Mercator, Fortaleza, v. 23, e23025, 2024. ISSN:1984-2201

UAV REMOTE SENSING APPLICATIONS IN BEACH-CLIFF SYSTEM MONITORING OF MORPHODYNAMIC PROCESSES

https://doi.org/10.4215/rm2024.e23025

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Article history:
Received 31 July, 2024
Accepted 04 November, 2024
Published 10 November, 2024

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ARTICLE

Abstract

This study aims to evaluate the morphodynamic changes in a beach-cliff system in northeastern Brazil using high resolution data collected by UAV-SfM techniques to understand the geomorphic changes of the coastal landscape. The study used the Geomorphic Change Detection (GCD) method applied to short-term monitoring. This method uses Digital Elevation Models (DEMs) to determine the morphological changes in terms of both erosion and deposition through DEMs of Difference (DoDs). The difference gridded models are acquired by drone-based remote sensing, which can accurately and efficiently provide ultra-high resolution imagery and digital surface model data to measure volumetric changes. The geomorphic changes are observed on high resolution maps. The multi-temporal analysis revealed significant volumes of erosion and deposition throughout the beach-cliff system over the study period. In the first interval (May/2021 - November/2021), the cliff recorded -8,715 m³ of erosion and 2,816 m³ of deposition, with the beach sector showing erosion in 86% of its area. In the second period (November/2021 - March/2022), more severe erosion rates were observed on the cliff, reaching -10,853 m³ with 51% of its area eroded, while the beach showed the opposite behavior to that previously analyzed, with 73% of the beach experiencing an accumulation of sand and a positive balance of 5,960 m³. The results of this study can be fruitful in identifying the different of geomorphology hazards, coastal impacts of cliff urbanization and in the use of remotely piloted aircraft in coastal monitoring. Furthermore, the results indicate that the management of the beach-cliff system must be integrated and never dissociated, as is generally done by coastal managers.

Keywords: Geomorphometry; DEMs; Drone-Based Remote Sensing; Mass Movement; Elevation and Volumetric.

Resumo / Resumen

APLICAÇÕES DE SENSORIAMENTO REMOTO POR VANT EM MONITORAMENTO DE PROCESSOS MORFODINAMICOS EM SISTEMAS PRAIA-FALÉSIA

Este estudo tem como objetivo avaliar as mudanças morfodinâmicas em um sistema de praia-penhasco no nordeste do Brasil usando dados de alta resolução coletados por técnicas de VANT-SfM para entender as mudanças geomórficas da paisagem costeira. O estudo usou o método de Detecção de Mudança Geomórfica (GCD) aplicado ao monitoramento de curto prazo. Esse método usa modelos digitais de elevação (MDEs) para determinar as mudanças morfológicas em termos de erosão e deposição por meio de MDEs de diferença (DoDs). Os modelos de grade de diferença são adquiridos por sensoriamento remoto baseado em drones, que podem fornecer com precisão e eficiência imagens de altíssima resolução e dados de modelo de superfície digital para medir as alterações volumétricas. As alterações geomórficas são observadas em mapas de alta resolução. A análise multitemporal revelou volumes significativos de erosão e deposição em todo o sistema praia-penhasco durante o período de estudo. No primeiro intervalo (maio/2021 - novembro/2021), a falésia registrou -8.715 m³ de erosão e 2.816 m³ de deposição, com o setor da praia apresentando erosão em 86% de sua área. No segundo período (novembro/2021 - março/2022), foram observadas taxas de erosão mais severas na falésia, chegando a -10.853 m³, com 51% de sua área erodida, enquanto a praia apresentou comportamento oposto ao analisado anteriormente, com 73% da praia com acúmulo de areia e saldo positivo de 5.960 m³. Os resultados desse estudo podem ser úteis para identificar os diferentes riscos geomorfológicos, os impactos costeiros da urbanização das falésias e o uso de aeronaves remotamente pilotadas no monitoramento costeiro. Além disso, os resultados indicam que a gestão do sistema praia-arriba deve ser integrada e nunca dissociada, como geralmente é feito pelos gestores costeiros.

Palavras-chave: Geomorfometria; MDEs; Sensoriamento Remoto Baseado em Drones; Movimento de Massa; Elevação e Volumetria.

APLICACIONES DE LA TELEDETECCIÓN POR UAV EN EL SEGUIMIENTO DE PROCESOS MORFODINÁMICOS EN SISTEMAS PLAYA-ACANTILADO

Este estudio tiene como objetivo evaluar los cambios morfodinámicos en un sistema playa-acantilado en el noreste de Brasil utilizando datos de alta resolución recogidos por técnicas UAV-SfM para comprender los cambios geomórficos en el paisaje costero. El estudio utilizó el método de Detección de Cambios Geomórficos (DGC) aplicado a la monitorización a corto plazo. Este método utiliza modelos digitales de elevación (MDE) para determinar los cambios morfológicos en términos de erosión y deposición mediante MDE de diferencias (MDE). Los modelos de cuadrícula de diferencias se adquieren mediante teledetección basada en drones, que puede proporcionar con precisión y eficacia imágenes de muy alta resolución y datos de modelos digitales de superficie para medir los cambios volumétricos. Los cambios geomórficos se observan en mapas de alta resolución. El análisis multitemporal reveló volúmenes significativos de erosión y deposición en todo el sistema playa-acantilado durante el periodo de estudio. En el primer intervalo (Mayo/2021 - Noviembre/2021), el acantilado registró -8.715 m³ de erosión y 2.816 m³ de deposición, con el sector de playa mostrando erosión en el 86% de su área. En el segundo periodo (Noviembre/2021 - Marzo/2022), se observaron tasas de erosión más severas en el acantilado, alcanzando los -10.853 m³, con un 51% de su superficie erosionada, mientras que la playa mostró un comportamiento opuesto al análisis anterior, con un 73% de la playa con acumulación de arena y un saldo positivo de 5.960 m³. Los resultados de este estudio podrían ser útiles para identificar los diferentes riesgos geomorfológicos, los impactos costeros de la urbanización de los acantilados y el uso de aeronaves pilotadas por control remoto en la vigilancia costera. Además, los resultados indican que la gestión del sistema playa-acantilado debe ser integrada y nunca disociada, como suelen hacer los gestores costeros.

Palabras-clave: Geomorfometría; MDE; Teledetección con Drones; Movimiento de Masas; Elevación Y Volumetría.

INTRODUCTION

Coastal systems, such as beaches and cliffs, are highly dynamic and constantly transforming due to complex natural processes. Beaches, formed by the accumulation of sediments like sand, gravel, and rocks, are influenced by tides, waves, and currents, resulting in diverse morphological characteristics that vary with environmental conditions (Mangor et al., 2017; Short, 2006). The dynamics of beaches are modulated by interactions between wave energy and sedimentation, shaping their transition zones between land and sea.

Cliffs, on the other hand, are vertical geological features that emerge in coastal and mountainous areas (Hampton, 2004; Sunamura, 2015). Erosion of coastal cliffs is a natural process resulting from the interaction between marine and subaerial processes, leading to the gradual degradation of rock material and mass movements over time (Trenhaile, 1987). This erosion is particularly pronounced in sedimentary rocks, where wear dynamics differ between more consolidated formations and those that are less resistant (Del Río et al., 2020; Kroon et al., 2022).

Cliff instability is influenced by various factors, including the height and slope of the talus (Kirkby, 2023). The morphology of the beach can directly affect cliff evolution, as the dissipation of wave energy along the shoreline plays a crucial role in protecting the cliff toe and preventing collapses (Hapke & Reid, 2012; Carpenter et al., 2014). Thus, understanding the morphodynamic processes between beaches and cliffs is essential for managing risks associated with these systems, especially in light of the increasing number of accidents in coastal areas (Hampton, 2004; Imam et al., 2023).

In recent years, remote sensing techniques, such as aerial photogrammetry using UAVs, have been widely employed to investigate changes in coastal morphology (Rosser et al., 2005; Jin et al., 2021; Bessin et al., 2023). Photogrammetry using Structure from Motion (SfM) algorithms allows for detailed reconstruction of terrain topography. To ensure the accuracy of the derived Digital Elevation Models (DEMs), it is essential to adhere to rigorous photogrammetric principles during flight planning and aircraft calibration (Sturdivant, 2017; Leal-Alves, 2020).

This study aims to analyze high-resolution data collected through UAV-SfM techniques to understand the morphodynamic behavior of a beach-cliff system, contributing to continuous monitoring and effective management of coastal dynamics. By deepening the understanding of the interactions between these systems, this research seeks to support public policies aimed at risk mitigation and the protection of human life.

STUDY AREA

The study area comprises a 700 m long active sea cliff at Pacheco Beach, located in the municipality of Caucaia, in northeastern Brazil (Figure 1). This cliff is practically uninterrupted, varying in height from 15 m (49.2 ft) to 20 m (65.6 ft), with an average slope of 80°. Its lithology dates back to the Miocene and is composed of sediments from the Barreiras Formation, with pre-Coastal Neogene siliclastic sedimentary constituents found along the northeast coast of Brazil (Bezerra et al., 2006). These sediments have their origin associated with epigenetic uplifts (Bezerra et al., 2001; Saadi et al., 2005; Nunes et al., 2011) and transgressive events (Arai, 2006; Rossetti et al., 2013). From a morphostructural point of view, Pacheco Beach is located in the Baturité and Jaibaras domain (Peulvast and Claudino Sales, 2004). This continental area is characterized by a mountainous relief, located about 15 km from the coast, which explains the deposition of sediments of the Barreiras Formation in this sector.

The coastline of Pacheco is characterized by a series of active cliffs interspersed with sandy beaches and coastal protection works. The process of retreat of these cliffs occurs through mass movements. (e.g., landslides, falling blocks, debris flows). The beach suffers from the combined action of waves and tides, with a narrow strip of beach no more than 60 m wide at low tide. At high tide, the strip of sand is completely submerged.

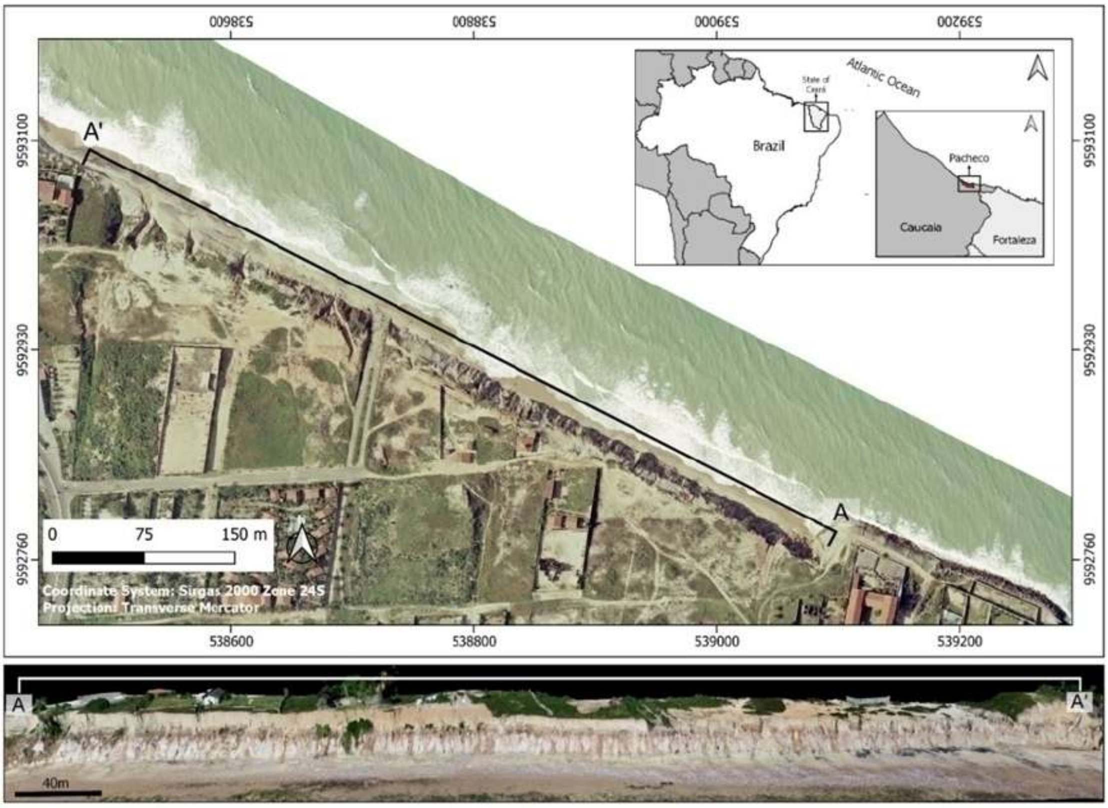

Figure 1 - Pacheco Beach sedimentary coastal cliffs (Northeast, Brazil).

In periods of extreme beach erosion, it is possible to observe the existence of a slightly inclined abrasion platform that extends from the high tide level at the base of the cliff to the submerged area of the beach. This rocky prominence is evidence of the pronounced action of wave abrasion acting on the cliff retreat (Gomes Neto, Morales and Hamelak, 2012), and its exposure only occurs at times when the sand level on the beach is very low.

The granulometry of the beach indicates that the dominant mode is composed of sediments of medium sand class. However, during periods of extreme beach erosion due to storm waves, the beach face is covered in gravel. In this case, where the width of the beach is smaller, erosion of the base of the cliff is more pronounced. It is also important to note that Pacheco Beach is included in a coastal erosion nucleus, which affects many beaches located in the Municipality of Caucaia. (Leisner et al., 2023).

In terms of meta-oceanographic conditions, the studied beach/cliff system is located in a region with a Köppen climate classification of Tropical Semi-Arid with Dry Winter, with total rainfall exceeding 1,000 mm/year and average temperatures between 24°C and 30°C (IPECE, 2013). It is a mesotidal zone with semi-diurnal variations. The amplitudes range from -0.2 m to 3.2 m. (DHN, 2021). The dominant waves are of short period, with an average value of 6 seconds and an average significant height (SH) of 1.3 meters. Preferred direction varies from 40º to 60º. To a lesser extent, there are long-period waves, generally generated in the Northern Hemisphere by low-pressure systems. These waves have an average period of 12 s, an average Hs of 1.8 m, and a predominantly N-NE direction.

MATERIALS AND METHODS

MONITORING BY UNMANNED AERIAL VEHICLE - UAV

To image the beach-cliff system at Pacheco, a Phantom 4 Pro V2 quadcopter UAV was used. The aircraft has a 20-megapixel small format digital camera (CMOS/F6310S), with an 84° FOV (field of view), 8.8mm/24mm, which provides images with a resolution of 4864 x 3648. For the Nadir view (90°), the camera is attached to a stabilizing gimbal (Table 1).

Aircraft characteristics	Specifications
Flight autonomy	30 minutes
Speed/distance	5 – 7 m/s
Radio control's maximum range	5 km
Dimension (without propellers)	350 mm (diagonal)
Weight	1375 grams
Max. wind resistance	10 m/s
Camera/Sensor	CMOS 1" 20 megapixels
Field of View (FOV)	84° 8,8 mm/24 mm
Image resolution	5472×3648
Stabilization	3 axes (tilt, rotate, swivel)
Tilt range	-90° a 30°

Table 1 - Technical specifications of the aircraft. Source: https://www.dji.com/br/phantom-4-pro-v2/specs.

The aerial surveys took place at different times of the year, taking into account the seasonal climate of the region. Three field campaigns were conducted: the first in May 2021, the second in November 2021, and the third in March 2022. During this period, it was possible to observe the dynamic behavior of the cliff at different times of the year. In this way, the data used to create the Digital Elevation Models are information from the two different periods in which they were obtained. The first interval covers the period from May/2021 to November/2021 (dry period) and the second comparison interval refers to the period from November/2021 to March/2022 (rainy period).

All flights were programmed and planned to use the DroneDeploy web application, which allows the configuration of various flight parameters, including height, coverage, number of overflight lines, angle, direction, lateral and frontal image overlap, and aircraft speed. For the 3D reconstruction of the terrain, the flight path was defined on a double mesh (longitudinal and lateral), in addition to the option of collecting images obliquely to the cliff (45°), maximizing the image overlap essential for the Structure from Motion - SfM approach (Westoby et al., 2012). It is important to note that the aerial surveys were conducted under favorable weather conditions, at low tide and syzygy, around 12 noon, to minimize shadows from the cliff slope. Details of the flight parameters are given in Table 2.

Date	Flight height	Evaluated area	Side/Front overlap	Travel speed	Total operating time (flight)	Number of imagens
May/2021	100 m	0.195 km²	75%	7m/s	22 min	195
November/2021	70 m	0.221 km²	75%	8m/s	32 min	384
March/2022	70 m	0.167 km²	75%	7m/s	34 min	390

Table 2 - Flight parameters used.

The UAV was set to fly at a constant speed between 7 m/s and 8 m/s to minimize motion blur. The camera was set at a right angle (90°) and 100 m altitude for the month of May and 70 m for the months of November 2021 and March 2022, reaching a Ground Sample Distance (GSD) of 3 cm and 2 cm, respectively. The total overflight time (longitudinal and transverse) varied between 22 and 34 minutes.

To ensure survey reliability and accuracy, 30 ground control points georeferenced the photogrammetric block. In addition, 15 control points were established to assess positional accuracy and validate the aerophotogrammetric models and products. These control points were divided into two categories: mobile and fixed. The mobile points consisted of plastic tarpaulin targets, a material resistant to wet beach soil, measuring 50 x 50 cm and distributed from the base of the cliff to the low tide line. The fixed points were cylindrical concrete structures with red painted tops to make them more visible in aerial photographs, positioned along the top of the cliff. The presence of vegetation meant that the area around the points had to be cleared to optimize visibility.

All control and check points were georeferenced using GNSS RTK (Real Time Kinematic) geodetic instruments (Figure 2a), with the acquisition of plane-time coordinates (X, Y and Z) (Figure 2c). The survey was carried out in RTK/UHF mode and using the UTM coordinate system, datum SIRGAS 2000 Zone 24S (EPSG:31984). The collected coordinates were sent to the platform of the Brazilian Institute of Geography and Statistics (IBGE) for GNSS data post-processing using Precise Point Positioning - PPP.

Figure 2 - GNSS-RTK Survey and Unmanned Aerial Vehicle UAV. a) GNSS-RTK base antenna; b) UAV Phantom 4Prov2; c) Fixed points on the cliff top; d) Control points on the beach face.

PHOTOGRAMMETRIC PROCESSING

For automated photogrammetric processing of the obtained images, Agisoft Metashape Pro version 1.8 was used. This tool is based on Structure from Motion multiview 3D reconstruction techniques and is suitable for processing UAV images (Dewez et al., 2016; Westoby, 2018; Gonçalves, 2021). The complete workflow, including initial flight planning, data acquisition hierarchy, photogrammetric processing steps and generation of final products is described in figure 3.

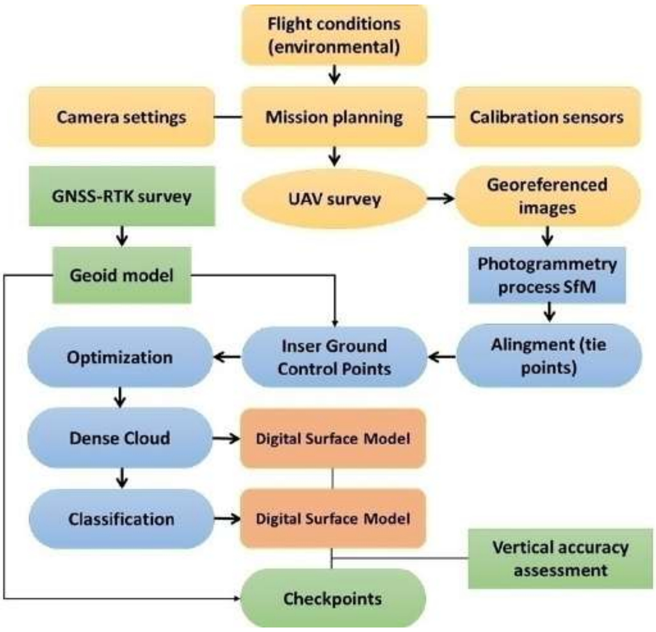

Figure 3 - Aerophotogrammetric workflow. Adapted from Leal-Alves (2020).

Photogrammetry using Agisoft Metashape software aligns and calibrates the collected images to create a point cloud with information about the position and relative orientation of the images. The next stage involves the semi-automatic insertion of markers for Control Points (CPs), improving positional accuracy based on the GNSS-RTK coordinates of the survey. This allows the processing products to be georeferenced in a Geographic Information System (GIS). The MVS algorithm optimizes camera alignment, resulting in a densified, RGB-coloured cloud. After projection error correction, the densified point cloud is used to generate additional photogrammetric products such as a 3D polygon mesh model, digital elevation model (DEM) and orthophoto mosaic. The high point density allows for accurate modeling of beach and cliff shapes.

GEOMORPHIC CHANGE DETECTION (GCD)

Geomorphic Change Detection (GCD) software linked to the ArcGIS 10.6 program was used to detect morphological changes in the beach-cliff system (Wheathon et al., 2010; James et al., 2017). GCD works to detect topographic changes, based on raster surfaces. The variations are calculated from the difference in the surface elevations of the digital elevation models. In this case, the GCD uses the DEM of Difference (DoD) algorithm to estimate quantitative changes in the land surface's landforms. The DoD algorithm calculates the differences by subtracting the pixel values of two different DEMs, using equation (1):

$$\delta_E = Z_2 - Z_1$$

Where: δ_E is a DEM output model with changes on a volumetric scale (m³). Z1 is the DEM from the previous period and Z2 from a later period (Weathon et al., 2010).

The output raster file shows volumetric changes, indicating positive values for surface uplift (deposition) and negative values for subsidence (erosion) (Gomez-Pazo et al., 2021). However, DoD-derived digital elevation models can have uncertainties due to various factors such as data collection methods, processing techniques, surface type and roughness, vegetation, and variations in point density (Blanchard et al., 2010; Williams, 2012; Kromer et al., 2017; Rumson et al., 2019).

To reduce uncertainties, the GCD tool allows the establishment and application of volumetric confidence intervals and minimum thresholds for detecting changes (Abellán et al., 2014). These values are referred to as the limit of detection (LoD), where changes below the user-determined limit are ignored, as they may be related to system errors or noise (Schimel et al., 2015; Esposito et al., 2018). Thus, the first step in determining a reliable detection threshold is to propagate the error in the elevation model used to calculate the elevation difference, using equation (2):

$$\delta_{DoD} = \sqrt{(\delta Z2)^2 + (\delta Z1)^2}$$

Where: δDoD is the propagated error of the DoD, δZ1 refers to the individual error of the most recent DEM and δZ1 to the individual error of the oldest DEM.

In this study, the root-mean-square error (RMSE) was calculated for the vertical uncertainty estimates in each model generated so that the combined error (δDoD) of each DEM was applied uniformly to the entire DoD. In addition, the significance level applied to the DoD was 95%, as indicated by Wheaton et al. (2010), where elevation changes that have a 95% chance of not being correct due to measurement error are considered significant and are therefore excluded from the analysis and considered uncertain for calculation.

For a more precise analysis of the results, the segmentation was carried out in three zones to detect geomorphic changes. The first zone corresponds to the cliff, demarcated from its base to its top. The second zone is related to the beach adjacent to the cliff, covering an area 30 meters wide from its base. The third zone, called "unclassified", is also delineated. It includes parts of the DEM that were not included in the calculation of geomorphic changes, such as areas at the edges of the DEM or changes whose values did not reach the detection limit.

RESULTS

The point clouds of May 21, November 21, and March 22 have a spatial density of 265 points/m2, 362 points/m2, and 299 points/m2, respectively. The DEMs resulting from the interpolation of the point data have absolute vertical accuracies of ± 9.0 cm (May/21), ± 10 cm (November/21) and ± 9.0 cm (March/22). The horizontal accuracies (x,y) of the DEMs for May/21, November/21 and March/22 varied between 12.5 cm and 18.2 cm.

MORPHODYNAMIC BEACH BEHAVIOR

The analysis of the detection of changes related to the months of May/21 and November/21 shows an overall negative change in elevations, with 86% of the beach area eroding, with a maximum variation of -2.5 m and an average of -0.62 m. Only a small stretch (14%) showed accumulation, with a maximum variation of 1.0 m and an average of 0.62 m (Table 3). The volumetric estimate of sediment eroded during the period considered is -8,846 m³, while the volume deposited was 1,196 m³.

This means a loss of -7,649 m3 of sand, with percentage values for erosion and accumulation estimated at 88% and 12%, respectively. These percentages refer to changes above the margin of error, which is considered a significant change. The changes that were not considered because they were below the error limit amounted to 2,007 m³ (22% of the total volume).

For the period November/21 and March/22, the results show the opposite behavior to the previous analyzed period, with an overall predominance of sand accumulation in 73% of the study area, with a maximum variation of 2.0 m and an average of 0.72 m. Only a small stretch showed erosion (27%), with a maximum variation of 2.0 m and an average of -0.72 m (Table 4).

Only a small stretch showed erosion (27%), with a maximum variation of 2.0 m and an average of -0.92 m (Table 4). In terms of volume, the beach showed an erosion of -4,306 m³ and an accumulation of 10,266 m³, resulting in a gain of 5,960 m³ of sand compared to the previous period analyzed. The unaccounted values do not exceed 15% of the total volume (2,684 m³) and are related to unaccounted changes according to the minimum limit of detection - minLoD and represent non-significant changes related to relatively stable areas.

Beach Zone Results	**May 2021 - November 2021**		**November 2021 - March 2022**	
Results in area (m²):				
Total area eroded	14.177		4.688	
Total accumulation area	2.229		13.025	
Volumetric results (m³):		**Error (±)**		**Error (±)**
Total erosion volume	-8.846	± 2.007	-4.306	± 1.326
Total accumulation volume	1.196	± 472	10.266	± 2.684
Total net volume difference	-7.649		5.960	
Vertical change variations (m):				
Negative change	-0.62	± 0.3	-0.92	± 0.3
Positive change	0.54	± 0.3	0.72	± 0.3
Total results:				
Percentage of erosion	88%		30%	
Accumulation percentage	12%		73%	

Table 3 - Results of the geomorphic change detection analysis in the area delimited for the beach.

MORPHODYNAMIC SEA CLIFF BEHAVIOR

For the zone delimited by cliffs, the analysis of the detection of changes related to the months of November/21 and March/22 shows an erosion behavior in 51% of its eroded area, with a maximum vertical variation of -3.0 m, and an average of -1.49 m (Table 5). Accretion occurs in 49% of the area, with a maximum vertical variation of 3.0 m and an average of 0.51 m. It is important to note that although 50% of this area showed an increase, these values are associated with material eroded from the cliff and deposited at its base, which does not mean that there was accretion of material on the cliff, as it is a highly erosive feature. This is evident when looking at the volumetric rates, where 2,829 m³ of deposition and -8,715 m³ of erosion were recorded, giving a negative balance of -5,899 m³, with percentage values of 76% erosion and 24% deposition. The unaccounted changes amounted to 1,238 m³ (11% of the total), and these are values related to the minimum detection limit (minLoD).

Significant changes were also observed during the periods of November 21 and March 22. In total, the cliffs show a behavior of 78% erosion and 22% accretion, so that 62% of the calculated area is eroded (Table 4). Maximum erosion values reach -3.0 m, with an average of -1.86 m, while deposition values reach 3.0 m and an average of 0.85 m. In volumetric terms, there was a big difference in this zone compared to the previous period analyzed, in which the DoD showed erosion of -10,853 m³ and deposition of 2,998 m³. The error values amounted to 1,652 m³ (12% of the total volume) and are values calculated according to the spatially uniform error surface (minLoD).

Cliff Zone Results	May 2021 - November 2021		November 2021 - March 2022	
Results in area (m²):				
Total area eroded	5.838		5.841	
Total accumulation area	5.517		3.506	
Volumetric results (m³):		**Error (±)**		**Error (±)**
Total erosion volume	-8.715	± 1.238	-10.853	± 1.652
Total accumulation volume	2.820	± 1.170	2.998	± 991
Total net volume difference	-5.899		-7.854	
Vertical change variations (m):				**Erro (±)**
Negative change	-1.49	± 0.3	-1.86	± 0.3
Positive change	0.51	± 0.3	0.85	± 0.3
Total results:				
Percentage of erosion	76%		78%	
Accumulation percentage	24%		22%	

Table 4 - Results of the change detection analysis in the area delimited for the Pacheco cliff.

CHANGE DETECTION

A more detailed analysis of the Differential Elevation Model (DoD), with emphasis on the beach system, revealed an accumulation of sediment at the eastern and western ends of the study area (Figure 4). It is noteworthy that the most pronounced vertical variations, with negative values reaching -1.0 m, were observed in the central-eastern part of the study area. This resulted in a significant reduction in the volume of sediment on the beach in this particular sector. It was in this same region that the cliff showed the greatest dynamism, with erosion rates of up to -3.0 m at the base of the feature. There is a direct relationship between the beach and the cliff, indicating that the erosion of the beach volume in front of the cliff compromises its effectiveness in protecting and dissipating the daily action of the waves.

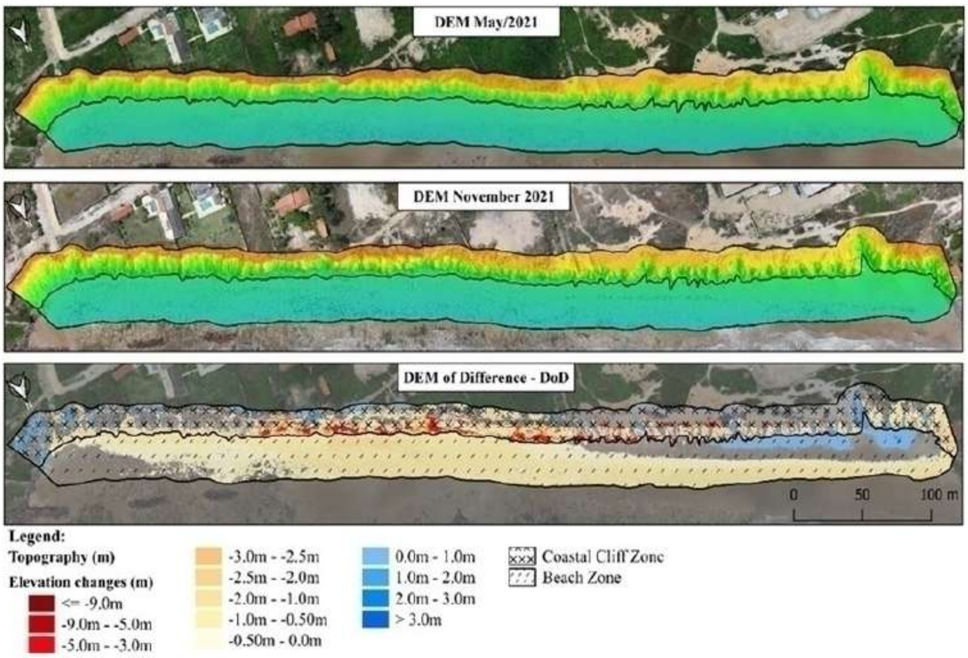

Figure 4 - Changes in elevation and volume recorded in the May/2021 and November/2021 ARP surveys.

In a second analysis, from November 21 to March 22, a different dynamic was observed compared to the previous period. The coastal system showed the opposite behavior to the one analyzed before, characterized by the accumulation of sand in the whole central-eastern part and by the erosion in the most western part of the study area. Erosion processes also affected the entire length of the cliffs, mainly concentrated in the upper part and on the face of the feature, with positive variations at the base related to the deposition of material displaced from the slope (Figure 5).

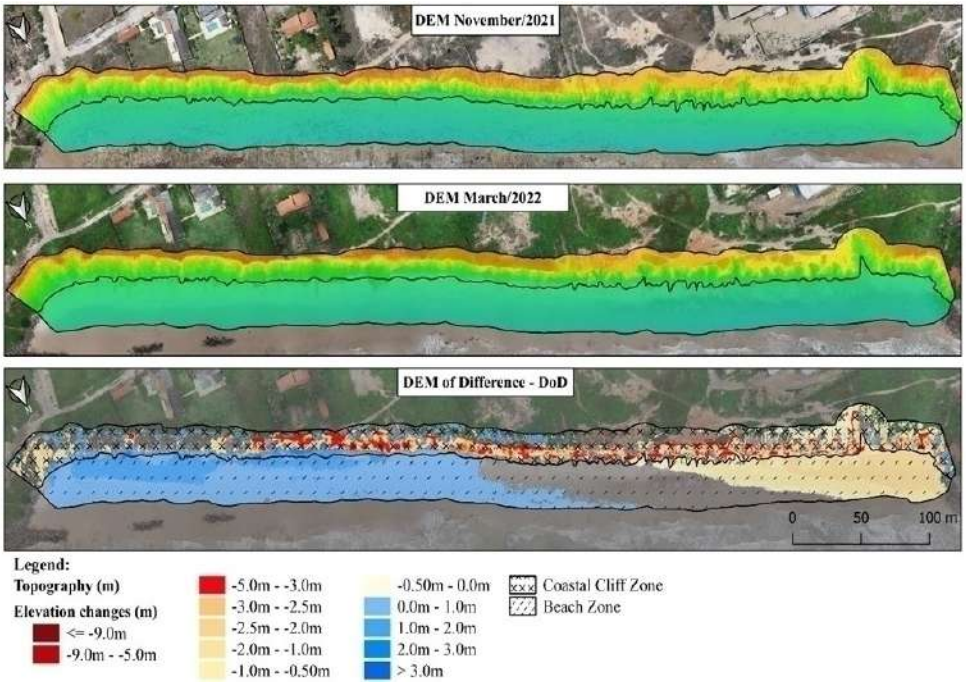

Figure 5 - Changes in elevation and volume recorded in the November/2021 and March/2022 UAV surveys.

DISCUSSION

UNCERTAINTY OF MODELS

The use of photogrammetric techniques to create Digital Elevation Models (DEMs) in the study area, followed by the comparison of these models at different time intervals, allowed the geomorphologic evolution of an active coastal cliff to be estimated over a relatively short period of about one year. This approach provided valuable insights into the dynamic processes that shape the coastal landscape. The high-resolution DEMs allowed the identification of subtle changes in cliff morphology, including erosion patterns, material redistribution, and potential areas of instability. In addition, the temporal sequence of the DEMs facilitated the quantification of erosion rates, volumetric changes, and the identification of critical hotspots prone to accelerated geomorphic transformations.

The use of GCD software makes it possible to quantify the calculation of the uncertainty in the height (δz) of the Digital Elevation Models (DEMs) used, and this uncertainty is then propagated by creating mask surfaces. These surfaces represent the spatial variation of δz in each DEM, estimated on the basis of empirically determined values, specifically the Root-Mean-Square Error (RMSE) of the control points empirically collected in each survey. This procedure allowed the creation of a threshold in the Differential Elevation Model (DoD) of a conservative nature, since it is based on a spatially uniform error with a minimum level of detection (minLoD) that is constant in space and independent of geographic location (Esposito et al., 2018).

Although previous studies, such as those conducted by Weathon et al. (2010) and Passalacqua et al. (2015), have indicated that a conservative approach may result in erosion values below a certain threshold not being detected, this study justifies the use of a more conservative minimum detection threshold (minLoD), considering that a less conservative threshold may introduce unrealistic changes in the differential elevation model (DoD). In addition, the results of the change detection analysis confirmed significant changes, i.e. high rates of cliff erosion and high volumetric variation in the Pacheco beach-cliff system. Therefore, an analysis aimed at estimating changes of medium and large magnitude eliminates the need to adopt a less conservative threshold for detecting small changes of less relevance.

The volumetric changes were quantified with a satisfactory level of precision, showing that the percentages of error obtained did not have a significant influence on the volumetric determinations. These errors were relatively small, ranging from 17% to 22%. These error ranges are consistent with those observed in studies that used the Digital Elevation Model Difference (DEMD) technique in their analyses, such as Allan James et al. (2012) and Cook (2017).

GEOMORPHIC CHANGES IN THE PACHECO BEACH-CLIFF SYSTEM

The results from the comparison of DEMs highlight the considerable geomorphic changes that have occurred in the Pacheco beach-cliff system in a short period of evaluation (November/2021 - March/2022). These changes are dominated by erosive processes, whether of marine or subaerial origin (Hall et al., 2002; Young and Ashford, 2008) and which denote the stochastic behavior of the active cliff under study.

The collection of data and the construction of DEMs at different climatic stations throughout the analysis allowed to assess the inter-annual influence of the processes involved in the retreat of the cliff and the volumetric variation of the beach. The first period analyzed (May/2021 - November/2021) is characterized by a dry climate, with low rainfall (historical average of 18mm) and oceanographic conditions with predominantly sea-type waves, with a significant height of 1.35m, a peak period of 7s and a predominant direction of E/NE (Leisner, 2023). The response to these processes was a greater concentration of erosion at the base of the cliff in the central-eastern part of the study area (Figure 6), the same part where the beach also suffered intense erosion and volumetric loss of sediment.

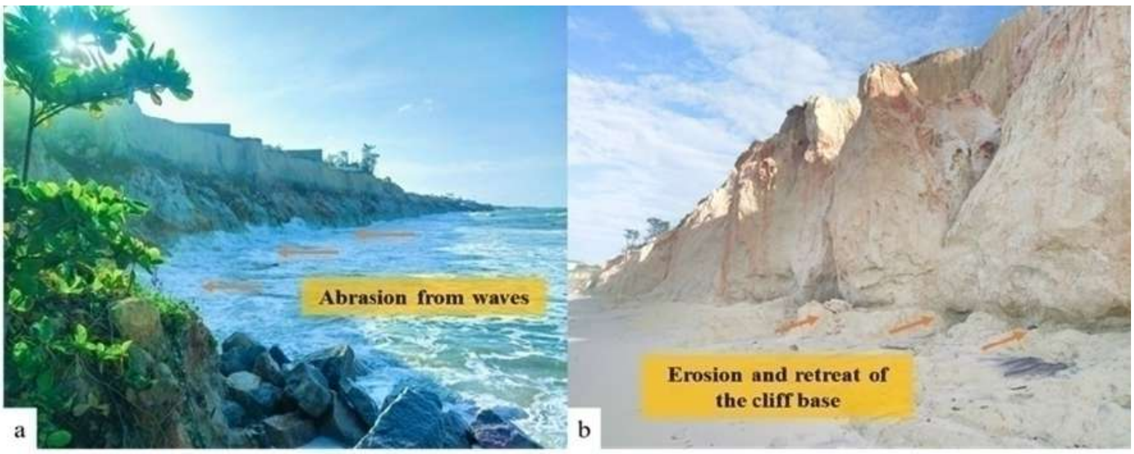

Figure 6 - Erosion of the base of the Pacheco cliff due to wave abrasion.

Therefore, we can observe a well-established pattern of erosion and retreat of the cliffs during the period under study, characterized by a significant reduction in the volume of the beach and more pronounced erosion at the base of the cliff. This phenomenon is widely recognized in the scientific literature (Emery and Kuhn, 1982; Del Río and Gracia, 2009; Sunamura, 2015; Arróspide et al., 2023). The influence of coastal processes on the base of cliffs is well-documented and understood. The force of the waves hitting the base of the cliff generates both mechanical and hydraulic pressure, resulting in the wearing away of rock layers and a reduction in the structural integrity of the cliff, as documented in previous studies (Young et al., 2009; Winoski et al., 2022, among others).

The role of the beach is also important in determining cliff retreat rates, as it acts to dissipate wave energy and regulate the frequency with which the base of the cliff is subjected to abrasive attack (Hobbs et al., 2002; Earlie et al., 2015; Pena et al., 2021). Lee (2008) observed the behavior and retreat rates of Pleistocene soft rock cliffs along the coasts of North Norfolk and Suffolk, England, and highlighted that changes in beach level can result in significant differences. In their assessment, average cliff retreat rates per year reach 2.53 m, a rate similar to the retreat of the Pacheco sedimentary cliff over the same 1-year period (Leisner et al., 2023).

Analysis of the period between November/2021 and March/2022 reveals a complex response of the cliff that is not limited to variations in beach level and abrasion by sea waves. In addition to these factors, its modeling is influenced by the constant action of weathering agents in the subaerial portion of the coastal feature (Lee, 2008). A comparison of the DEMs shows a significant frequency of mass movements, such as debris flows and block falls, that occurred during this period (Figure 7). These events confirm the high erosion rates recorded on the Pacheco beach-cliff system and highlight the complexity of the processes that contribute to the geomorphologic evolution of coastal cliffs.

Figure 7 - Exemple of mass movement in January 2022.

The increase in erosion rates obtained for the Pacheco beach-cliff system is related to the rainy season. In this stretch of the Ceará coast, rainfall rates reach 1250 mm, concentrated in only 6 months of the year (July-December) (Pessoa et al, 2017), directly influencing cliff retreat through subaerial processes and mechanisms such as mass movements, infiltration and surface erosion, which further intensify the degradation of active coastal cliffs (Benumof and Griggs, 1999, Duperret et al., 2005, Gilham et al., 2019).

The occurrence and magnitude of mass movements such as landslides are strongly influenced by the lithology of the cliff, its rock structure and geotechnical properties (Kuhn and Prüfer, 2014). In this case, the friable lithology of the cliff and its susceptibility to erosion could be verified during field expeditions. The samples collected and the observations made showed that this is a material of low resistance, which can be easily fragmented by harder objects such as geological hammers, stones or wood. This resistance of the rock can be classified as low according to the Prémaillon scale (2018), which means that the rock requires few blows to fragment.

The deposition rates on the bluff section are intrinsically linked to the methodology used to compare the DEMs, where the deposition information is predominantly linked to the DoD approach, which shows the accumulation of colluvial or talus material following the occurrence of mass movements on the bluff slopes. However, it is crucial to note that these talus deposits are not permanent, as the erosive processes associated with wave action and coastal drift currents in this region tend to erode them rapidly, contributing to the ongoing dynamics of cliff erosion.

CLIFF INSTABILITY, HAZARDS AND ASSOCIATED RISKS

The results provide a clear representation of the constant and accelerated retreat of the Pacheco cliffs, in which the natural geodynamics of cliff evolution, amplified by the erosion process resulting from mass movements, plays a prominent role. This geological peculiarity has led to numerous challenges and impacts for the local population, beach visitors and coastal managers (Del Río, 2009; Kennedy et al., 2013; Moore and Davis, 2015). The consequences of these dynamics include an increased risk of landslides and blockfalls, which directly threaten the safety of people and coastal structures, and the gradual loss of land area, which affects the availability of coastal space and infrastructure (Lee et al., 2001; Westoby et al., 2018). The impacts go beyond immediate security concerns and affect the socioeconomic activities of the region (e.g., tourism, business, port, and real estate sectors). Recurrent cliff retreat poses an ongoing challenge to coastal communities, requiring adaptation and protection strategies and resilience planning to mitigate potential hazards and protect human and financial capital.

The DoD analysis revealed segments of the area that exhibited steeper trends and significant magnitudes of mass movement, particularly in the central-eastern portion of the study area, where the highest volumetric rates were recorded. The presence of these movements in this region is a significant concern, especially considering that the upper portion of the bluff contains urban infrastructure such as houses, walls, posts, and roads.

CONCLUSIONS

The aim of this study is to propose a reliable and accurate analytical methodology for evaluating the behavior, evolution, volumetric changes and retreat estimates of beaches with active sedimentary cliffs, based on aerophotogrammetric monitoring data and elevation model comparisons. It also presents a set of aerophotogrammetric parameters and techniques that can be successfully applied in future studies using UAVs.

The results obtained from UAV monitoring highlight the importance of short-term primary data for assessing and reconstructing geomorphic evolution in coastal areas with cliffs, especially in environments that present hazards. Combining and reliably comparing multitemporal cliff slope DEMs has proven to be a complex task due to the steep morphology and the different spatial accuracies of the derived DEMs. However, the approach used in this study, with evaluation and estimation of vertical uncertainties using GNSS-RTK checkpoints, allowed the construction of DoD detection thresholds that, while conservative, allowed for highly reliable data and assessment of real geomorphic change.

The approach used proved to be a valuable solution for improving and advancing change detection analyses for cliff evaluation. The volumetric change rates are comparable to those documented in other coastal environments characterized by (soft) sedimentary rocks that are easily eroded by marine and subaerial processes.

In this study, based on a multitemporal analysis (May 2021 - March 2022), the high differences in volumetric rates during the two climatic periods of the year reveal the large transfer of mass, mainly attributed to subaerial processes dominated by precipitation-induced surface erosion. These high rates, influenced by processes (marine + subaerial), highlight the resistance of the material and the geological structure of the Pacheco cliffs, characterized by the friable sedimentary lithology of the barrier formation, as the most important conditional factors dictating the evolution and erosion of this relief.

It should be noted that the use of UAVs, among other observation methods, provides a detailed understanding of the dynamics and mass movements of cliffs, compared to classical field observation, since it can quantify changes in geometry and volume. This technique has also proven to be suitable for the assessment of inaccessible or unstable and dangerous areas, such as the Pacheco cliffs. Therefore, the quantification of mass loss processes or erosion rates provides a substrate for future predictions of coastal relief, as well as providing managers, planners and decision makers with valuable information that can be used in planning measures and implementing sustainable coastal management strategies. The detailed insights provided by the use of UAVs, coupled with other observation methods, greatly enhance the potential for effective coastal management strategies.

Finally, it is important to share the research findings with local communities to raise awareness of coastal dynamics and associated risks. This can be arranged with the Pacheco residents' association so that information can be brought to those who really need it. By using this information, coastal managers can make more effective and sustainable coastal management of environments with beaches and cliffs.

ACKNOWLEDGEMENTS

The authors would like to thank the National Council for Scientific and Technological Development (CNPQ 420516/2022-0; Scholarship PQ 309102/2022-7; PQ 310887/2021- 6) and the Post-Graduate Program in Geography (PROPGEO/UECE) for their support. This study was supported by the Ceará Foundation for Support for Scientific and Technological Devel-opment (FUNCAP) through Projetcts (PS1-0186-00333.01.00/21 / UNI-0210-00736.01.00/23.

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