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Morphometric characterization of Banho and Caúra beaches in the municipality of São José de Ribamar, São Luís Island, state of Maranhão, Brazil

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RESUMO

Este estudo objetiva a caracterização morfodinâmica e sedimentar das praias do Banho e Caúra, localizadas no município de São José de Ribamar – MA (2°33'25" - 2°33'52"S e 44°02'21" W - 44° 03'13" W). A morfodinâmica e a geologia foram analisadas nas duas praias, em campanhas realizadas no período de estiagem (outubro/2016). Perfis perpendiculares à linha de costa foram monitorados durante o ciclo de marés de sizígia nas duas praias e foram coletados sedimentos para a classificação dos grãos e permeabilidade. A direção da corrente de deriva litorânea foi avaliada, utilizando-se como traçador um corante orgânico vermelho. Os resultados mostraram uma maior extensão de sedimentos na praia do Banho, com uma antepraia (foreshore) de 624 metros de perfil praiial, enquanto a praia do Caúra revelou um perfil praiial correspondente a uma extensão de 105 m, com um avanço da maré em vários pontos, bem como a presença de calhas, bancos de areias e falésias. A granulometria das praias variou de areia média a areia fina, para as praias do Banho e Caúra, respectivamente. O ensaio de permeabilidade do sedimento mostrou uma relação inversa com a granulometria. A praia do Banho obteve menor coeficiente de permeabilidade (k) e maior classe textural (areia média), enquanto a praia do Caúra registrou maior coeficiente (k) e menor classe textural (areia fina). O experimento de verificação da deriva litorânea na praia do Banho, em condição de maré vazante, mostrou um escoamento paralelo à linha de costa com uma velocidade de 0,10 m.s⁻¹.

Palavras-chave: perfil praiial, granulometria, sedimentos, deriva litorânea.

ABSTRACT

The aim of the present study was to perform a morphodynamic and sedimentary characterization of Banho Beach and Caúra Beach, which are located in the municipality of São José de Ribamar, state of Maranhão, Brazil (2°33'25"S - 2°33'52"S and 44°02'21"W - 44°03'13"W). Morphodynamic and geological studies were performed on both beaches in campaigns carried out in the dry season (October 2016). Sediment samples were collected along the beach profiles at both beaches for the determination of grain classification and permeability. The direction of the coastal drift current was determined using a red organic fluorescent tracer at Banho Beach. The results showed a greater width of sediments on Banho Beach, with a 624-meter foreshore, whilst Caúra Beach had a width of 105 m, with the advance of the tide at several points, as well as a trough system, sand bar and cliffs. Regarding granulometry, medium-coarse sand was found at Banho Beach and fine sand predominated at Caúra Beach. The sediment permeability test showed an inverse relation to particle size. In the foreshore region, Banho Beach had a lower permeability coefficient (k) and a higher textural class

(medium sand), whereas Caúra Beach had a higher coefficient (k) and lower textural class (fine sand). Mean granulometry at Banho Beach was predominantly in the range of 1.48 to 1.79 ϕ , which is classified a medium-coarse sand, whereas the sand at Caúra Beach was classified as fine (2.31 ϕ). The coastal drift experiment at Banho Beach revealed flow parallel to the coastline at a speed of 0.10 ms^{-1} .

Keywords: beach profile; granulometry, sediments; coastal drift.

Introduction

Brazil has one of the largest national coastlines in the world, extending for approximately 9,000 km between latitudes 4°N and 34°S. The coast is a classic trailing edge coast typified by numerous long meandering rivers, generally low gradient regressive coastal plains, an abundance of sediment and extensive beach-barrier systems (Short and Klein, 2016). Andrads et al. (2020) highlight that beaches are fundamental habitats that regulate the functioning of several coastal processes and key areas contributing to national and local budgets.

The disorganized occupation of the Brazilian coast has caused changes to the sedimentary balance and the configuration of the shoreline by limiting the action of natural coastal processes. Understanding the changes in the beach profile involves a set of variables required for the creation of morphodynamic forecasting models (Calliari et al., 2003).

Government officials have established a program for monitoring, managing and conserving the current coastline of Brazil considering anthropogenic and natural pressures and the need for long-term planning, with the aim of maintaining the characteristics and environmental services provided by coastal areas (MMA, 2018a).

Several types of beaches occur in response to a wide spectrum of waves, tides and sedimentary conditions. Thus, the morphodynamic classification does not include all possible regions in terms of typology and morphodynamic stages (Andrade, 2016; Mallmann et al., 2014). Morphological surveys evaluating the relation between morphology and the hydrodynamic and sedimentary characteristics of beaches are widely used in the application of classical morphodynamic models (Mascagni et al., 2018).

Knowledge on the morphodynamic state of a beach as well as its spatial and temporal variations is important to integrated management strategies in coastal regions and the solution of environmental problems, especially those related to sandy beaches (Maria, 2016). Such knowledge enables estimating levels of risk that can be used for accident prevention programs directed at beach goers (Short and Hogan, 1994). Despite the ecological and social importance of these ecosystems, sandy beaches are significantly impacted by human interference, chemical and

organic pollution, tourism and global climate change (Amaral et al., 2016). Sandy beaches are for erosion, transportation and, finally, granulometric distribution (Ranieri and El-Robrini, 2020).

The morphodynamics of beaches on São Luís Island in the state of Maranhão, Brazil, is directly associated with wave action and tidal energy, which mold the hydrodynamic behavior that reshapes the shoreline and affects the sedimentary balance by establishing a predominance of accretion processes in the dry season and erosion in the rainy season (MMA, 2018b). Structural interventions on the coast, such as containment engineering projects designed to minimize or even impede erosive processes, need to be monitored by studies that consider climatological and oceanographic forces to avoid irreversible environmental harm as well as material losses due to poorly designed projects (Oliveira et al., 2011). For Ranieri and El-Robrini (2020) the coastal currents, waves, tidal currents are the main conditions for topography and sediment transport on macro-tidal beaches (range > 4 m).

The island, located in an ecotone (a transition zone between two ecosystems), is considered to have high plant biodiversity. Anthropogenic pressures threaten the island's environment, leading to changes in geomorphology, hydrology, and sedimentary processes (Rêgo et al., 2018).

The municipality of São José de Ribamar is located on the eastern coast of São Luís Island, 30 km from the center of the state capital. According to the most recent census, the municipality has a demographic density of 419.82 residents/km² in an area of 388.37 km² (Brasil, 2016). São José de Ribamar has undergone an intense process of urbanization that has led to an increase in occupied area and exposed soil, reaching the coastal zone of the municipality, where urban densification has accelerated in the last ten years (Masullo; Rangel, 2012).

Due to the characteristics of the beaches, the region has sandy granulometry, with a dissipative morphodynamic stage triggered by the intense action of the wind, waves, tides and coastal currents (Oliveira et al., 2014; El-Robrini et al., 2006). At the end of the 1980s, the municipality of São José de Ribamar was undergoing a process of increasing erosion that affected the beaches and

threatened a portion of the waterfront, forcing the public authorities to invest in the mitigation of the problem with the construction of a seawall at Banho Beach.

The aim of the present study was to perform the morphodynamic and sedimentary characterization of Banho Beach and Caúra Beach, which have considerable touristic and economic importance in the region. We test the hypothesis that changes in the morphodynamic state of the beaches investigated are associated with continuous processes of poorly planned interventions and anthropogenic actions resulting from the expansion of urban density vectors. The data generated will enable an understanding of coastal variables and the evaluation of the effectiveness of the seawall built at Banho Beach regarding the control of coastal erosion. Such

information can help guide future studies and assist in governmental decision making with regards to coastal management in the state of Maranhão, Brazil.

Material and methods

The municipality of São José de Ribamar is located on São Luís Island, 25 km from the state capital (São Luís).

The study area on São José Bay was 2.5 km of waterfront encompassing Banho Beach and Caúra Beach ($2^{\circ}33'25''$ - $2^{\circ}33'52''$ S and $44^{\circ}02'21''$ W - $44^{\circ}03'13''$ W) (Figure 1). A tidal channel, known as Vieira Creek, is located between the two beaches: Caúra Beach on the left bank of the creek and Banho Beach is on the right bank, where the seawall was built.

Figure 1. Map showing location of study area on Banho Beach and Caúra Beach, São José de Ribamar, Maranhão, Brazil.

As occurs on other beaches of São Luís Island, the main oceanographic agents on the shoreline of São José de Ribamar are waves, coastal currents, tides and winds, which exert a significant influence on the local morphodynamics and are responsible for the main morphological and environmental features, such as beaches, dunes, cliffs, tidal plains, saltwater marshes and

mangroves (Silva et al., 2009). The inner continental shelf of the Maranhão Gulf, which includes São José Bay, is characterized by sandbanks measuring 8 to 20 m in height (Lefèvre et al., 2017, Silva et al., 2018). The region has semi-diurnal tides, the range of which can reach 7.2 m, as well as tidal currents of 2.5 m/s and wave heights ranging from 0.6 to 1.4 m (Santos et al.,

2020). The winds are constant and interact with the NE trade winds, with a mean annual velocity of 3.0 m.s^{-1} (Muehe, 2006).

The present data were collected during campaigns conducted in the dry season (October 2016). Morphodynamics (beach profile and coastal drift) and geology (sedimentology and permeability) were analyzed on the two beaches. To characterize beach morphology, two profiles perpendicular to the coastline were monitored during the spring tide cycle. For such, a CST/Berger topographic level (32 X) on a tripod, a graduated sight measuring five meters in height and a measuring tape were used to determine the distance between the lines of sight, as recommended by Birkemeier (1981).

Sediment samples were collected along the beach profiles at both beaches for the determination of grain classification (Krumbein, 1934; Wentworth, 1922). In the laboratory, aliquots of 50 g were quartered for dilution to remove the salts and oven-dried at 60°C . Fine grains were separated using a sieve with a mesh of 0.062 mm. Grains smaller than this mesh size were placed in a test tube for the granulometric determination using the pipetting method (Suguio, 1973). Grains with a diameter larger than 0.062 mm were processed in a set of sieves with intervals of $1/2 \phi$ (2.00, 1.41, 1.00, 0.71, 0.50, 0.351, 0.250, 0.177, 0.125, 0.088 and 0.062 mm) with standard manual shaking for five minutes. The data were processed using the SYSGRAN 3.0® software program (Camargo, 2006) and analyzed using the statistical methods described by Folk and Ward (1973). The permeability of the samples was determined using a permeameter following the method adopted by Caputo (1975) and quantified using the permeability coefficient (k) (Darcy, 1856; Darcy, 1857).

Statistical analyses were performed using the PAST 3.14 program to calculate the descriptive statistical parameters, such as median, mean, mode, sorting (standard deviation), skewness and kurtosis.

The direction of the coastal drift current was determined using a red organic fluorescent tracer released at Banho Beach approximately 700 m from the coast. A stopwatch was used to determine the spreading time of the fluorescent tracer and a drone (Phantom 4) was employed to capture the aerial images.

Results and discussion

Banho Beach in São José de Ribamar had a large width of sediment, with a foreshore

measuring 624 meters. This was likely associated with the seawall, which enabled the nourishment of the beach. The management of coastal areas is necessary to maintain and protect existing permanent structures. Current global options for sandy beach management fall into hard (engineered man-made solutions, e.g., jetties and seawalls) and soft (natural or nature-based solutions, e.g., dunes and living shorelines) categories (Charbonneau et al., 2019).

Daly et al. (2015) used a morphodynamic model to simulate the development of an embayed beach, considering different environmental conditions and geological settings (i.e., topography and geometry) to reach static equilibrium conditions without the input of external sediment. Simulations of this nature are essential to expanding knowledge and improving the capacity for predicting beach dynamics.

Coastal structures, such as seawalls, breakwaters and containment walls, block the input of sediment along the shoreline, leading to the deposition of sediment upstream and causing erosion downstream, impeding the current from continuing its natural flow in the distribution of sediment along the coast (Castello and Krug, 2015). Standard defense methods for combating erosion include hard/soft protection measures (hold/advance the line), accommodation, and managed retreat and sacrifice. However, the choice of the best management strategy must be based on knowledge of the processes, magnitudes and causes of erosion (Williams et al., 2017).

Besides the seawall serving as a receptor of sediment transported by the longshore current, other agents, such as wind and river flow, also contribute to this input, favoring a broader foreshore at Banho Beach. According to Muehe (2006), beaches on the northern shore of São Luís Island have a mean width of 250 m, which varies with the range of the tide.

The profile of Banho Beach was determined on a stretch of 624 m, on which bars, restaurants and homes are found on the backshore. Vieira Creek is located in the middle foreshore region and sand banks are found on the lower foreshore. A 210-m seawall is located to the east of the foreshore (Figure 2a). The sloped beach has a maximum elevation of -7 m, crossing through the channel of Vieira Creek (Figure 2b). Critical problems are seen in the beach hazard zone, leading to costly coastal remediation and a general degradation of the beach, especially houses and bars that have been built on the foredune, resulting in erosion and the destruction of some of the buildings (Short and Klein, 2016).

Figure 2. Banho Beach: a) Panoramic view of topographic profile, showing human constructions in background; b) Beach elevation profile.

Gravel-size grains were found on the left side of the creek, whereas finer grains were found on the right side (Figures 3a and 3b). Gravel and organic matter may occur due to the inability of the currents to transport this coarser material, which is deposited on the bottom (Figure 3c). Sediments with grain sizes classified as sand and gravel were

also found, along with bivalve shells (Figure 3d). Currently, there is a growing interest in understanding the behavior of gravel beaches, as coarse sediment is widely used as nourishment material to replenish eroded coastlines (Grottoli et al., 2017).

Figure 3. a) Panoramic view of end of beach; b) Panoramic view of channel of Vieira Creek; c) Gravel and organic matter; d) Sediment with sand and gravel grain sizes and bivalve shells; f) Ripples; (e) Mega ripples.

The topographic profile of Caúra Beach reveals a width of 105 m, the first 60 m of which

contain a trough, followed by sand banks at 65 m and another trough at 80 m (Figure 4a and 4b).

Figure 4. Caúra Beach: a) Panoramic view of topographic profile; b) beach elevation profile.

The morphological analysis of Caúra Beach revealed the advance of the tide at several points along the beach as well as containment walls in the backshore region (Figure 5a). Charbonneau et al. (2017) postulate that beach–dune systems will continue to be our most economical and natural form of coastal defense to maintain coastal homes, habitats and recreation areas.

Seasonal climatological events that occur on São Luís Island between August and December (dry period) lead to intensive winds that cause the migration of sandy sediments by way of longshore currents, especially during high tide, whereas the deposition of a large quantity of sediment occurs during the ebb tide, leaving ripples and mega ripples (Figure 5b). These features indicate the

direction of the currents, with the longer dimension occurring perpendicular to the current (Feitosa, 1996; Press et al., 2006).

Cliffs and troughs were also found near the left side of the beach, whereas two clay-muddy facies were found to the right, one of which was yellow and white, with bioturbations and gravel (Figure 5c), whereas the other had a greyish-brown color with intrusions of organic matter, covered with mussel and clam shells (Figure 5d). In Brazil, coastal erosion exceeds shoreline progradation, with beaches, cliffs and estuaries exhibiting higher rates of erosion (Rodríguez et al., 2016). Heavy minerals were found on the face of the beach, likely associated with the local hydrodynamics (Figure 5e) and the proximity of a berm crest (Figure 5f).

Figure 5. a) Backshore; b) Ripples; c) Gravel and clay material; d) Clay and bivalve shells; e) Heavy minerals; f) Face of beach and berm crest.

Regarding granulometry, the beaches investigated had medium-coarse and fine sands, following a logarithmic scale ϕ (1.618). At Banho Beach, an increase in the granulometry of the sediment of the lower foreshore ($> \phi$) was found in comparison to the upper foreshore ($< \phi$). The mean granulometry at Banho Beach was predominantly in the range of 1.48 to 1.79 ϕ , which is classified a medium-coarse sand, whereas the sand at Caúra Beach was classified as fine (2.31 ϕ).

Akpofure and Akana (2019) analyzed the grain size of beach sediments from Bonny Beach in the Niger delta and recorded mean grain sizes for

the dunes (2.0 ϕ), backshore (1.92 ϕ) and beach face (1.82 ϕ), revealing that grains are slightly coarser at the beach face and gradually become finer towards the dunes. This may be due to the removal of finer materials by waves and the current at the beach face.

In terms of selection, sediment samples exhibited behavior ranging from moderately selected to well selected. Regarding asymmetry and kurtosis, the samples from Banho Beach and Caúra Beach exhibited positive asymmetry in the upper and lower foreshore, which are leptokurtic characteristics (Table 1). Skewness measures the

symmetry of the grain size distribution on a cumulative curve and is a positive or negative dimensionless number. Positive skewness characterizes a beach with deposition of sand, whereas negative skewness indicates erosion or non-deposition. Sediments that are symmetrically skewed indicate an environment in which the effects of erosion and deposition are virtually balanced (Akpofure and Akana, 2019).

Several scientists have studied changes in sediment grain size and onshore-offshore sorting across the beach profile using the basic statistical granulometric parameters, such as mean, median, mode, standard deviation, skewness and kurtosis (Titocan et al., 2018).

Table 1. Classification of sediment samples. Abbreviations: M = mean; Md = median.

Beach	Region	M	Class	Md	Selection	Class	Asymmetry	Class	Kurtosis	Class	% Gravel	% Sand	% Silt	% Clay
Banho	Upper Foreshore	1.487	Medium sand	1.444	0.635	Moderately selected	0.262	Positive	1.597	Very leptokurtic	0	100	0	0
	Lower Foreshore	1.799	Medium sand	1.817	0.469	Well selected	-0.08	Approximately symmetrical	0.899	Platykurtic	0	100	0	0
Caúra	Lower Foreshore	2.31	Fine sand	2.276	0.354	Well selected	0.102	Positive	1.407	Leptokurtic	0	100	0	0

The permeability tests were performed in the middle and lower foreshore on Banho Beach and Caúra Beach, respectively. Using seawater as the fluid, the permeability coefficient (k) was 3.061 cm.s^{-1} at Banho Beach and 3.917 cm.s^{-1} at Caúra Beach. Hydraulic conductivity of the beach, and consequently the quantity of infiltrating water, is related to grain size. The greater the permeability, the less the backwash strength and the less efficient the seaward transport of grains (Bujan et al., 2019).

There is generally a direct relation between the permeability and granulometry, as large grain sizes lead to greater permeability of the sediment. However, this pattern was not found at either of the two environments studied. A smaller k coefficient and larger textural class (medium-coarse sand) were found on the foreshore of Banho Beach in comparison to Caúra Beach, which had a larger k coefficient and smaller textural class (fine sand). This finding is likely associated to the site where the test was performed, as Banho Beach is located near the channel of Vieira Creek, diminishing the permeability of the sediment and leaving the environment saturated with water, despite the larger texture in comparison to the other beach.

The rainfall data of the region during the sampling month were nil, as the study was conducted at the height of the dry season. On the day of the experiment, the wind speed was 3.3 m.s^{-1} , which is considered too weak for the transport of large quantities of sediment (Press et al., 2006).

The coastal drift experiment occurred on Banho Beach at low tide near the seawall and channel of Vieira Creek (Figure 6). In the sampling area, it was not possible to determine coastal drift due to the conditions of the environment (low tide and before the surf zone). During the experiment, the flow was different than what was expected. Rather than flow in the offshore direction during

the ebb tide, the flow followed a north-south direction longitudinally to the coastline, with a velocity of 0.10 m.s^{-1} . This may be explained by the fact that the seawall causes a shadow zone on the currents in the area, blocking the flow in this sector despite the strong offshore flow during ebb tide. As the environment is semi-closed and has shallow depths, waves are the main forces of coastal drift, changing it to the opposite direction.

Based on the Hjølström curve (Pinet, 2009), which relates current velocity (cm.s^{-1}) to grain diameter (mm), Press et al. (2006) considered weak currents to be those with a velocity less than 0.20 m.s^{-1} and, consequently, unable to transport larger grains.

The current flow at Banho Beach (velocity of 10 cm.s^{-1}) and the sediments on the phi scale between 1.48 to 2.3, with granulometry ranging from 0.062 to 2 mm in diameter on the Wentworth scale (1922), indicate a very weak local current incapable of eroding any type of sediment other than very fine suspended sediments, such as silt and clay.

Several types of information derived from tracer experiments have been useful to the characterization of subsurface flow and transport (Rasa et al., 2013). Tracer experiments have been performed in energetic surf zones on natural beaches and beaches near structures to measure the short-term longshore sand transport rate. The analysis of tracer spreading is widely used in observational oceanography to study subsurface ocean circulation and material transport. In tracer release experiments, distinct water masses are marked with conservative (i.e., remaining constant and not growing or decaying with time) and passive (i.e., not affecting the ocean flow) chemical constituents (Wagner et al., 2019).

Figure 6. Panoramic view of dispersion area of current.

Conclusion

The morphodynamic and sedimentary characterization of Banho Beach reveals that this is the most urbanized stretch along the oceanfront of the municipality. The seawall at this beach produces an artificial input of sediments, as demonstrated by the nourishment of the beach.

Although with a lower percentage of urbanization, Caúra Beach has strong evidence of coastal erosion, demonstrated by the narrow beach, which affects the natural dynamics of the waves.

The sedimentological characteristics of each beach reveal medium-coarse sand at Banho Beach and fine sand at Caúra Beach. The origin of the medium-coarse sand at Banho Beach is believed to be from the mouth of Vieira Creek and the effect of the seawall, which blocks coarser sediments from the effects of the longshore current. The fine sand at Caúra Beach is believed to be due to the action of the winds.

The permeability coefficients are closely related to the morphodynamic stages of the environments. A smaller coefficient was found on the more dissipative Banho Beach adjacent to the mouth of Vieira Creek, whereas a slightly larger

coefficient was found on the beach with an intermediate tendency (Caúra).

The coastal drift experiment performed on Banho beach during ebb tide revealed a different flow than expected, occurring parallel to the coastline at a velocity of 0.10 m.s^{-1} , likely associated with the seawall, which creates a shadow zone on the currents in the area, blocking the flow in this sector, despite the strong offshore flow of the ebb tide.

With an increase in investments, refined versions of these experiments should expand knowledge on the effect of the longshore transport rate on such factors as the beach slope, wave type (wave asymmetry) as well as the size and specific gravity of the sand.

Knowledge on the morphodynamic state of beaches in urban areas is of considerable importance to the effective management of areas under constant threat of high coastal erosion rates.

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