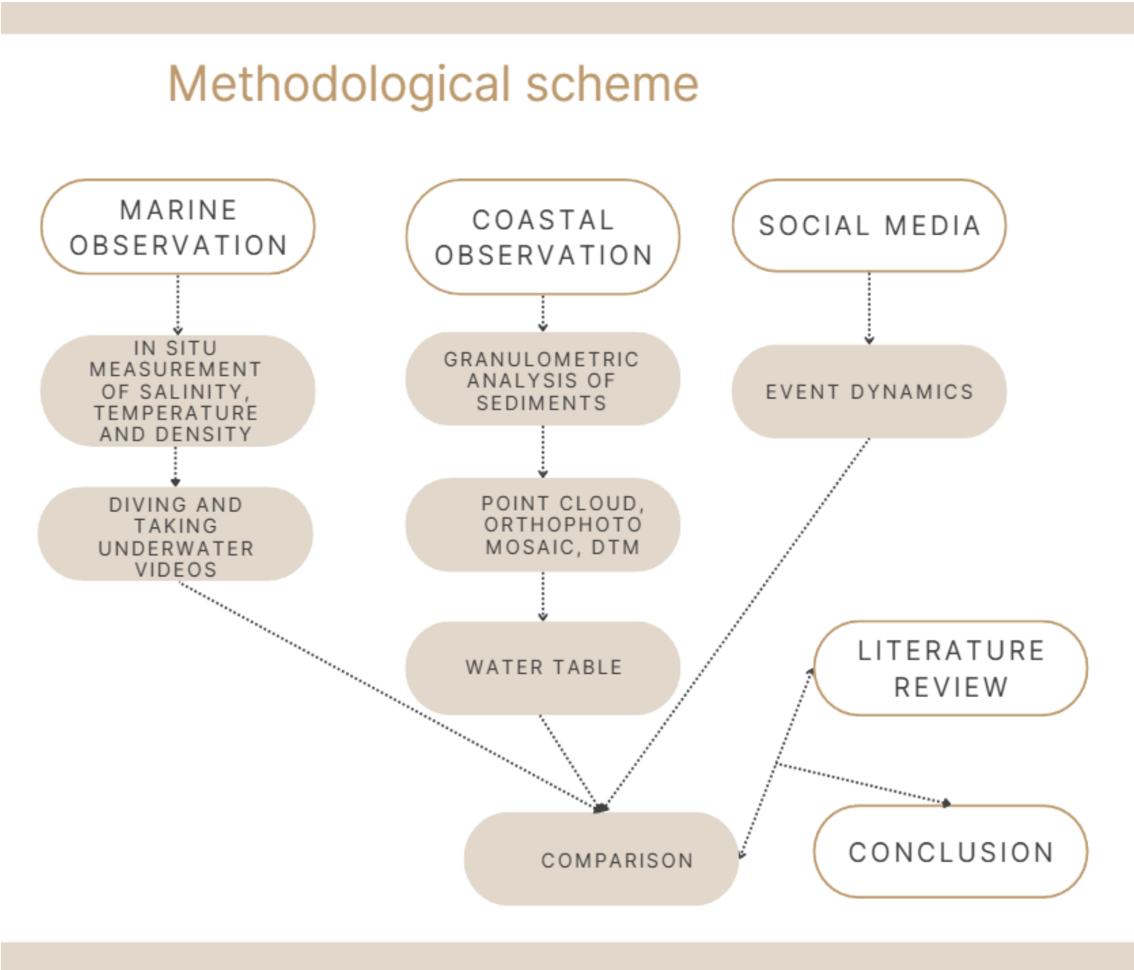


Figure 2. Schematic representation of the research methodology.

3.1. Background information

Google Earth imagery was used to identify the occurrence of analogous processes within the study area by examining shoreline configurations indicative of events like that of February 2024. The search was conducted between 2006 and 2024, with a total of 16 images available: one for 2006, two for 2008, one in 2009, one in 2013, one in 2015, one in 2017, two in 2021, two in 2022, four in 2023, and one in 2024.

3.2. Coastal and oceanographic variables

Salinity, temperature, and density profiles were obtained using a Sontek CastAway Conductivity-Temperature-Depth (CTD) profiler operating at a 5 Hz sampling rate, along the affected shoreline, with 5 m spacing between stations along a 30 m transect, conducted four days after the event (Figure 3). These profiles were performed aiming to assess any possible irregularities in the variables mentioned, that could lead to the event happening. Salinity was also measured at Puerto Jiménez beach, a nearby unaffected beach, compared with the salinity of the event site. Additionally, short dives were conducted to record the underwater aftermath of the retrogressive breach failure using a subaquatic camera called GoPro 10 (Figure 3). That material was used to complement the material taken on land.

3.3. Beach characteristics

Surface sediment samples were collected along cross-shore transects following the method described by Emery (1961). The beach profile was divided into two morphodynamic zones: the backshore (from the vegetation line to the berm crest) and the foreshore (from the berm crest to the swash zone) (Short, 1999). Within each zone, three subsamples were taken at a depth of roughly 3 cm at regularly spaced intervals and combined into a single composite sample of approximately 100 g. A 50 g subsample was then obtained using an eight-channel riffle splitter for particle size distribution analysis, following the classification of Folk & Ward (1957). Grain size analysis was performed by dry sieving using a mechanical shaker.

Field inspection was undertaken to identify indicators of shallow groundwater conditions within the study area. The assessment followed a qualitative hydrogeological approach (Todd & Mays, 2005), evaluating three field indicators: the presence of freshwater seepage at the surface, proximity to river channels, and water table depth obtained from local reports. The inspection focused on detecting evidence of a perched or seasonally elevated water table that could influence coastal stability processes.

An Unmanned Aerial Vehicle (UAV) survey was performed to generate spatial datasets, including a high-resolution point cloud digital elevation model (DEM), and an orthomosaic of the coastal zone. The survey consisted of two phases: (1) reconnaissance flights for preliminary visual documentation through photography and videography, and (2) systematic photogrammetric flights following pre-planned paths to ensure adequate three-dimensional terrain reconstructions. Photogrammetric survey specifications: coordinate system WGS 84 (EPSG:4326), number of images: 87, flying altitude: 54.6 m, ground resolution: 1.11 cm/pix, coverage area: 0.0251 km^2, and UAV model: DJI Mavic 2 Pro.

Bathymetric surveying was carried out with a single-beam echosounder equipped with a Teledyne Odom Hydrographic ECHOTRAC E20 single-beam echosounder equipped with an RTK GPS system for tidal and wave correction. The system operated at a frequency of 200 kHz, providing a vertical resolution of 1 cm and an accuracy of ±2 cm ± 0.1% of the measured depth. The acquired data was processed using HIPAC software. A survey grid was established with lines running both parallel and perpendicular to the shoreline, spaced 40 m apart.

The comprehensive methodology employed in this investigation is summarized in Figure 2 and the field survey areas can be visualized in Figure 3.

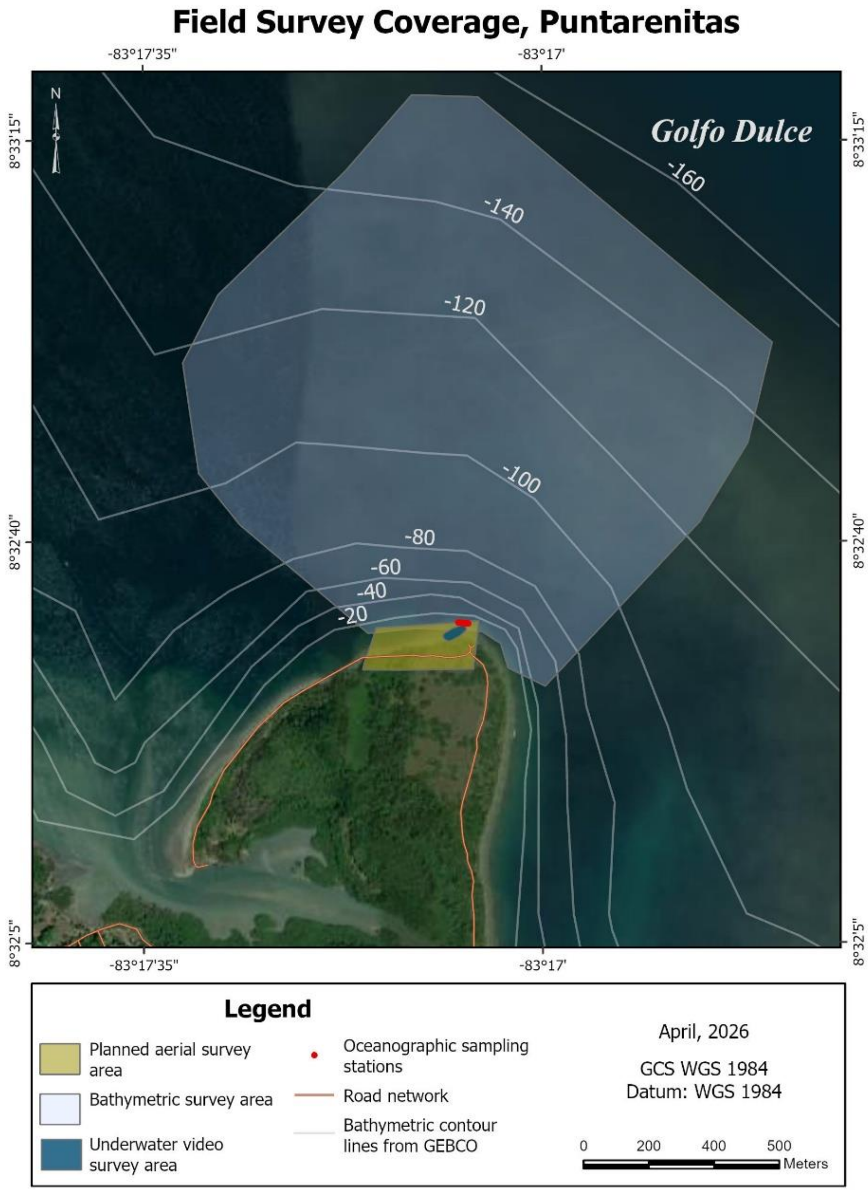


Figure 3. Field survey coverage in which we performed aerial video surveys, bathymetric measurements, underwater video recordings, oceanographic samplings, and measurements.

4. Results

4.1. Recent preceding events and the current one

As reported by local inhabitants, evidence of similar past events can be identified, particularly those occurring in February 2008 (Figure 4 A) and January 2017 (Figure 4 B). Notably, one of the three scarp crowns identified from the 2008 event coincides with the location where the 2024 event occurred (Figure 4 C).

Figure 4. Remaining evidence of three events mapped on Google Earth imagery. Yellow lines mark the evidence of scarp crowns that are visible in the images. A) The February 9th, 2008 event, in which three scarp crowns are visible: the one on the right is located at the same site as the February 2024 event, although it is smaller, while the other two on the left are in similar positions to the scarps observed in the 2017 event. B) Marks the evidence of the January 27th, 2017 event, showing two crowns, one to the left and the other toward the center, although it is unclear whether one occurred at the same location as the February 2024 event. C) The February 8th, 2024 event, captured in an image taken on March 7th, 2024. Source: Google Earth (2008, 2017, 2024).

Newspaper reports suggest that another similar event occurred in October 2022: "A massive collapse occurred at Puntarenitas Beach, at the entrance to Golfito Port, alerting authorities and scientists throughout the country. The feature extends more than 50 meters from the coastline and was initially detected by residents [...] and the oceanographer Omar Lizano indicated that this could have resulted from several converging factors, including the highest tide recorded in recent times on Thursday, which reached 3.28 meters" (Méndez, 2022).

4.2. Coastal and oceanographic characteristics

The average temperature and salinity values at Puntarenitas Beach were 31.7 °C and 31.3 PSU, respectively. At Puerto Jiménez Beach, the average values were 32.0 °C and 31.1 PSU for temperature and salinity, respectively. These values are higher than those previously reported by Rincón and Ballestero (2015), with an average temperature of 30.5°C and 30.5 for salinity (PSU). Profiles were taken in a transect at the affected area and no significant differences were being noticed on the three measured variables. No colder or less salty water masses were detected during the measurements (Figure 5). Even further, no significant low salinity values (< 30 PSU) were detected in our measurements and those made by Ricón and Ballestero (2015) in the affected area, which would point to freshwater infiltration. Density did not vary significantly during sampling of the seven profiles along the shoreline. Nonetheless, the measurements were taken 4 days after the event. During the immersion conducted, it was possible to observe that the two escarpments visible on land continued underwater in a step-like shape with remnants of terrestrial grasses observed (Figure 6).

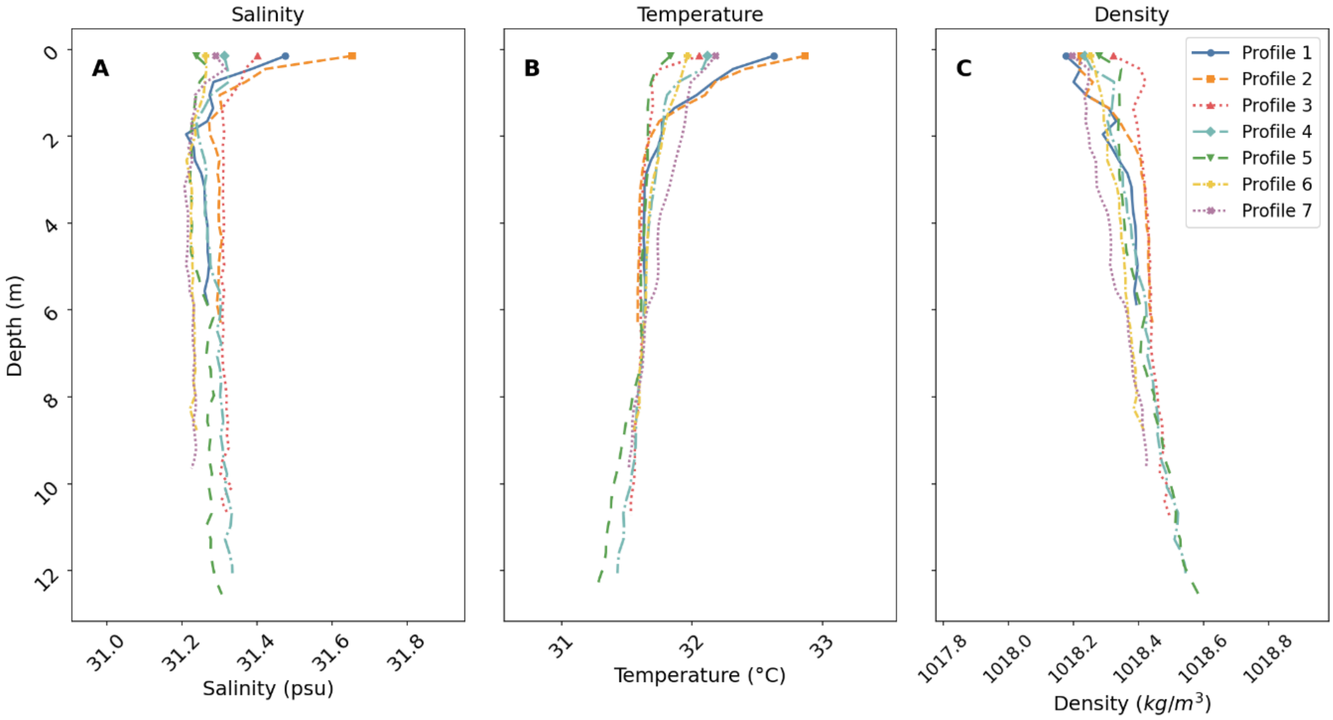


Figure 5. A) Salinity, B) temperature, and C) density profiles at different depths from the seven samples performed with the CTD profiler at the beach in Puntarenitas where the event occurred in Puerto Jiménez, on February 8th, 2024. No significant differences or anomalies in the variables indicating the occurrence of the event can be seen from the profiles of the three variables as some cold or fresh water would be expected giving origin to the RBF analyzed in this paper.

Figure 6. Qualitative demonstration of grass debris (A and B) transported downslope from higher grounds and deposited at the base of the slide mass during the February 8th, 2024 event.

The mean tidal amplitude in this region is 1.76 m (Lizano, 2006), whereas the significant wave height and mean period for the South Pacific coast of Costa Rica are 1.36 m and 12.0 s, respectively (Lizano, 2007). The tidal projection data from the MIO-CIMAR for Golfito indicates that the week of the event approached a spring tide occurring on Friday, February the 9th, during a new moon at its perigee (University of Costa Rica, n.d.). The tide had maximum amplitude values of approximately 2.7 m, 0.0 m, 2.6 m, and 0.1 m; the tidal coefficient was 97 (very high), with a range between 1 m and 3 m (Figure 7). On the day of the event, the range of the tide was approximately 2.0 m, with an important low tide in comparison to previous days. These very low tide events expose the sand in upper layers which tend to destabilize it, leading to falling blocks of sand. During the same week, the global wave forecast data from NOAA, representative for offshore conditions in the South Pacific, predicted wave heights of 1.2 m on average, with swells with a period of 12 seconds coming from the South-Southwest (WAVEWATCH III, 2009), these values are consistent with the average significant wave height of 1.36 m and period of 12.13 s reported by Lizano (2007), and therefore do not represent anomalous conditions. Likewise, the meteorological conditions recorded in the days preceding the event corresponded to normal values for the season (Alvarado et al., 2024).

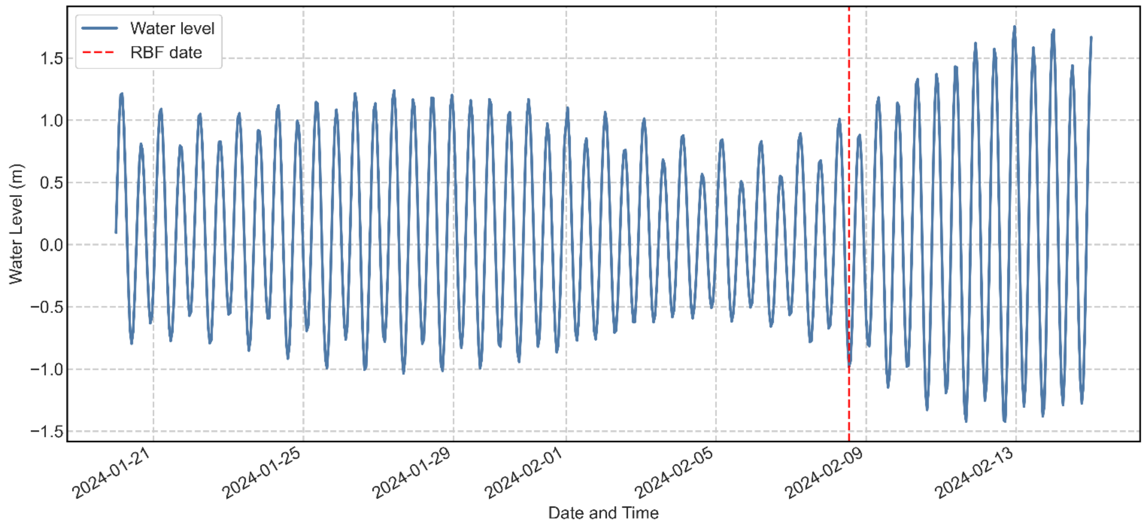


Figure 7. Tide observations from a local station close to the event location, ranging from 1 m up to more than 3 m, typical of these coasts: A spring tide was present in the following week with tide range of up to more than 3 m (Flanders Marine Institute, 2025). The approximate time for the beginning of the RBF event, as suggested by the evidence acquired from social media and news videos, is marked with a red dotted line.

4.3. Morphological, morphometric, and granulometric characteristics of the coastal event

An affected area of 410 m² was estimated using the orthophoto mosaic constructed from the drone flights and the coastal limit at the instantaneous waterline on the July 2nd, 2023 image (Figure 8). Within the affected area, a main escarpment (i.e., crown) and three secondary escarpments were recognized. Lengths of 167.7 m were recorded for the main crown and 64.4 m, 20.1 m, and 29.1 m for the secondary escarpments, respectively, from west to east (Figure 9).

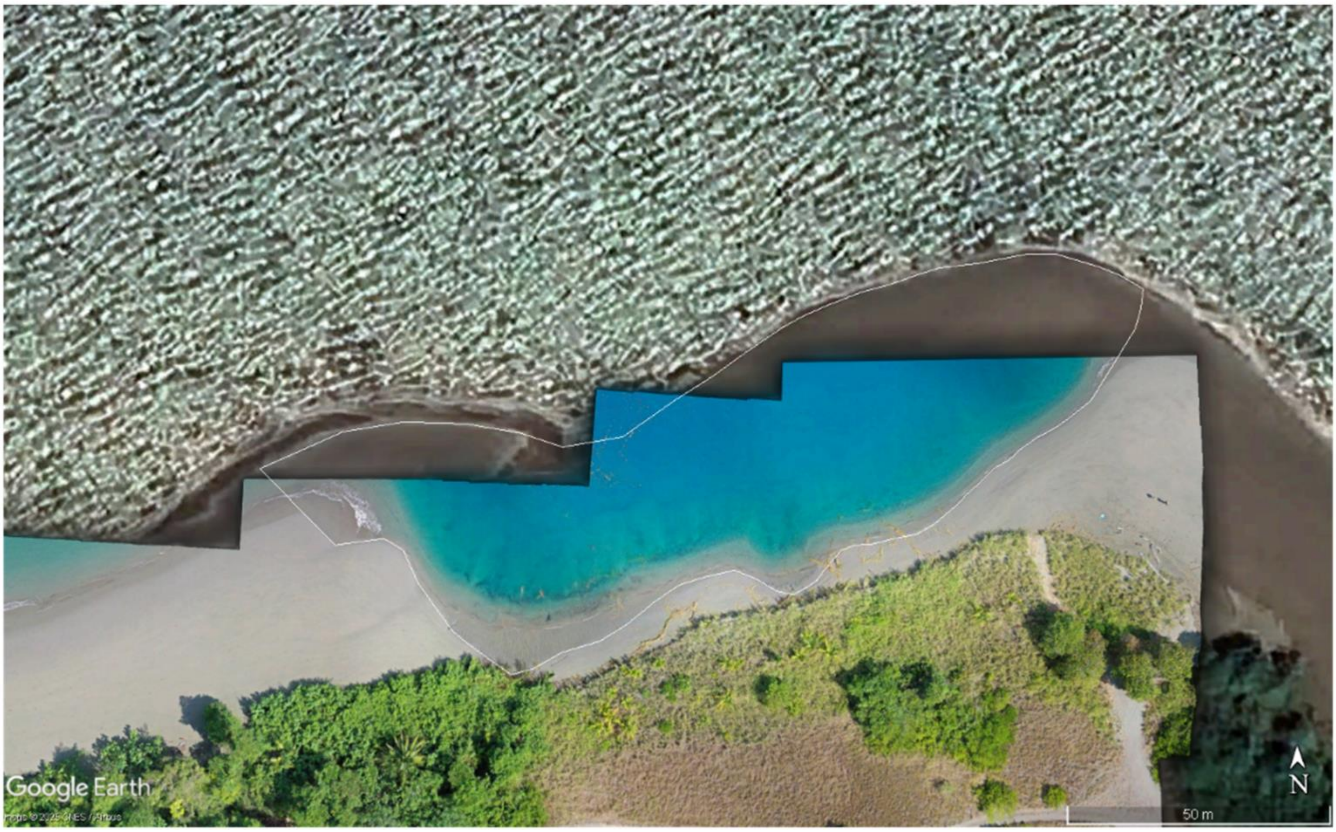


Figure 8. Estimated boundary of the beach area lost (indicated by the white line on the image). Bottom: Google Earth satellite imagery (July 2, 2023). Top: UAV-derived orthophoto mosaic, acquired and processed on February 13th, 2024.

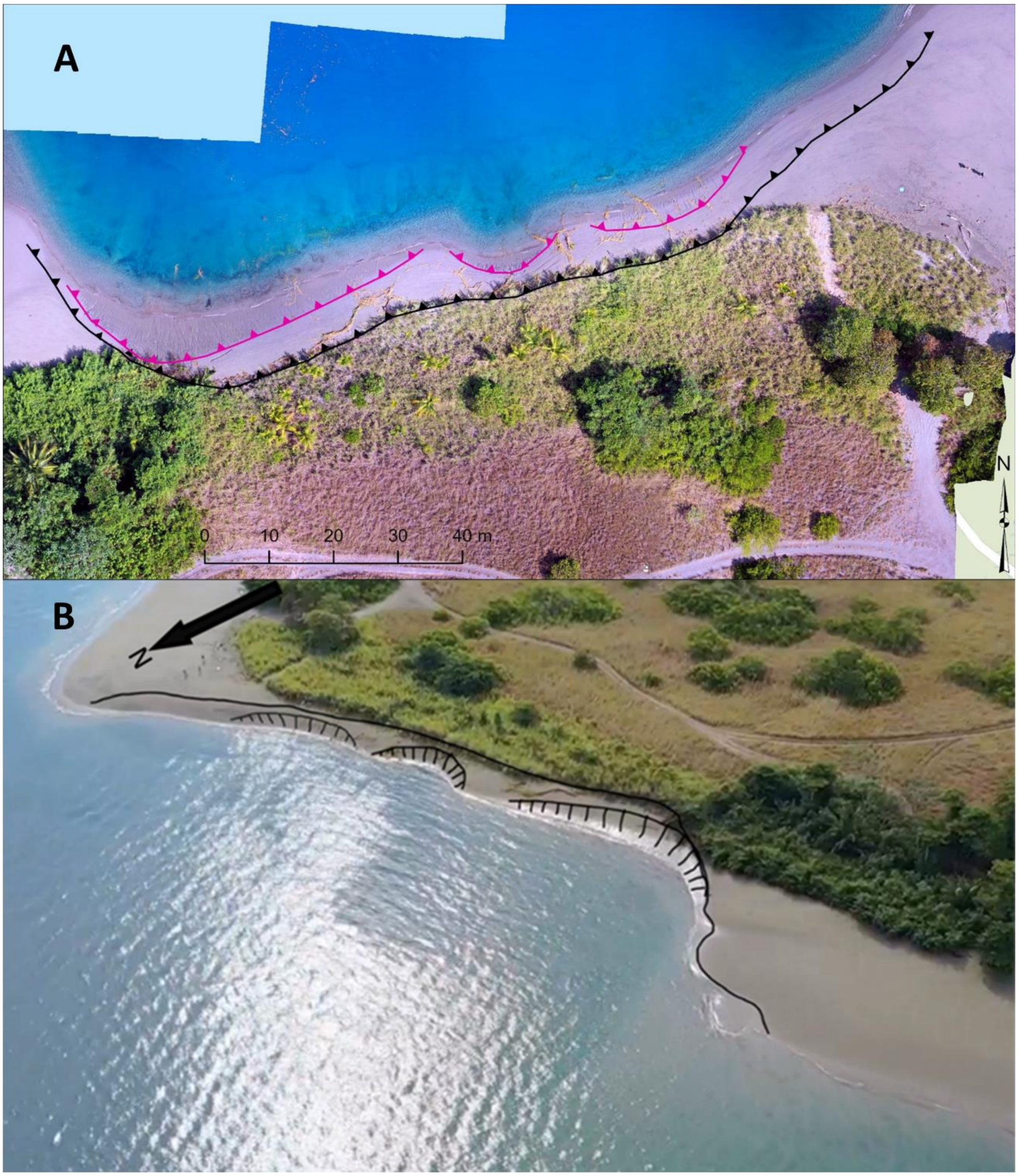


Figure 9. Supratidal morphology. Top: Escarpment delineation from orthophotography, showing primary (black line) and secondary (purple line) features. Bottom: Oblique perspective derived from oblique aerial imagery. Based on photointerpretation of aerial photographs acquired February 12th, 2024.

A maximum height of 2.8 m was recorded for the main escarpment, while the secondary escarpments located in the western sector were measured at a maximum of 1.6 m. The central escarpment was measured at 0.7 m in height, while the easternmost escarpment was recorded at approximately 1 m (Figure 9). Maximum slope angles of 20° to 30° were observed in the steepest sections, which extended underwater. Steps or small escarpments tilted landward were observed, with distances of 60 to 85 cm on land (Figure 10A) and were found to continue underwater (Figure 10B).

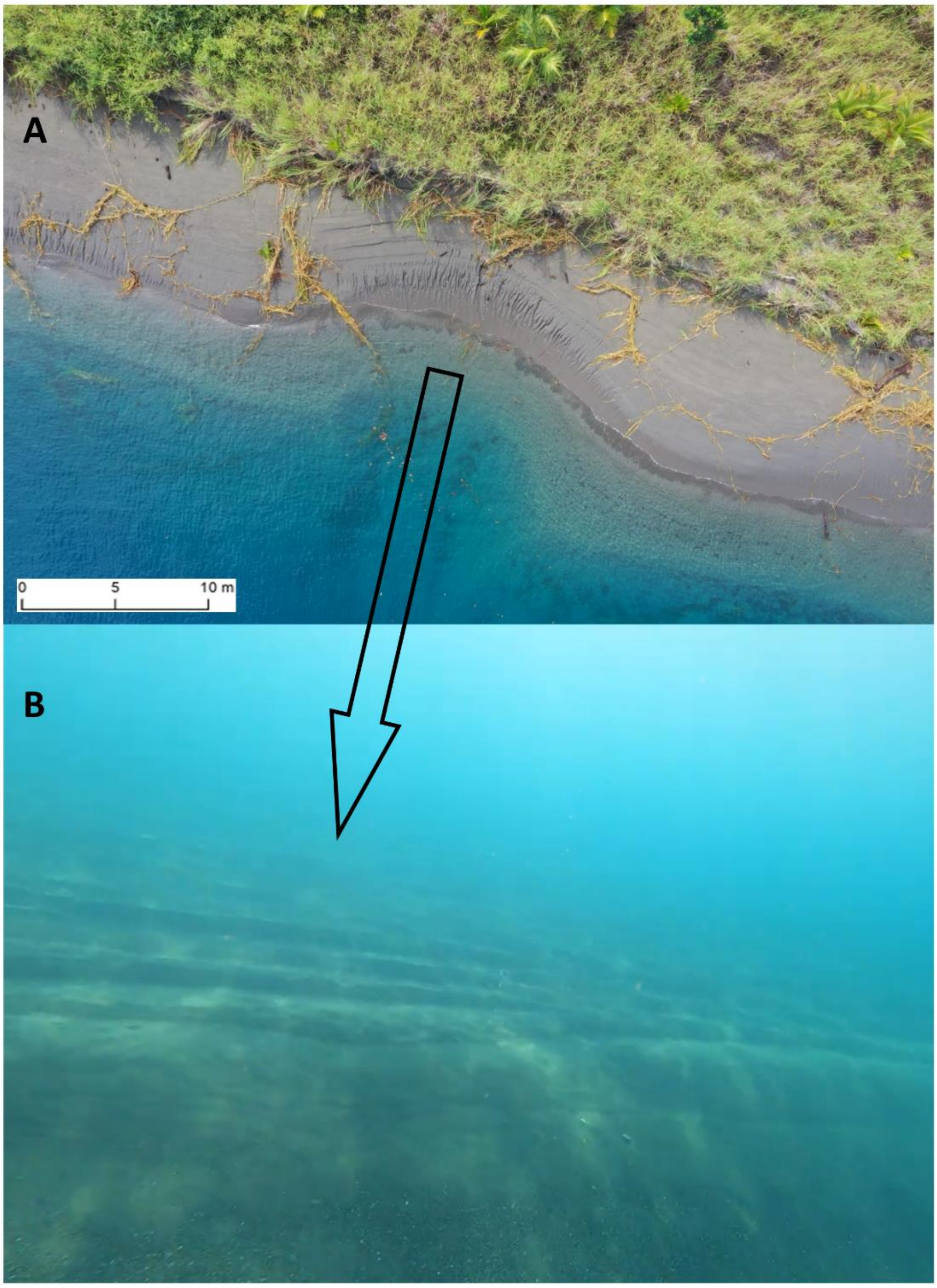


Figure 10. Details of the central escarpment in Figure. 11. A) note the semi-circular retrograding escarpment at the center of the photograph. B) Continuation of the retrograding escarpment below the waterline, observed at an estimated depth of seven meters. Flight and immersions performed on February 12th, 2024.

A slope map was derived from bathymetry data (Figure 11), from which a ramp was detected between −10 m and −30 m depth, exhibiting slope angles of 10° to 16°. This ramp corresponds to a transitional zone between shallow and deep waters.

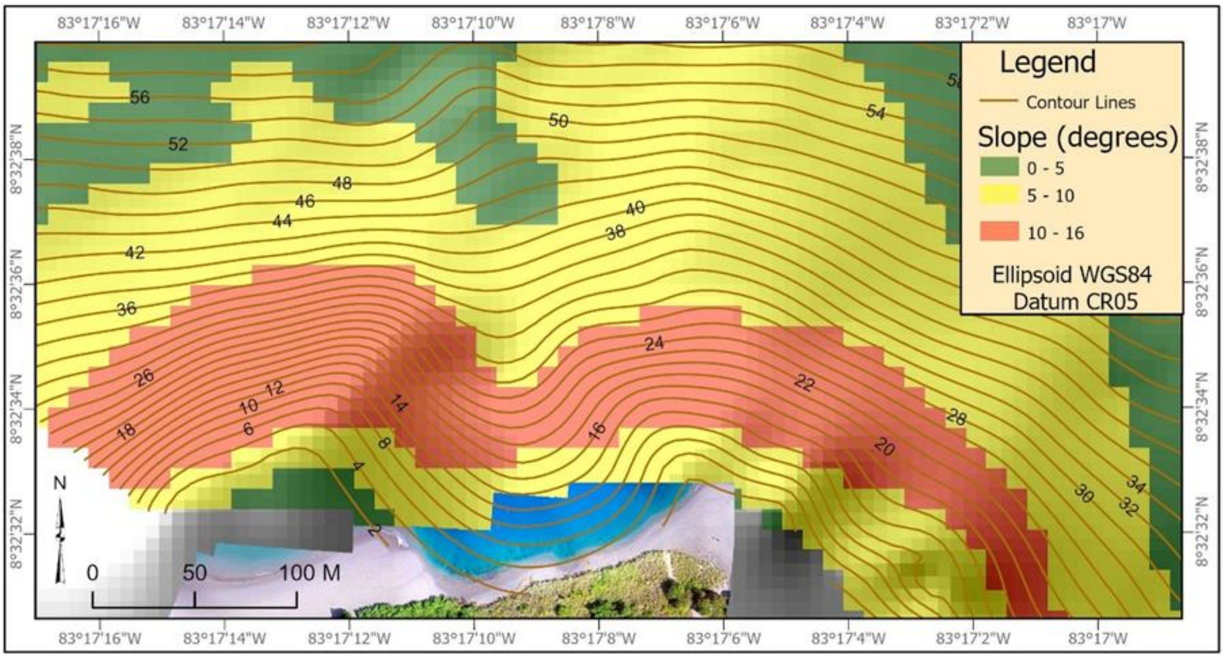


Figure 11. Seabed slope map at the tip of Puntarenitas, generated from bathymetric contour lines. To the south, the colored area shows the orthomosaic created from the February 12, 2024, flight.

Additionally, a bathymetric map allowed to determine the distribution of depths versus distance from the coast, and the identification of the landslide morphology. Figure 12 shows the presence of a convergent concave rupture plane beginning at the surface and ending at a depth of about 34 m. Likewise, it is possible to identify a sand deposit seeming to correspond to the material mobilized from the rupture area, an elongated mound to the north that ends at a depth of approximately 72 m (Figure 12). It is interesting to notice the presence of submarine channels (white lines in Figure 12) along the walls of the deep outer basin until it reaches its flat bottom (Rincón & Ballestero, 2015).

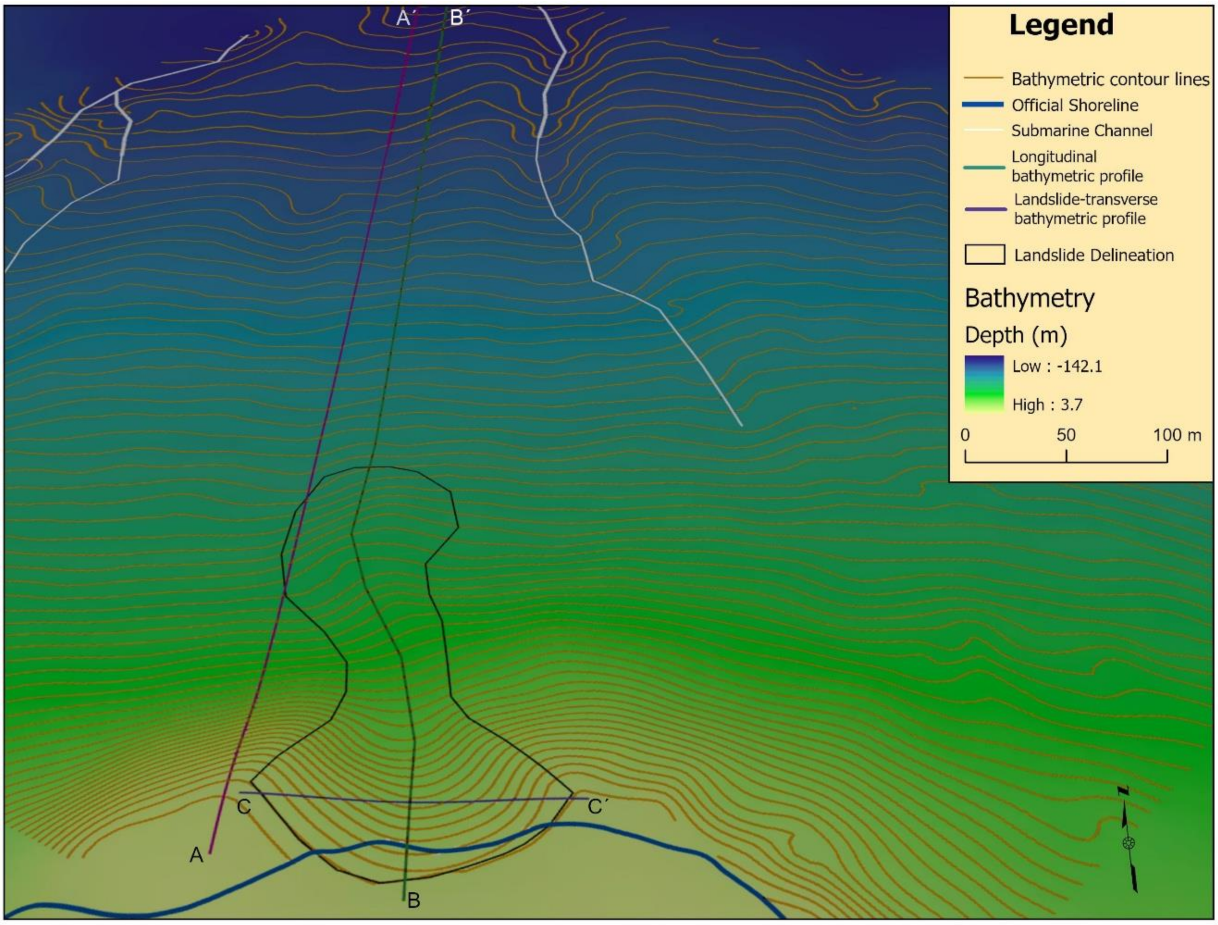
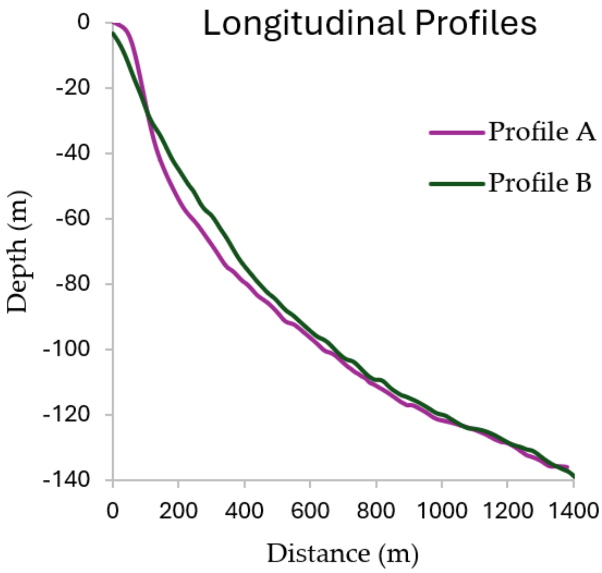


Figure 12. Bathymetric map created from data collected at the site on May 27th, 2024. The morphology of the landslide and deposition areas are conspicuous (black line). The event happened on February 8th, 2024.

Two profiles were extracted from the bathymetric map to evaluate the morphological changes between the pre-failure slope (profile A in Figures 12 and 13) and the landslide failure surface (profile B in Figures 12 and 13). In the first profile (A), a steep submarine slope is observed within the first 200 meters from the shoreline, forming part of the southern flank of the deep basin of the Golfito Gulf, which has been reported to reach depths of approximately -200 m in its deeper sections (Rincón & Ballestero, 2015). In Profile B, the slope gradient becomes moderate as a result of material removal by the landslide and its subsequent deposition, beginning at approximately -30 m in depth. Finally, profile C displays a concave section resulting from the geometry adopted by the failure plane along which the material was removed (profile C in Figures 12 and 13 right).



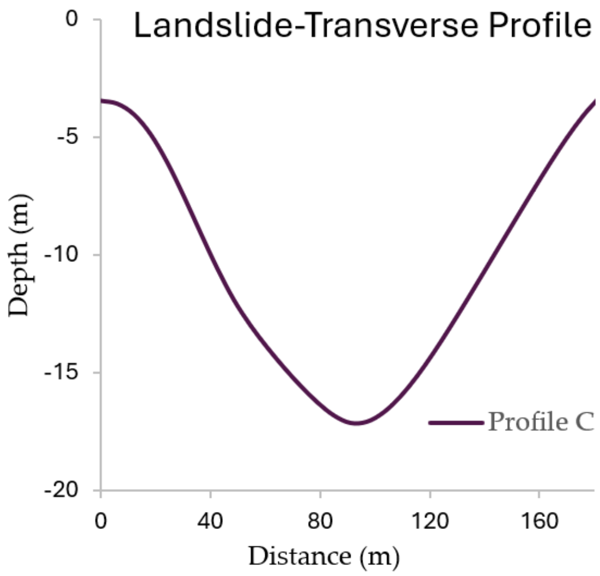


Figure 13. Bathymetric profiles extracted from the bathymetric map. Profiles A and B (left) correspond to longitudinal sections, and Profile C (right) corresponds to a landslide-transverse section; the locations of these profiles are indicated in Figure 12.

On the other hand, a wetland located approximately 300 m away from the shoreline suggests the presence of a shallow water table (1 to 2 m deep) at the study site (Figure 14) and found at approximately 4 m of depth at the sandy spit, located 400 m to the south (Barrantes et al., 2024).

Figure 14. Groundwater emerged just a few meters right beside the affected area. Source: Barrantes et al. (2024).

Granulometric analysis was performed on sediment samples collected from two morphological units of the beach profile, the backshore (from the vegetation line to the berm crest) and the foreshore (from the berm crest to the swash zone). The dominant sediment on the foreshore is moderately fine sand (Figure 15A), whereas medium sand predominates on the backshore (Figure 15B).

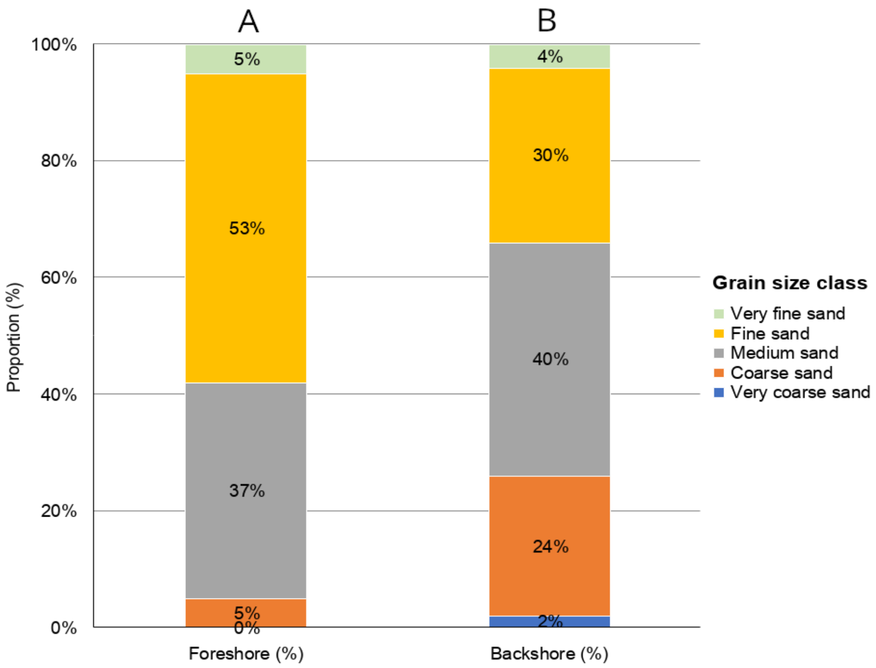


Figure 15. Grain-size distribution of sediment samples from Puntarenitas Beach in A) the foreshore zone and B) the backshore zone.

4.4. Event dynamics

Based on amateur videos posted on social media it was possible to observe the development of part of the event: the formation of vertical escarpments, successively replaced by similar ones moving inland and causing the frontal escarpment to collapse into the sea and curve towards the land during its descent, while the next escarpment developed (Figure 16). This process resulted in a step-back failure morphology (Figure 10). A strong bubbling was observed, appearing as a whitish layer of foam in front of the retreating escarpment.

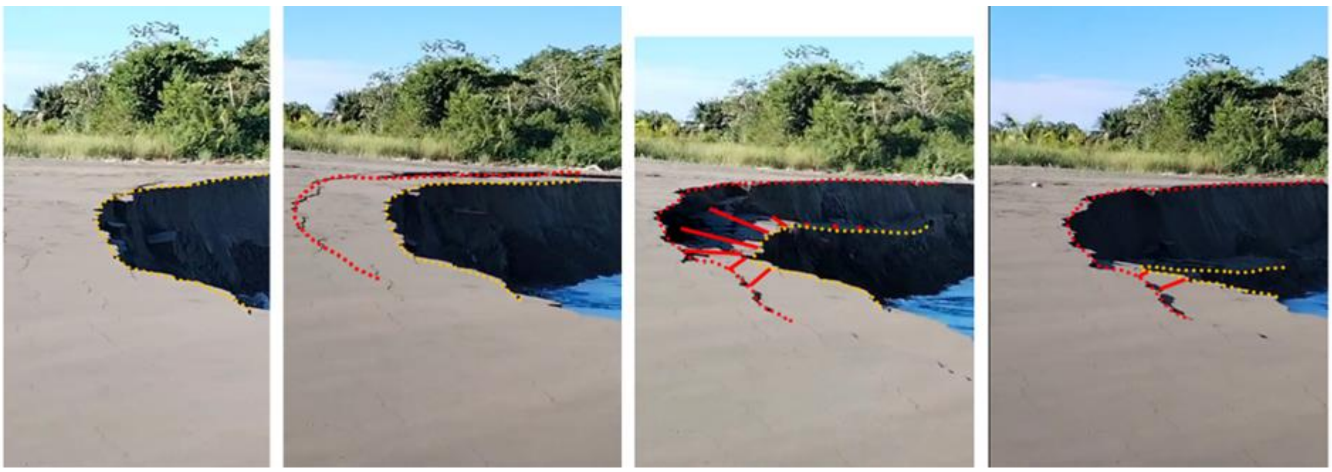


Figure 16. Sequence of escarpments documented during the event, from left to right, corresponding to the western escarpment observed in Figure 9. Yellow dashed line: first scarp position; red dashed line: crack and boundary of the subsequent scarp. Note the near-vertical geometry and progressive retrogressive failure pattern, whereby successive slabs fail sequentially, each exposure revealing a similar escarpment morphology.

5. Discussion

Breaching or RBF are associated with distinct coastal morphodynamical and sedimentological settings (Mastbergen et al., 2019; Alhaddad et al., 2024). Coastal environments are typically characterized by active littoral drift that infills bathymetric depressions, and by the proximity of subaqueous channels to the shoreline. The sediment in our study area comes from two different sources. The first source is the result of coastal erosion occurring between Tamales and Zapote beaches, with average erosion rates of around 1.5 m/a (Sáenz, 2020). These sediments are transported by littoral currents to the tip of the spit. The second source is the sediment discharges from Platanares River estuary (Figure 1). These sediments formed a moderately steep submarine slope between the beach and the southern flank of the deep basin of the Gulf of Golfito. Submarine channels identified further downslope (Figure 12) may serve as conduits for turbidity currents, directing sediment-laden flows along the basin wall toward its flat bottom. However, in this event, the mobilized sediment was deposited at the base of the landslide, producing an infill that smooths the slope along the basin wall (Figure 13).

The stratigraphic framework commonly comprises unconsolidated, Holocene-aged fluvio-marine sediments, predominantly composed of fine-grained, water-saturated sands (Mastbergen et al., 2019; Alhaddad et al., 2024). In this case, fine and very fine sand accounted for more than 50% of the sediment composition of the foreshore adjacent to the sediments removed by the event (Figure 15). As a transition towards coarser materials occurs the fine and very fine sand fraction decreases to 34%, in our scenario corresponds with the section proximate to the vegetation line, with medium sand becoming the dominant fraction. These materials are commonly deposited on steep submarine foresets (Mastbergen et al., 2019; Alhaddad et al., 2024). In our study area, the foresets form a transitional zone between shallow and deep waters, exhibiting slope angles ranging from 10° to 16° and relief reaching up to 30 m (Figures 13 and 14), built through sediment accretion by littoral currents. These morphological conditions generate a mechanically unstable substrate that predisposes the area to slope failure and retrogressive erosion processes.

The failure event we assessed progress as a dynamic, multi-stage process typically unfolding over several hours (Mastbergen et al., 2019; Alhaddad et al., 2024). It initiated, with the development of a near-vertical failure scarp, followed by a retrogressive retreat of the headwall as successive blocks detached and collapsed landward (Figure 16). These processes resulted in the formation of a characteristic amphitheater-shaped scar that extends landward, locally surpassing the shoreline in some sections (Figures 11, 12 and 14), where it terminates upon encountering a reduction in gradient and a transition to a coarser substrate (Figures 13 and 15). The morphological analysis of the post-failure seabed reveals an hourglass-shaped erosional–depositional pattern, indicative of concentrated sediment transport pathways. Our measurements show evidence of sediment dilatancy and remobilization, consistent with shear-induced deformation and possibly with a liquefaction process. The mobilized material was transported downslope, possibly through a gravity-driven turbidity current or suspension flow, culminating in the deposition of the sediment load, which begins approximately 130 m from the main scarp at a depth of approximately −43 m (Figure 12).

The resulting morphology was characterized by a well-defined concave rupture surface at the point of detachment, followed by a sequence of retrogressive escarpments extending both above and below the waterline (Figure 10). Down-gradient from the failure zone, a depositional lobe of accumulated sediments marks the terminus of mass transport, signifying the final emplacement of displaced material and completing the geomorphological reconfiguration of the seabed (Figure 13) (Mastbergen et al., 2019; Alhaddad et al., 2024). The evidence leads to conclude that the Puntarenitas events represent Retrogressive Breach Failures, also known as Subaqueous Dilative Slope Failures (Breaching). At least three previous events were identified (February 2008, January 2017, and October 2022), representing recurrence intervals ranging from approximately 1 to 9 years. Although the record is likely incomplete, the evidence clearly indicates that this is a recurring phenomenon.

The salinity survey conducted at the site showed no evidence of submarine groundwater discharge that could support the hypothesis of sediment wall failure driven by freshwater pressure. However, it must be considered that measurements were taken four days after the event, and that the water table was estimated at shallow depth. Therefore, a contribution of groundwater to the failure process cannot be entirely ruled out, although it is not considered to have been the triggering mechanism. Besides, according to tide gauge measurements and wave forecasts, neither extraordinary low tides nor exceptionally severe wave conditions were recorded. Nevertheless, both parameters were elevated and may have acted in conjunction with other contributing factors to trigger the

Retrogressive Breach Failure event. In this regard, a potential relationship with extreme tidal conditions has been suggested as a contributing factor in the 2022 event (Méndez, 2022).

This kind of event constitutes a natural hazard due to its recurring nature, highlighting the need for measures focused on tourist safety and land-use planning, including monitoring systems and restricting the construction of infrastructure near the beach front. It is worth noting that the majority of RBF events documented in the literature occur in one of two main bathymetric settings: tidal channels, with typical depths ranging from 10 to 50 m, or fluvial and estuarine margins, with depths of a few to tens of meters (Beinssen et al., 2014; Mastbergen et al., 2019). The Puntarenitas case is geomorphologically distinguishable in that it develops along the flank of a tectonically formed, semi-enclosed deep basin, whose steep margins are associated with regional fault systems (Malzer & Fiebig, 2008), reaching depths of up to 210 m (Vargas et al., 2021).

RBF events occur without clear warning signs and develop within a matter of hours (Mastbergen et al., 2019; Man et al., 2025). Puntarenitas beach constitutes a sun-and-sand tourist attraction that may be compromised by the occurrence of these events; therefore, the management of this coastal zone should include the delineation of the susceptible area and the installation of signage and warnings regarding the possibility of recurrence. In Costa Rica, the Maritime-Terrestrial Zone (Zona Marítimo-Terrestre, ZMT) regulates the first 200 m of coastline: the first 50 m from the ordinary high-water mark are State patrimony, while the remaining 150 m are administered by the local government (Costa Rica, 1977). In this regard, the Municipality of Puerto Jiménez should refrain from granting concessions linked to the construction of private infrastructure in this specific sector, to prevent further hazard exposure, currently restricted to the gravel roads providing access to the seaward tip of the spit.

No RBF reports for Latin America were found in the literature, which may reflect both the highly specific nature of these events and the fact that they occur rapidly and are therefore difficult to document, with systematic observations in the region only now beginning to emerge. Nonetheless, there are reports of RBFs that happened in other locations, such as the ones reported by Mastbergen et al. (2019) in the Netherlands (8 locations), the United States (6 locations), Australia (4 locations), and countries like France, Canada, India, and the Philippines (at least 1 event each). Among the documented RBF cases occurring on coastal sandy spits, two particularly relevant analogues are Amity Point, on North Stradbroke Island, Queensland, Australia, and Inskip Point, on the Inskip Peninsula, Queensland, Australia. At Amity Point, a low spit of Holocene-deposited fine silica sand, a deep tidal channel of 22 m runs close to the shoreline. Frequent RBF events have been occurring here for over a century, often collapsing on the beach and sometimes penetrating into the vegetation further inland. These events are particularly vigorous, with breach of wall heights of up to 7 m, leaving behind a characteristic amphitheater-shaped morphology at the upslope end. At Inskip Point, large-scale events were recorded in May 2006, June 2011, and August 2013, each estimated at over 150 m in diameter and 6 m in depth, progressing into the beach and the vegetated area with an active phase of approximately 3 hours (Beinssen et al., 2014; Mastbergen et al., 2019). At Puntarenitas, the perimeter of the failure event reached 167.7 m and the main scarp attained a height of 2.8 m, likewise extending to the vegetation line and displaying a clearly recognizable amphitheater-shaped scar, particularly evident in the secondary scarps.

6. Conclusions

On February 8, 2024, a coastal erosion event occurred at the Puntarenitas beach, Puerto Jiménez. The event was characterized by the formation of nearly vertical scarps on the beach front that rapidly collapsed into the sea. As sections failed, new scarps formed landward at intervals of centimeters, creating a succession of steps or terraced escarpments still currently visible both above and below the waterline, with a landward-dipping orientation. Morphodynamical characteristics include active longshore sediment transport that infills previous failure events; the presence of predominantly fine-grained, water-saturated sand; steep underwater slopes with deposit heights of 30 m; concave inward-curving submarine morphology; and the occurrence of successive scarps from intermittent shallow landslides collectively indicating that this process indeed represents a Breaching or Retrogressive Breach Failure. The event assesed in our study, was characterized by an almost vertical breach face terminating due to changes in sediment granulometry, gradual retrogressive erosion over several hours, an amphitheater-shaped scar extending to the shoreline, an hourglass-shaped erosion-deposition pattern according to bathymetric data, and shear-induced dilatancy effects observed in amateur video footage. These characteristics are consistent with the behavior of an RBF.

The Puntarenitas RBF event is analogous to those documented at other coastal sandy spits, sharing diagnostic characteristics including the amphitheater-shaped failure scar, the near-vertical breach face, the retrogressive headwall retreat extending to the vegetation line, and the downslope deposition of remobilized sediment. However, the geomorphological context of Puntarenitas is singular within the documented literature, as the breaching developed along the flank of a tectonically formed, semi-enclosed deep basin. This distinctive configuration implies a substantially greater potential energy gradient available to sustain turbidity currents over longer transport distances, as evidenced by the sediment deposition recorded at approximately 130 m from the main scarp at a depth of −43 m. This study highlights the need for further research into how deep-basin boundary conditions modulate the initiation and propagation of RBF events in tropical mesotidal environments.

We were able to confirm the local knowledge affirming the recurrent nature of RBF events by satellite imaging. Nevertheless, no prior documentation exists for these events, and similar occurrences could not be identified elsewhere in Central America. Among the potential triggering mechanisms for the event are extraordinarily low tides combined with elevated groundwater levels. Given the possibility that these conditions may recur following coastal recovery, and considering the documented history of previous events, we conclude that this represents a natural hazard requiring the application of measures oriented toward ensuring the safety of tourist and local activities and preventing increased exposure of coastal infrastructure.

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