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Short-Term Beach Rotation Processes in Distinct Headland Bay Beach Systems*§

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ABSTRACT

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This paper investigates morphological changes in headland bay beaches with emphasis on short-term beach rotation processes, elucidating how it is affected by the planform/degree of curvature of the beach, and by the different morphodynamic characteristics of the beach systems monitored. The beaches monitored in the present study were Balneário Camboriu, Brava and Taquaras/Taquarinhas beaches. They have different lengths, degrees of curvature, and levels of exposure to the incident waves, and represent different beach types. Indentation ratio and the SL/CL ratio were measured, and beach profile surveys every 15 days were made in order to measure variations of beach volume and width for each beach. Visual wave and beach observations were recorded daily. Results indicate that morphological changes in headland bay beaches are influenced mainly by beach planform and indentation ratios, presence of rip currents and submerged bars, shoreline length, and beach type. The beach volume and with variations demonstrated that headland bay beaches have defined sectors with different behaviour, as influenced by headland impact on incident waves and longshore currents. Short-term beach rotation is manifested as out of phase variation of beach volume and width between opposite ends of a headland bay beach. Rotation amplitude of about 20 meters was observed at a dissipative beach (Balneário Camboriú), and on the reflective beach of Taquaras/Taquarinhas. Brava beach did not show clear patterns of short-term beach rotation, but there was a subdivision of the beach into two sectors with different magnitudes of sediment removal and behaviour. The occurrence of short-term beach rotation processes in some of the beaches indicates that, erosive events are often caused by a realignment of the beach shoreline in response to a shift in incident wave direction. In these cases the sediment eroded is not lost from the beach system but deposited elsewhere along the beach, and often returning to the initial location in response to a new shift in wave direction.

ADDITIONAL INDEX WORDS: *Embayed beaches, Brazilian sandy beaches, Beach morphodynamics.*

INTRODUCTION

Oceanic sandy beaches are extremely dynamic environments. According to CARTER (1988) beach systems and adjacent zones dissipate a large amount of wave energy, and experience morphologic variability in temporal scales that vary from a few seconds to decades. Better understanding of the magnitude and spatio-temporal behavior of beach systems, in seasonal and long term-scales, is required to correctly plan beach management strategies.

In rocky coastal zones such as occur along Santa Catarina state coast in southern Brazil, headland bay beaches are a common occurrence. The term headland bay beach or embayed beaches defines a sandy shoreline bounded by rock outcrops or headlands where its shoreline assumes some form of curvature (SHORT and MASSELINK, 1999; KLEIN and MENEZES, 2001). Headland bay beaches often develop an asymmetric form, that is characterized by a shadow zone with strong curvature adjacent to the downdrift headland, a gently curved transition zone, and a straight end, that is normal to the angle of incidence of the more energetic waves. In this case they are also called parabolic beaches (HSU and EVANS, 1989; SILVESTER and HSU, 1993; SHORT and MASSELINK, 1999).

Although SHORT and MASSELINK (1999), reported that 51% of the worlds coastline presents headland bay beach morphology, not much research has been conducted in this environment. Between the research developed in headland bay beaches there are the works published by YASSO (1965), SHORT (1979), FINKELSTEIN (1982), CARTER (1988), HSU and EVANS (1989), JACKSON and NORDTROM (1992), SILVESTER and HSU (1993), SHYER MING and KOMAR (1994), SHORT *et al.* (1995), COWELL *et al.* (1996), KOMAR (1997), SHORT and MASSELINK (1999), SHORT *et al.* (2000), MASSELINK and PATTIAR-

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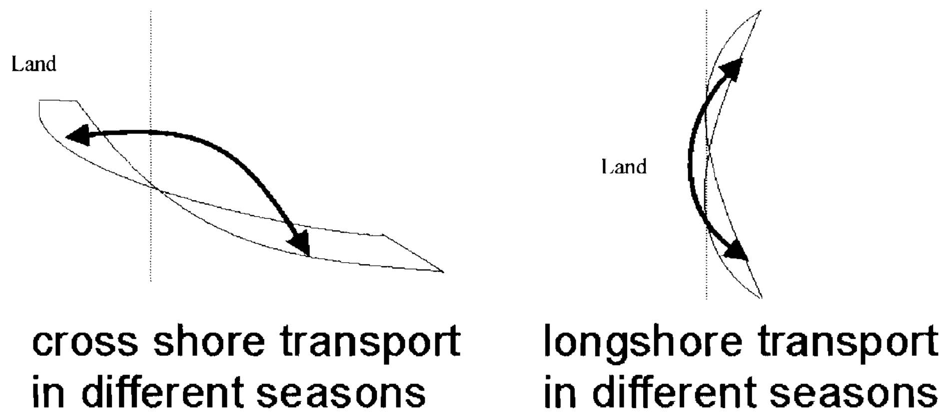


Figure 1. Cross-shore and longshore transport components in headland bay beaches and their resultant interactions. The diagram to the right represent the rotation of the beach planform, as a result of shifts in longshore drift direction at headland bay beaches (modified from VERHAGEN, 2000).

ATCHI (2001). In Brazil there is also some research conducted in headland bay beaches by KOWSMAN (1970), MUEHE (1979), FARIAS *et al.* (1985), BITTENCOURT *et al.* (1987), CASTILHOS (1995), MENEZES and KLEIN (1997), KLEIN *et al.* (1997), TEMME *et al.* (1997), MENEZES (1999), BENEDET FILHO *et al.* (2000), MIOT DA SILVA *et al.* (2000), KLEIN and MENEZES (2001).

KLEIN and MENEZES (2001) suggested that the range of alongshore beach morphology for a headland bay coast is a result of the distance from headland, shape of the bay, wave obliquity, indentation ratio, longshore grain size distribution and nearshore slope.

In headland bay beaches beach rotation processes are a common occurrence. According to SHORT and MASSELINK (1999), this process refers to a shift in alongshore sand transport between opposite extremities of headland bay beaches; this shift is attributed to periodic or long-term changes in wave climate, especially in wave direction. This process can occur over a range of time scales, incurring large variation and movement of the coastline, without net gain or loss of sediment in the system.

Seasonal longshore and cross-shore sediment transport take place in headland bay beaches simultaneously. While the cross-shore component is responsible for interactions between subaerial beach and submerged bars, longshore transport is responsible for the rotation of the beach planform, as shown in Figure 1.

The purpose of this report is to investigate morphological changes in headland bay beach systems, with emphasis on the short-term beach rotation processes, elucidating how it is affected in planform by the degree of beach curvature, and by morphodynamic characteristics of the beach systems.

ENVIRONMENTAL SETTING

Three beaches were monitored in the present study, Brava, Balneario Camboriu, and Taquaras/Taquarinhas. Those beaches are located in the central-north coast of the State of Santa Catarina between 26°30′ S and 27°20′ S (Figure 2), in the coastal macro-compartment of the Crystalline Scarps (MUEHE, 1998). Northeasterly winds are predominant and are interrupted by southwesterly quadrant winds associated with the arrival of cold fronts (NOBRE *et al.*, 1986). The direction of more energetic incident waves is south southeasterly (ALVES, 1996). The local tide is microtidal, mainly semidiurnal with small inequalities, with a mean range of around 0.8 m and a maximum tide of 1.2 m (CARVALHO *et al.*, 1996; TRUCOLO, 1998). The meteorological influence of sea level is very important because storm surges can raise at least one meter above the normal astronomical tide (CARVALHO *et al.*, 1996; TRUCOLO, 1998).

Balneario Camboriu is an arc headland bay beach that is delimited by two rocky outcrops with a central salient. The salient results from the diffraction of incident waves when they meet das Cabras Island, a physical emerged obstacle. The shoreline is 5840 meters long, with a medium dry beach width of 17 meters, and a NW-SE orientation. The northern portion of the beach is exposed to waves from the SE, and its southern sector is in a more sheltered zone. This dissipative beach is composed by fine sand (0.16 mm), and shows morphologic characteristics such as beach cusps with 15 to 20 meters long (TEMME *et al.*, 1997; MENEZES, 1999; BENEDET FILHO *et al.*, 2000; MIOT DA SILVA *et al.*, 2000, KLEIN and MENEZES, 2001).

Brava beach is a headland bay beach with little curvature between rocky outcrops. The shoreline is 2650 meters long, with a medium dry beach width of 34 meters, N-S orientation, and exposed to waves from the SE direction. This intermediate beach is composed by medium sand (0.32mm), has submerged bars, beach cusps with 25 to 30 meters long, and megacusps spaced about 160 meters between horns, strong rip currents are also present (MENEZES, 1999; BENEDET FILHO *et al.*, 2000; KLEIN and MENEZES, 2001).

Taquaras/Taquarinhas beaches are divided by a rocky outcrop that extends about 10 meters offshore, located in the northern sector of the beach arc. For this study these beaches are considered to be part of the same beach system, as they belong to the same beach arc and the outcrop does not inter-

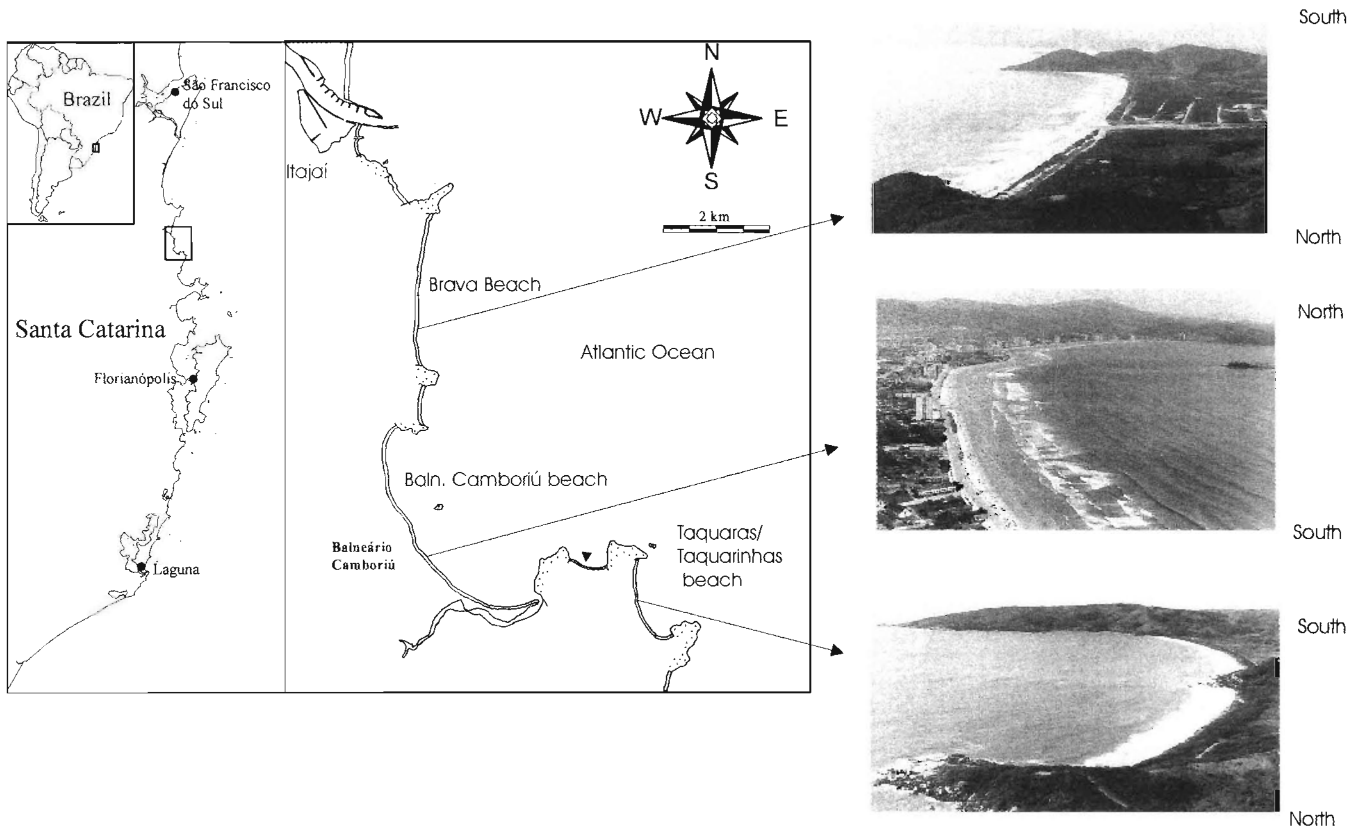


Figure 2. Study site map and oblique aerial photos of Balneário Camboriu, Brava, and Taquaras/Taquarinhas beaches.

rupt the continuity of the shoreline. They also have similar sedimentary characteristics (MIOT DA SILVA *et al.*, 2000) and sediment exchanges (BENEDET FILHO *et al.*, 2000). This beach system has a parabolic planform, with a curved zone, a transitional zone, and a straight end. The shoreline is 1570 meters long, with a medium dry beach width of 27 meters (MENEZES, 1999). This reflective beach is composed by coarse sand (0.90 mm), has a N-S orientation, and is exposed to the waves from the SE quadrant. Morphologic characteristics include beach cusps spaced 30 to 35 meters apart, and there are no submerged bars (MENEZES, 1999; BENEDET FILHO *et al.*, 2000; KLEIN and MENEZES, 2001).

SAMPLING AND ANALYSIS

Point of Greater Indentation and Indentation Ratio

The following parameters were estimated from aerial photos from 1978 (1:25,000 scale) and from 1995 (1:12,500 scale): control line (R_o), predominant wave direction (β), and greater indentation (a), following the methodology proposed by HSU and EVANS (1989), SILVESTER and HSU (1993) (see Figure 3). Two basic parameters in their method are the reference wave obliquity β and *control line* length R_o (Figure 3). Variable β is a reference angle of wave obliquity or that between the incident wave crest (assumed linear) and the *control line,* which is the line joining the upcoast diffraction point to the near straight downcoast beach (Figure 3).

The greater indentation is drawn normal from the control line to the point of more pronounced retreat of the bay shoreline. The point between the downdrift headland and the greater indentation is the shadow zone of the bay, protected from the direct attack of the incident waves. The indentation ratio (a/R_o) indicates the degree of curvature of the headland bay beach.

Relation Between Embayment Width (CL) and the Length of the Embayment Shoreline (SL)

To measure the shoreline curvature (deepness of the bay), and make further comparisons with the indentation ratio from SILVESTER and HSU (1993), and with the morphological changes observed at the headland bay beaches, the relation between the shoreline length and the embayment width (SL/CL) is used. The parameters SL, and CL are illustrated in Figure 3, and were derived from the nondimensional embayment scaling parameter (δ') described by SHORT and MASSELINK (1999).

Beach Profile Measurements

Balneário Camboriu Beach profiles were obtained between January 1994 and February 1996. Eighteen profiles were

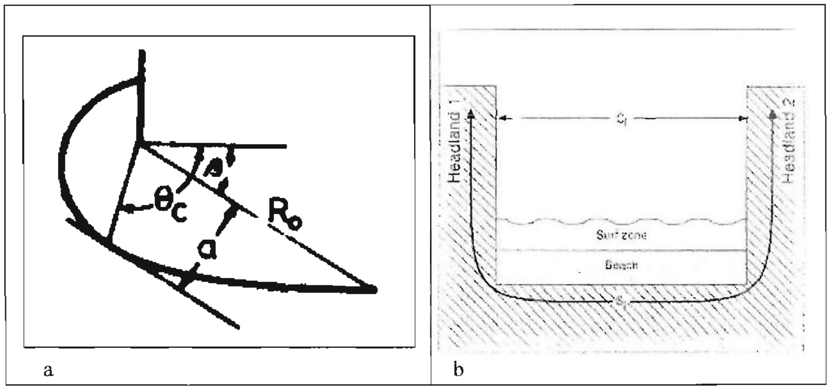


Figure 3. Illustration of the "a" and R_0 parameters according to SILVESTER and HSU (1993), and the CL and SL parameters according to SHORT and MASSELINK (1999).

monitored monthly along the beach shoreline, 6 profiles were chosen for the present report. The profiles were monitored with a leveling instrument as proposed by BIRKEMEIER (1981) and evaluated by the Interactive Survey Reduction Program, (ISRP) (BIRKEMEIER, 1986).

At Brava and Taquaras/Taquarinhas Beaches profiles were obtained between January and November, 2000. Five profiles were monitored at Brava Beach and six profiles at Taquaras/Taquarinhas Beach, a total of 17 surveys were conducted. The profiles were obtained using an electronic theodolite, according to the method proposed by BORGES (1977) that consists in a profile measurement using trigonometry. Beach profiles surveys were made every 15 days.

A scheme of the beach profile envelope is shown in Figure 4. The x-axis extends seawards, and the y-axis extends vertically upwards. The origin of the co-ordinates is located at mean sea level at a fixed reference point. The morphological variables are computed using the landward boundary (×1) and the seaward boundary (×2) as recommended by TEMME *et al.* (1997). The landward boundary (×1) is constant per profile. The locations of these points were determined using the profile envelopes as shown in Figure 4. The location of ×1 is chosen so that this part of the profile is not included in the analysis. The seaward boundary, the location of the mean sea level (×2) is used in all cases, as a consequence, only the subaerial parts of the profile change are analyzed

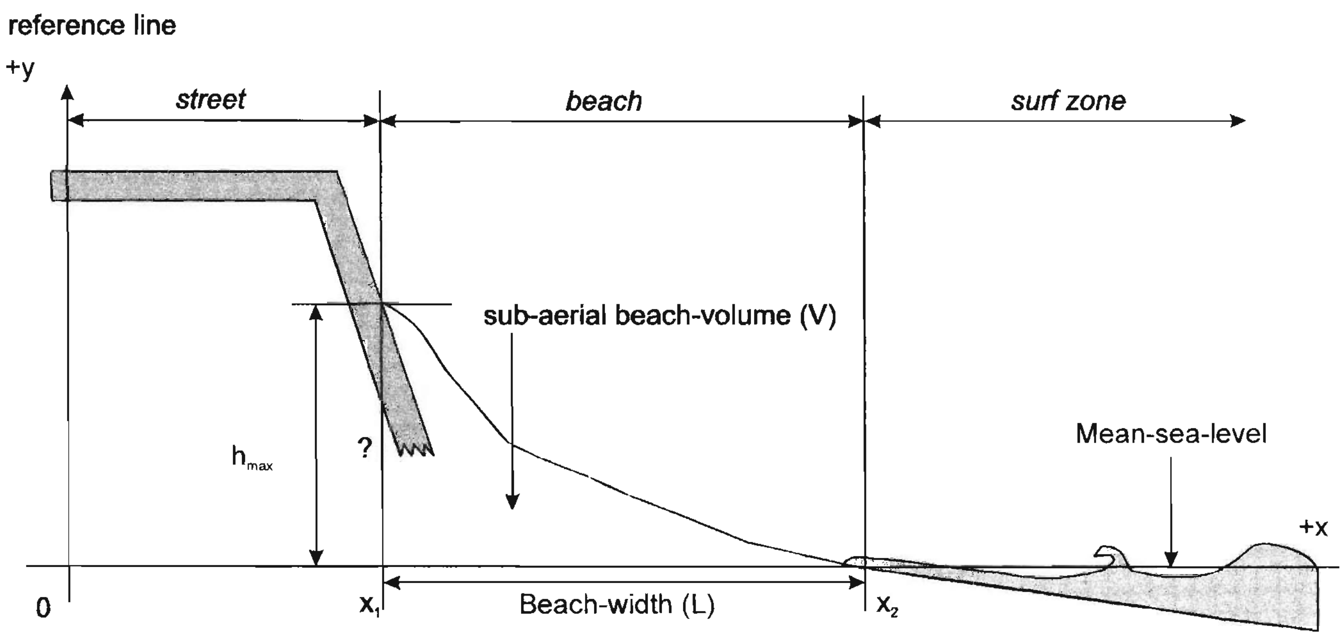


Figure 4. Profile envelope and morphometric variables obtained, beach volume (m3/m), and beach width (m) (extracted from TEMME *et al.*, 1997).

(mobile subaerial zone). The beach volume (V) is defined as the cross-sectional area within the boundaries ×1 and ×2 per unit length of the shoreline (SONU and VAN BEEK, 1971). The width of the beach (L) is defined as the distance between the boundaries ×1 and ×2.

Simple linear correlation tests were made between the beach volume and beach width variations in the different profiles of the same beach. Correlation were considered to be significant with $p<0.05$. The correlation tests were conducted to check for positive or negative correlation between the variations of beach width and beach volume in the profiles located on opposite ends of the headland bay beaches.

Small period fluctuations were filtered using moving average with the interval of two surveys, and anomalies were calculated, in an effort to enhance the graphic visualization of the beach volume and width fluctuations.

Visual Wave Estimations

Visual wave observations were made almost daily on the northern end of Brava Beach from January to November 2000. The visual wave estimations were made using the methodology adapted from the sea sentinels project (MELO, 1993). The following wave parameters were collected:

1) Wave direction was obtained from the top of the headland, from the direction of propagation of wave trains in deep water, relative to coastline orientation, which was obtained from nautical charts.
2) Wave breaker height was visually estimated in intervals of 0.5 m, as the difference between the wave crest and trough.
3) Wave period was estimated using a chronometer, as the interval of time elapsed between the passage of two consecutive wave crests past a fixed point such as boats, surfers floating, or fixed structures. The procedure is repeated three or four times for calculations of an average.

Simultaneously to visual wave observations, daily wave forecast models were recorded from the following Internet sites: www.atlasul.inpe.br and www.fnmoc.navy.mil. These model images were used to visualize the fetch of the incident waves, as well the predominant direction of wave propagation in the offshore zone.

There were a total of 238 daily wave observations. Wave height was represented in a temporal series to visualize the peaks of greater wave height. The wave period was divided in five classes and frequency of occurrence for each class was calculated. Wave direction data was divided in three main directions of approach, and their monthly frequency of occurrence were calculated, to detect shifts in predominant wave direction throughout the year.

RESULTS AND DISCUSSION

Beach Planform Measurements and its Relation to Profile Mobility

Figure 5 exhibits the planform of the beaches monitored, their respective control line (Ro) and indentation (a), accompanied by the profile variations in the sheltered zone and the volume variations in the exposed and sheltered zones plotted together. Indentation ratios (a/Ro) and the values of Sl/Cl are shown in Table 1.

The more indented beaches, Balneario Camboriu and Taquaras/Taquarinhas have shown a/Ro values in the order of 0.4 and 0.39 respectively, and the less indented Brava beach a value of 0.26.

At Figure 5 it is possible to visualize the discrepancies in the volume variations between the sheltered and exposed zones at Balneario Camboriu and Taquaras/Taquarinhas Beaches, and a more similar behavior at Brava Beach. While at Taquaras/Taquarinhas Beach in the exposed profile three volume variations in the order of $77m^3/m$ were measured, the sheltered profile 6 presented volume variation in theorder of $15m^3/m$ during the whole period (80% less). At Balneário Camboriu, maximum volume variation measured was $19m^3/m$ for the exposed profile 3. At the sheltered profile 15, maximum variation measured was in the order of $1.7m^3/m$ (92% less). At Brava beach this difference was less pronounced, with maximum beach volume variation on the order of $38.2m^3/m$ at profile 2, against $14.9\ m^3/m$ at profile 5 (59% less).

Based on these results a relationship between beach profile mobility (variations of beach width and volume throughout the year) and the curvature of headland bay beaches is evidenced. Profiles located between the point of greater indentation and the downdrift headland, had smaller mobility in the headland bay beaches monitored. Examples are profiles 11 and 15 at Balneário Camboriu, profile 6 in Taquaras and profile 5 at Brava beach (see Figure 5). Highly curved beaches, those with an indentation ratio around 0.40 or SL/CL around 1.8 experience greater headland influence on profile mobility, and have a well defined shadow zone. Beaches with less curvature, smaller indentation ratio (around 0.20) and smaller SL/CL (around 1.18), experience less headland impact on profile mobility, and have a small, and not well defined shadow zone.

Southeastern waves have major influence on the planform of the beaches analyzed, as previously described by KLEIN and MENEZES (2001). Consequently the greatest impact of the headlands on the beach planform, and profile mobility, occurs toward the south end of each beach analyzed.

As a result of different degrees of curvature and different orientation, previous authors classified these beaches in relation to their degree of exposure to southeast swells (MENEZES and KLEIN, 1997; MENEZES, 1999; KLEIN and MENEZES, 2001). These authors classified the beach of Balneário Camboriu as semi-exposed and the beaches of Taquaras/Taquarinhas and Brava as exposed.

The relation between the shoreline length and the embayment width (SL/CL) demonstrated similar results as to those obtained with the indentation ratio (a/R_0) (see Table 1). However the relation SL/CL provides no definition of a transition point of greater curvature on the bay shoreline.

As the curvature of a headland bay beach increases, the portion protected from the direct attack of the incident waves (shadow zone) increases. As a result greater variations of morphodynamic parameters such as profile mobility, beach volume and width, and wave breaker height along the head-

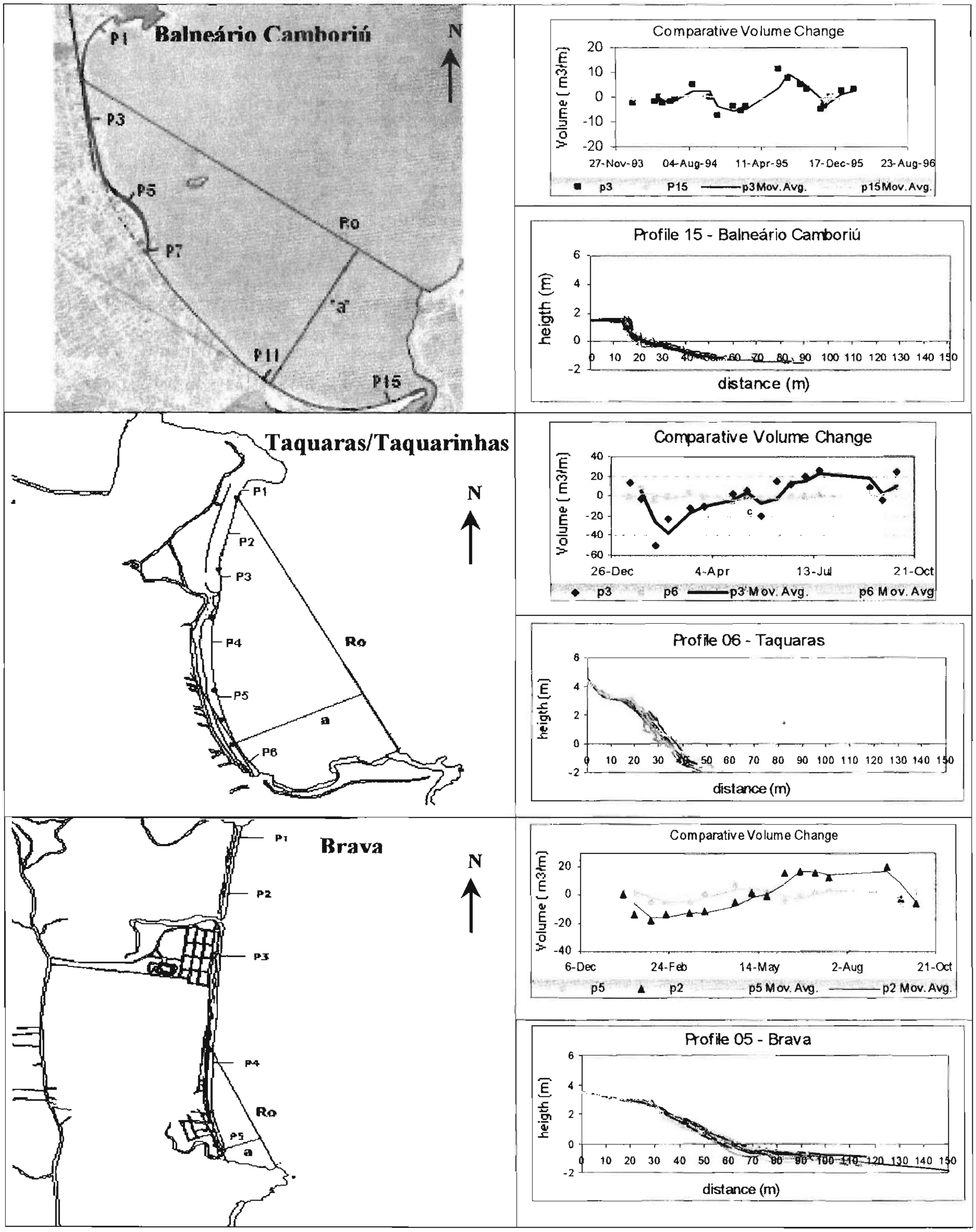


Figure 5. Definition of the greater indention point, definition of "a" and Ro, beach volume fluctuations at profiles with bigger and smaller mobility, and less mobile profile for each beach monitored. Extracted from aerials at a 1:25,000 scale (Balneário Camboriu), and at a 1:12,500 scale (Taquaras/Taquarinhas and Brava beaches).

Table 1. *Relations a/R_0 and SL/CL in the monitored beaches.*

Beach	a/R₀	SL/CL
Balneário Camboriú	0.40	1.82
Brava	0.26	1.18
Taquaras/Taquarinhas	0.39	1.86

land bay beach shoreline is observed in highly curved beaches. In these beaches the exposed straight end will experience greater profile mobility, larger breaker height, and greater fluctuations of beach volume and width values when compared to the sheltered section of the beach. On the other hand, as the curvature of a headland bay beach decreases and it assumes a straight planform, it tends to have a smaller shadow zone, and the fluctuations in beach volume and width will have similar magnitudes along the headland bay beach shoreline.

Wave Observations:

Wave data resultant from the 276 observations conducted between January and October 2000 is presented in Figures 6 and 7 and summarized in the following paragraphs.

Wave breaker height, and wave periods is shown in Figure 6a and b respectively. During the monitored period average breaker height was 0.8 m, and three storm events were observed, with wave heights above 1.8 meters (Figure 6a).

Predominant class of wave period was 7 to 9 seconds, with 43% of the observations, followed by 9 to 11 seconds waves with 34% of the occurrences (Figure 6b).

Predominant wave direction was S/SE with 49% of the occurrences, followed by N/NE waves with 34% of the occurrences (Figure 7a). Shifts in predominant wave direction occurred during the year of 2000 (Figure 7b and 7c). At the months of March and April, S/SE waves were predominant with about 58% of the occurrences, and during the months of September and October N/NE waves were predominant, with 62% of the occurrences (Figures 7b and 7c). These shifts in

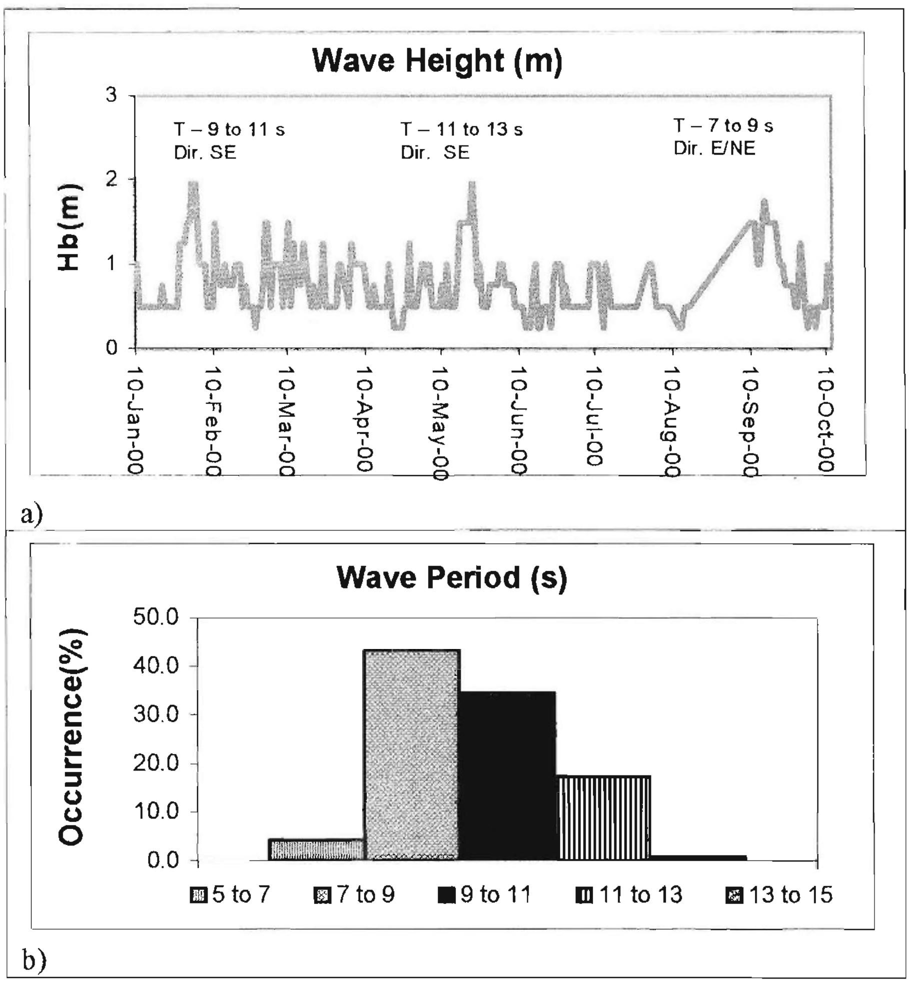


Figure 6. a) Temporal series of wave breaker height (Hb) and b) wave period intervals of predominant occurrence.

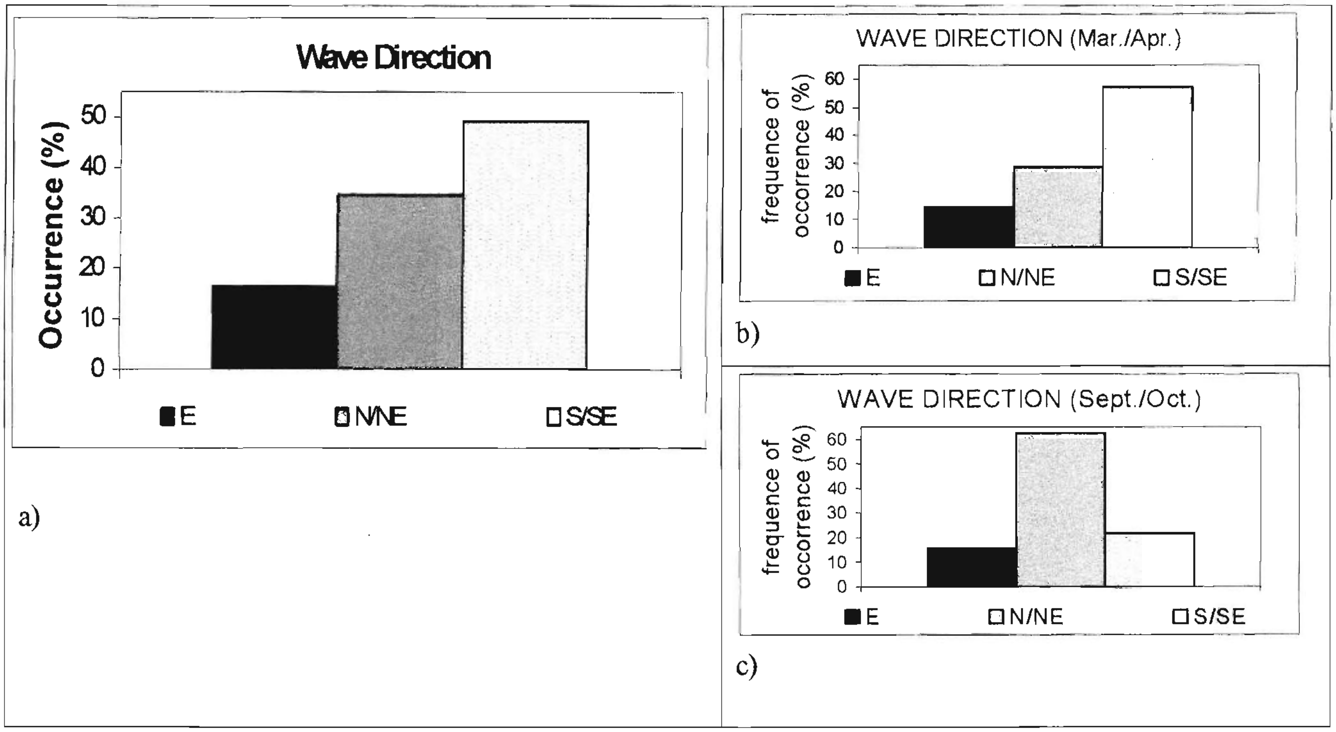


Figure 7. Predominant wave direction during the whole monitorment period (7a) and during the months of March/ April (7b) and October/September (7c).

wave direction strongly influenced the behavior of the headland bay beaches monitored, as discussed in the following sections.

Short Term Beach Rotation Process

As a response to shifts in wave direction fluctuations of beach volume and beach width in headland bay beaches can be out of phase between opposite ends, manifesting an apparent beach rotation. Headlands represent a physical obstacle to the littoral drift. The beaches monitored in this study exhibited this kind of out of phase behavior, at different scales, showing distinct patterns according to their particular morphodynamic characteristics. The following examples briefly illustrate the behavior of the three beaches monitored in the present research.

Taquaras/Taquarinhas Beach

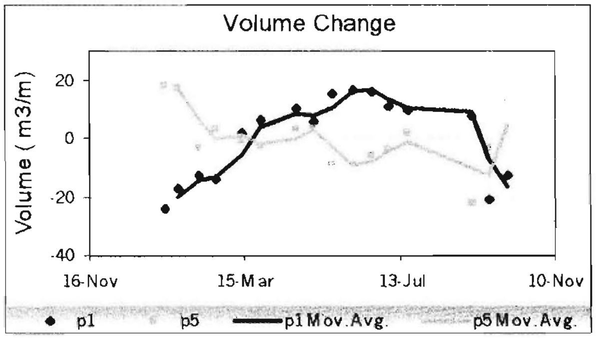
Beach volume variation in different sections of the beach is presented in Figure 8. Looking at the figure clockwise starting from the top left the beach volume variations in profiles 1 and 5 during the same period is shown. Note the opposite trends between these two profiles, while profile 1 is eroding profile 5 is accreting, and vice versa. Profile 1 is located in the northern end of the beach, while profile 5 is located at the southern end of the beach (Figure 5). The opposite behavior between these two profiles might be a result of shifts in wave direction observed, illustrated in the figure on the top to the right. Simple linear correlation between the volume variations in the different profiles is shown on the right bottom and similar variations of profiles two and three in the central north section of the beach is shown in the left bottom.

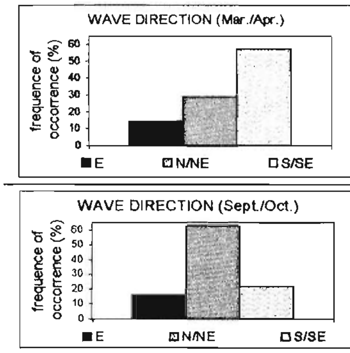
The periods of accretion on the northern extremity correlated significantly ($p < 0.05$) with periods of erosion on the southern extremity and vice-versa (see Figure 8), in other words, the variations between opposite ends are out-of-phase. It was observed that between January to June while profile 1, located on the northern extremity of the beach eroded, profile 5 (in the southern) accreted. From July to beginning September, two inverse cycles occurred almost monthly, and in September/October while profile 1 experienced great erosion, profile 5 accreted (Figure 8).

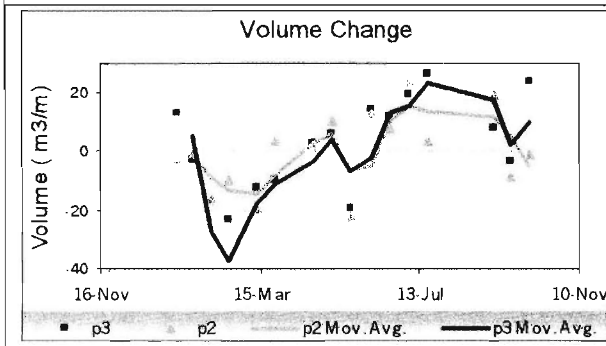
Profiles in the central portion of the beach did not significantly correlate with those at the extremities of the beach. However, there is a general trend of similar behavior between profiles 1, 2 and 3 (see Figure 8).

Periods of erosion on the northern extremity of the beach were related to the previous occurrence of east/northeast waves like during September and October of 2000, and periods of erosion on the southern extremity were related with the previous occurrence of south/southeast waves like what happened during May/June (see Figure 8), and described by BENEDET FILHO *et al.* (2000).

The out of phase variations between opposite ends observed at Taquaras/Taquarinhas Beach during the period of study







	P2	P3	P4	P5	P6
Profile 1	0.39	0.26	0.25	*- 0.63*	*-0.43*
Profile 2	-	*0.69*	0.28	- 0.22	0.02
Profile 3	-	-	0.28	0.13	0.29
Profile 4	-	-	-	0.21	-0.25
Profile 5	-	-	-	-	0.31

Italic gray numbers $p<0.05$.

Figure 8. Inverse beach volume changes between profiles 1 and 6, similar volume variation between profiles 2 and 3, and correlations coefficients between all profiles at Taquaras/Taquarinhas beach and wave direction at the months of March and April and September and October.

suggests an apparent rotation of the beach planform, and this rotation might be a response of the periodic shifts in the predominant wave direction. According to the data obtained in the field, Taquaras/Taquarinhas Beach exhibited a behavior similar to the one described by the theoretical model presented in Figure 9. In this beach, erosive events in one extremity implies that sediment is being transported and redistributed to another sector of the beach. It shall return to its original location when new shifts in the predominant wave direction occur.

Brava Beach

Figure 10 exhibits the main results for Brava Beach. On the top of the figure, the variations of beach volume for profiles 1, 2 and 3 is show. The figure bellows exhibit the variations for profiles 5 and 4, and in the bottom figure the correlation coefficients between the volume variations in all profiles is presented.

At this beach out-of-phase variations of beach volume between opposite ends were not observed.

Positive correlations between profiles located on the north and central sector of the beach (1, 2 and 3), and between profiles of the southern end of the beach (4 and 5) were verified. However no correlation between these two compartments was observed. This suggests a division of the beach in two sectors with different behaviors, the central north sector represented by profiles 1, 2 and 3, and the southern sectors, represented by profiles 4 and 5 (Figure 10).

During the same period of monitoring the occurrence of short term beach rotation processes at Taquaras/Taquarinhas beach was verified, but no evident rotation occurred at Brava beach. It is thus necessary to consider the different characteristics of these two particular beach systems.

Taquaras/Taquarinhas is a reflective beach without the occurrence of submerged bars, and rip currents. On the other side, Brava Beach is an intermediate beach, with remarkable characteristics such as mobile submerged bars and strong rip currents. Inverse patterns of erosion and accretion between opposite ends at Brava Beach might be occurring, but were not detected by the current analysis, as underwater measurements of bar migration were not performed. Another important factor that has to be considered is that the northern headland of Brava beach does not totally block the littoral drift. In events where breaker height observed exceeded 1.5 m, the breaker line extended about 20 m offshore of the headland, headland bypassing occurs in this case, and the sediments are transported to the neighbor beach, instead of accumulate against the northern headland.

The occurrence of strong rip currents can also represent a very important mechanism of sediment transport (SHORT, 1999). The profiles monitored in this type of beach can manifest some erosion, and this erosion may not be directly related to high waves or oblique wave incidence. Rather some of these erosive events may be directly related with the occurrence of strong rips in front of, or in the adjacent areas of the beach profiles monitored (Figure 11). According to SHORT

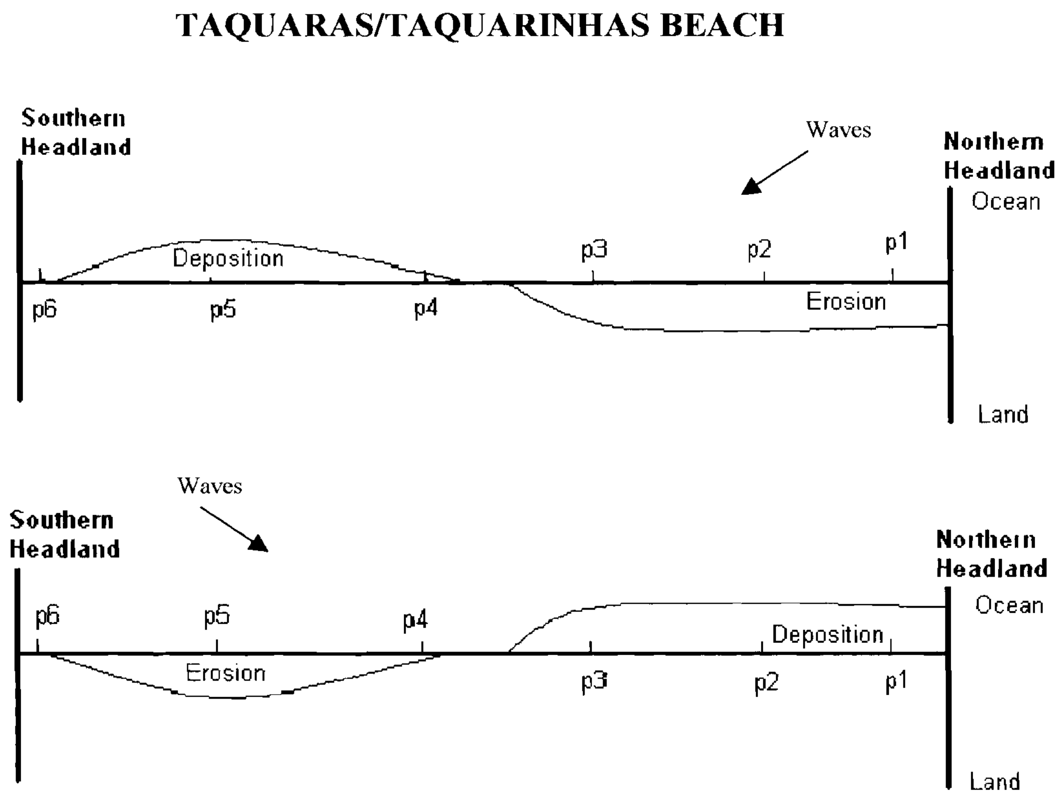


Figure 9. Morphologic model representing the general trend of sediment removal at Taquaras/Taquarinhas Beach.

(1999) rip currents are responsible for the transport of beach sediments offshore.

The data obtained in the present study for Brava Beach demonstrate a behavior similar to the one illustrated by the model proposed in Figure 12. As observed in this beach, during erosive events the whole beach erodes, with different magnitudes. Smaller magnitudes of profile mobility were verified in the southern extremity, and greater magnitude was verified in the central and northern extremity. The same behavior is observed in depositional periods. The occurrence of erosive or depositional trends at Brava beach did not show a clear relation with the wave direction, as observed in Taquaras/Taquarinhas Beach (see Figure 8).

Balneário Camboriú Beach

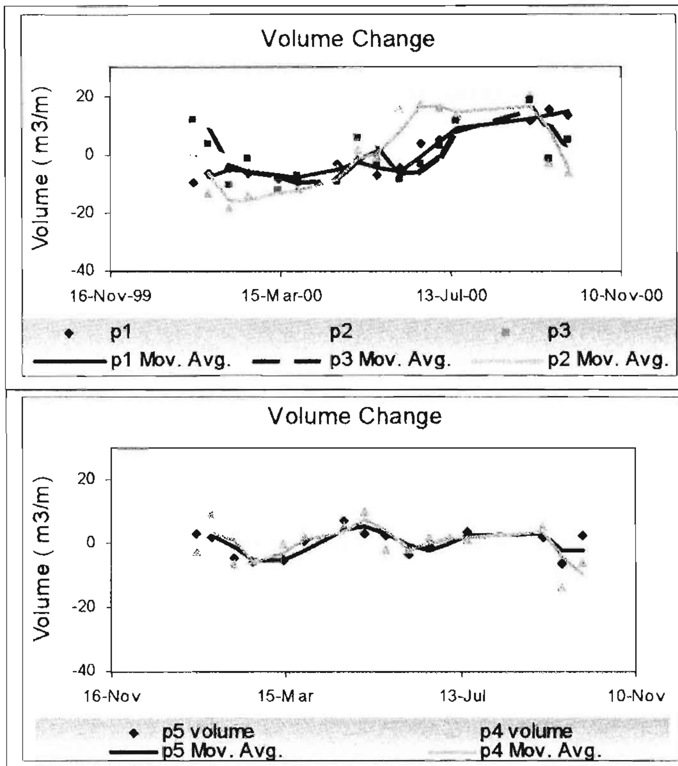
The beach of Balneário Camboriú is divided in two large sectors in this study, which form two distinct beaches with distinct behavior. Those two sectors are divided by a salient formed adjacent to the das Cabras Island (see Figures 1 and 14).

Figure 13 summarizes the main results for Balneário Camboriú beach. Looking clockwise from the top left it is shown: the beach planform with the profile measurement locations, on the top right the variations of beach volume for the profiles on the southern section is shown, and on the bottom right the volume variations for the northern section is presented. At the bottom left, simple linear correlation between the profiles is presented.

Southward of the salient, the area represented by profiles 15, 11 and 7 at the shadow zone of the beach, the variations of beach volume and beach width verified were minimal when compared with the northern exposed sector (see Figure 13), and with the other beaches monitored. As previously showed by TEMME *et al.* (1997), and KLEIN and MENEZES (2001) this is caused by the strong influence that the southern headland, and the das Cabras Island have on this sector of the beach. As a consequence this zone is protected from the direct attack of southeast swells, the most energetic ones on this coastline, thus the waves do not have the same capacity of carrying the sediments around.

The northern sector of the salient, represented by profiles 1, 3 and 5, is directly exposed to waves from a range of directions, and consequently experience a greater mobility, and greater morphologic variability.

Profiles 3 and 5 exhibited a very similar behavior, while profile 1 behaves in an opposite manner (Figure 13). From these results it can be inferred that in this sector of the beach, inverse patterns of erosion and accretion between opposite ends are occurring. The depositional periods at the north extremity (profile 1) correlated with erosive events in the central and southern extremity (profiles 3 and 5) and vice-versa, manifesting an apparent rotation of the beach planform.



	Profile 2	Profile 3	Profile 4	Profile 5
Profile 1	0.47	0.49	-0.24	0.05
Profile 2	-	0.48	0.24	0.24
Profile 3	-	-	0.25	0.41
Profile 4	-	-	-	**0.63**

Figure 10. Similar volume variations between profiles 1, 2, and 3 and between profiles 4 and 5 at Brava beach, representing the two compartiments of this beach, and correlation coeficients between these profiles. Values between the profiles cited above are significant with $p < 0.05$.

However while beach rotation was well defined in 1995 to beginning of 1996; it was not so clear in 1994 enforcing the need of a long term monitoring programs (see Figure 13). Unfortunately, there is none wave data in these years that could make possible an association with the beach behavior observed. The beach rotation observed 1995 to beginning of 1996 occurred in cycles of about 3 to 4 months (Figure 13).

The data acquired for this beach can be summarized in Figure 14. In the southern protected sector minimal sediment removal was observed, and in the northern sector out-of-phase variations of beach volume and beach width occurred between its extremities.

As a main result of these analyses, it was found that the different extremities and the different sectors of the headland bay beaches did not respond in the same way to higher energy wave events. There was no defined seasonality in beach volume and width fluctuations, rather each section of the beach has its own behavior.

Other examples of this behavior in the literature are presented in MASSELINK and PATTIARATCHI (2001). These authors attributed the morphological variations observed in the Perth beaches, Western Australia, to a seasonal variation in the littoral drift direction, which for the Perth area, is toward north in the summer and south in the winter. These authors verified that beaches located south of coastal structures or headlands have their width increased during the summer, while beaches located north of coastal structures/headlands experienced erosion in the same period, and the inverse is true for the winter period.

Comparison of the Magnitude of Short Term Beach Rotation Processes in Different Beach Types

Measured beach profile variations at the exposed section of each of the beaches monitored can be observed in Figure 15. Profile mobility was greatest on the reflective exposed beach of Taquaras/Taquarinhas, followed by Brava beach, an intermediate exposed beach, and smallest on the dissipative semi-exposed beach of Balneário Camboriú.

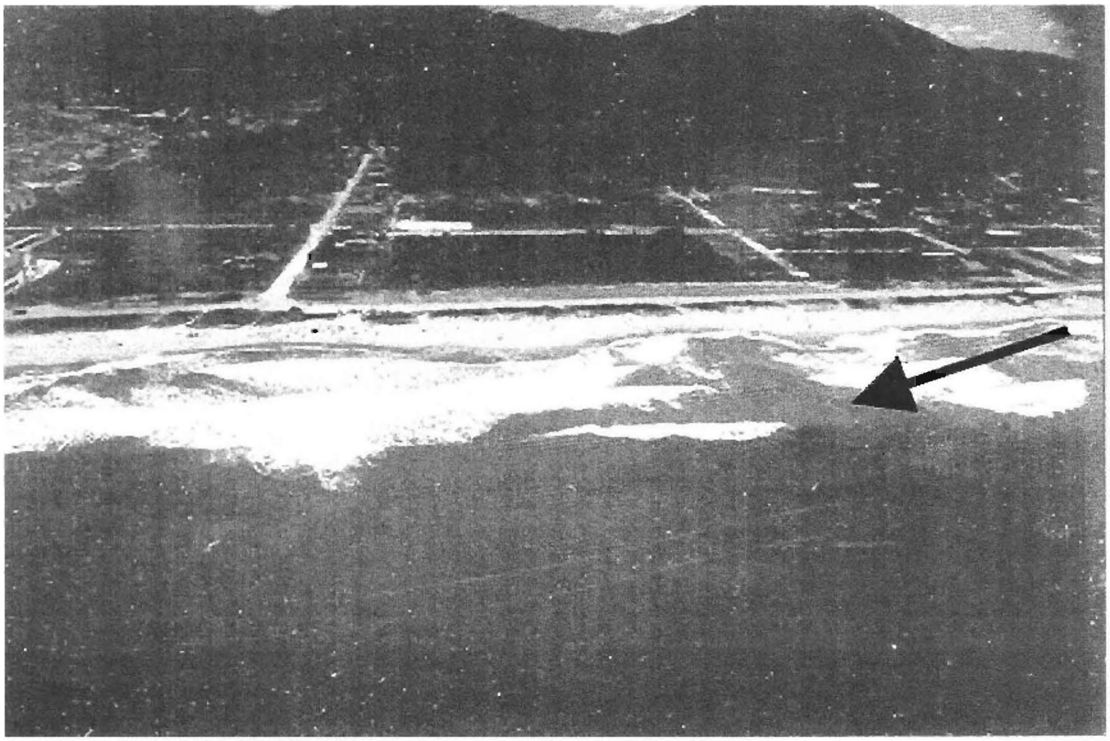


Figure 11. Rip current channel located between profiles 4 and 3 at Brava beach.

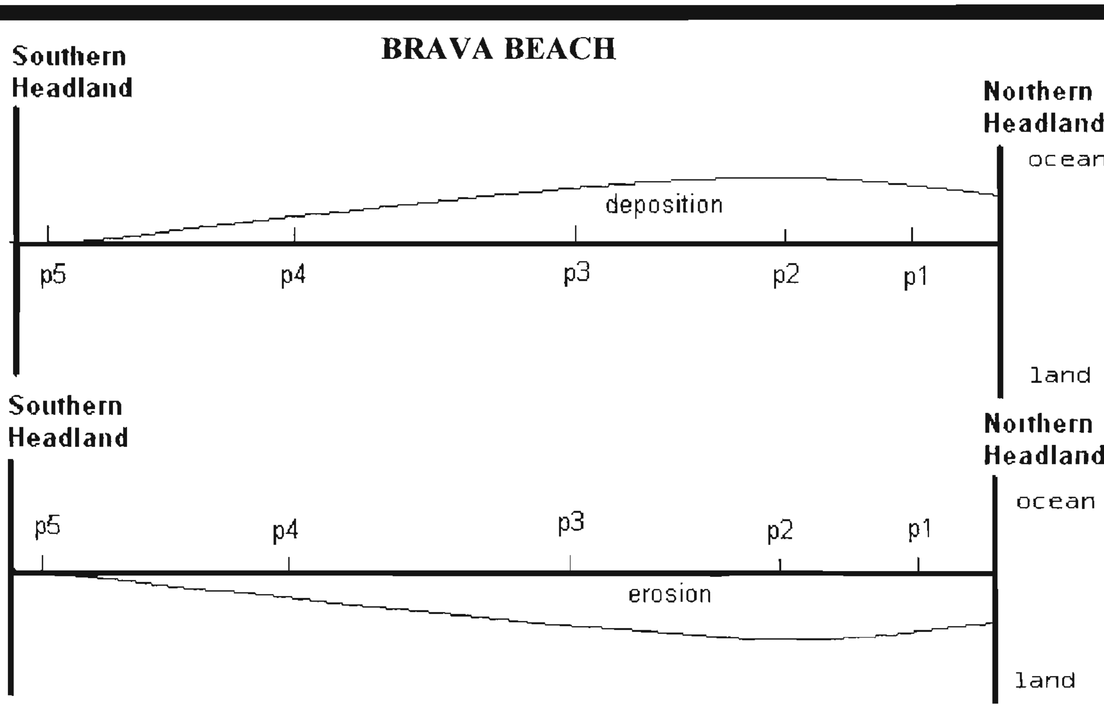
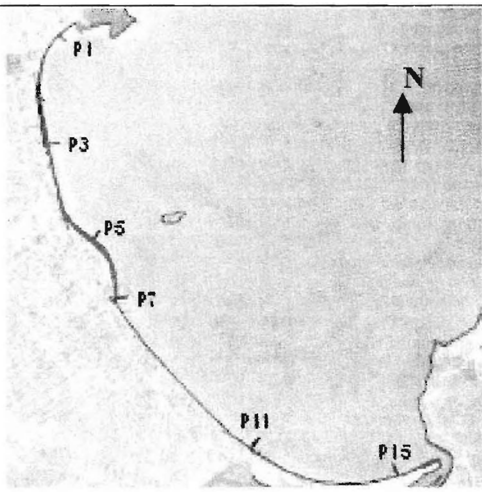


Figure 12. Morphologic model representing the general pattern of sediment removal at Brava beach, where depositional and erosive events occurs simultaneously along the beach, however with different magnitudes.



	Profile 3	Profile 5
Profile 1	**-0.62**	**-0.70**
Profile 3	-	**0.94**

	Profile 11	Profile 15
Profile 7	**0.74**	0.09
Profile 11	-	-0.06

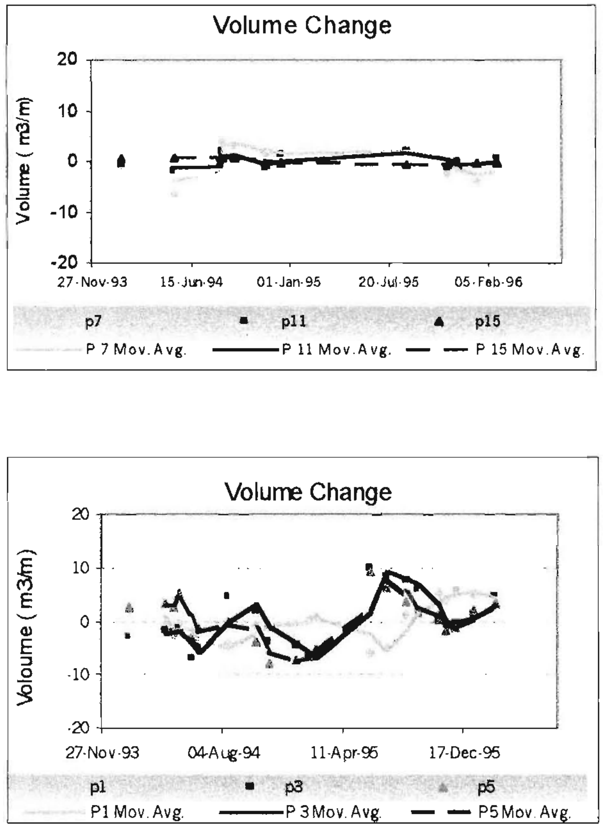


Figure 13. Beach volume variations at the sheltered (profiles 7, 11 and 15) and exposed (profiles 1, 3 and 5) sectors of Balneário Camboriu, correlations coefficients between these profiles where values in bold means $P<0.05$ and overview of the profile locations.

Like profile mobility, short-term beach rotation processes can differ significantly between dissipative, reflective and intermediate beaches, and as well between beaches with different degrees of curvature and exposure to the incident waves. In this work, short-term beach rotation processes in the subaerial beach were more easily detected in exposed reflective beach (*e.g.* Taquaras/Taquarinhas). In this case, with the absence of submerged bars, wave energy collapses directly on the beach slope, leading to greater profile mobility and removal of larger amounts of sediment in the subaerial beach. As a result, the occurrence of oblique waves on these kinds of beach systems causes sediment exchange between its ends. In other words, beach rotation, where the sediment eroded from one extremity of the beach is deposited in the opposite extremity.

In exposed intermediate beaches (*e.g.* Brava Beach), the occurrence of hydrodynamic features like strong rip currents, cellular circulation, and morphologic features such as mobile submersed bars, and the small size of the northern headland may have lead to different beach behavior. These phenomena blocked the occurrence of, or made undetectable by the present methods, short-term beach rotation. In this type of beach, long term monitoring of the subaerial and submerged part of the beach, and of the northern neighboring beach are necessary in order to better understand its temporal and spatial variations. SHORT *et al.* (2000) identify beach rotation in an intermediate type beach 3.6 km long in the Sydney area (Narraben beach), with cycles of rotation ranging from 3 to 8 years.

In exposed dissipative beaches (*e.g.* Balneário Camboriu northern sector), beach rotation is seen from out-of-phase variations of beach volume and beach width between opposite ends. This rotation had a three to four months cycle. However sediment removal was in smaller magnitude than at the reflective beach (Taquaras/Taquarinhas). Balneário Camboriu results also demonstrated that beach rotation processes could show interannual variability, which requires long term monitoring. The results did not show any clear trend of erosion or deposition. Rather the fluctuations observed were beach responses to high wave events, where sediment is not lost from the system, but redistributed to other sectors of the beach, in accordance with the direction of wave incidence. KLEIN and MIOT DA SILVA (*in preparation*), and MIOT DA SILVA *et al.* (2000), studying the pattern of sediment distribution at

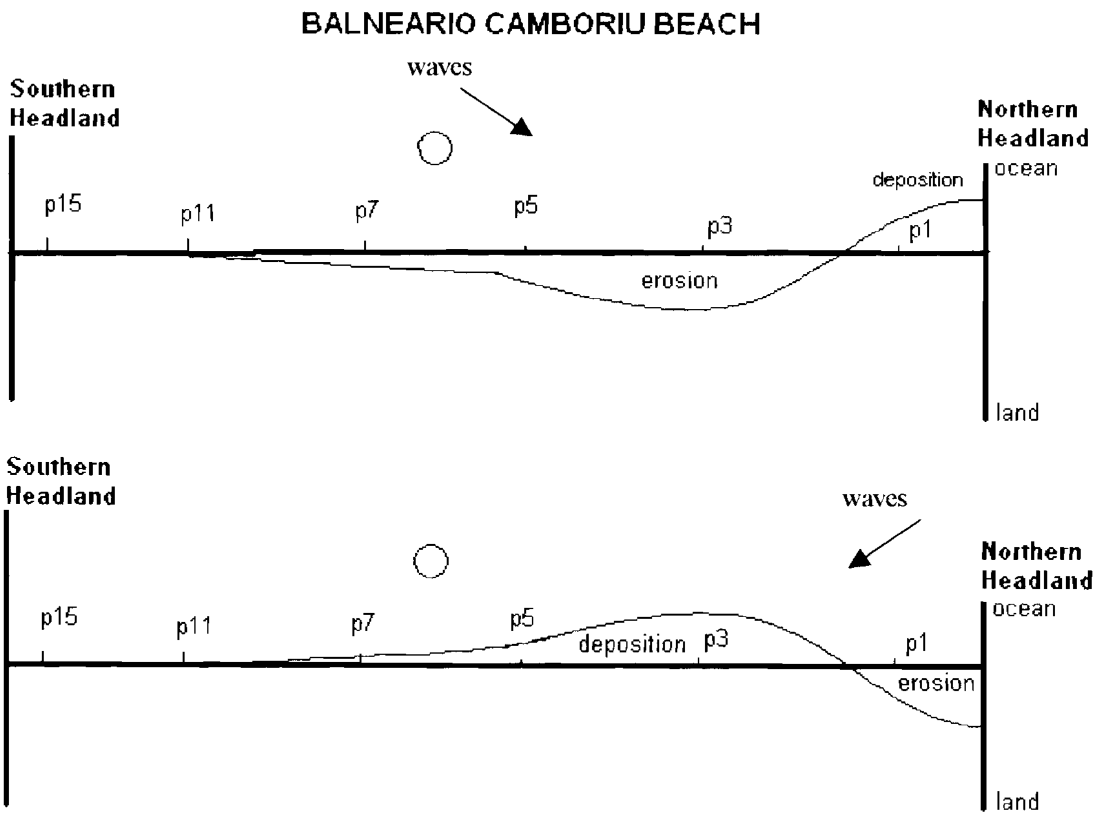


Figure 14. Morphologic model representing the general trend of sediment removal at Balneário Camboriu beach, where depositional and erosive events occurs out of phase in the northern sector, and the southern sheltered sector presents minimal sediment removal.

these beaches identified distinct sediment characteristics. They emphasize that no sediment exchange between these beaches is occurring.

Relation Between the Amplitude of Beach Rotation and the Headland Bay Beach Length

COWELL *et al.* (1996) proposed for the amplitude of beach rotation in Headland bay beaches, the following equation:

$$Ax = 0.0139L \quad (1)$$

Where Ax is the amplitude of rotation in meters, and L in the shoreline length. According to this relation, the beach of Taquaras/Taquarinhas would show an amplitude of rotation of 22 m, and the northern sector of Balneário Camboriu would experience an amplitude of rotation of 28 m. Comparison of amplitude values for beach rotation observed in field, versus those predicted by the equation above in available in Table 2.

A simple linear regression using the data of COWELL *et al.* (1996) and our data (see Figure 16) resulted in a equation similar to the one predicted by these authors, supporting the idea of a relation between the amplitude of beach rotation and the beach length. However, this relation is influenced by other parameters besides beach length, and at this state-of-the-art there is not enough data to definitely validate such a relation. Long term detailed studies of beach rotation processes in beach systems with distinct degrees of curvature and distinct morphodynamic characteristics are necessary in this manner. These would lead to an more realistic equation that could predict the amplitude of beach rotation in headland bay beaches. As demonstrated in this study, other factors such as beach type, beach curvature and its exposure to the incident waves have a direct influence on the profile mobility and magnitude of sediment removal. It is then expected that these factors will influence in the amplitude of beach rotation in different headland bay beach systems.

FINAL CONSIDERATIONS

The headland bay beaches studied in SC, Brazil exhibited different patterns of sediment removal as a function of the following parameters:

1) Degree of curvature of the beach: This can be measured by the indentation ratio or by the SL/CL ratio. In highly curved beaches, there is a well-developed shadow zone and a range of morphodynamic conditions, from a sheltered low energy beach adjacent to the downdrift headland to a high energy exposed beach on the straight end of the headland bay beach. The less curved beaches instead, tend to show a more uniform behavior, because

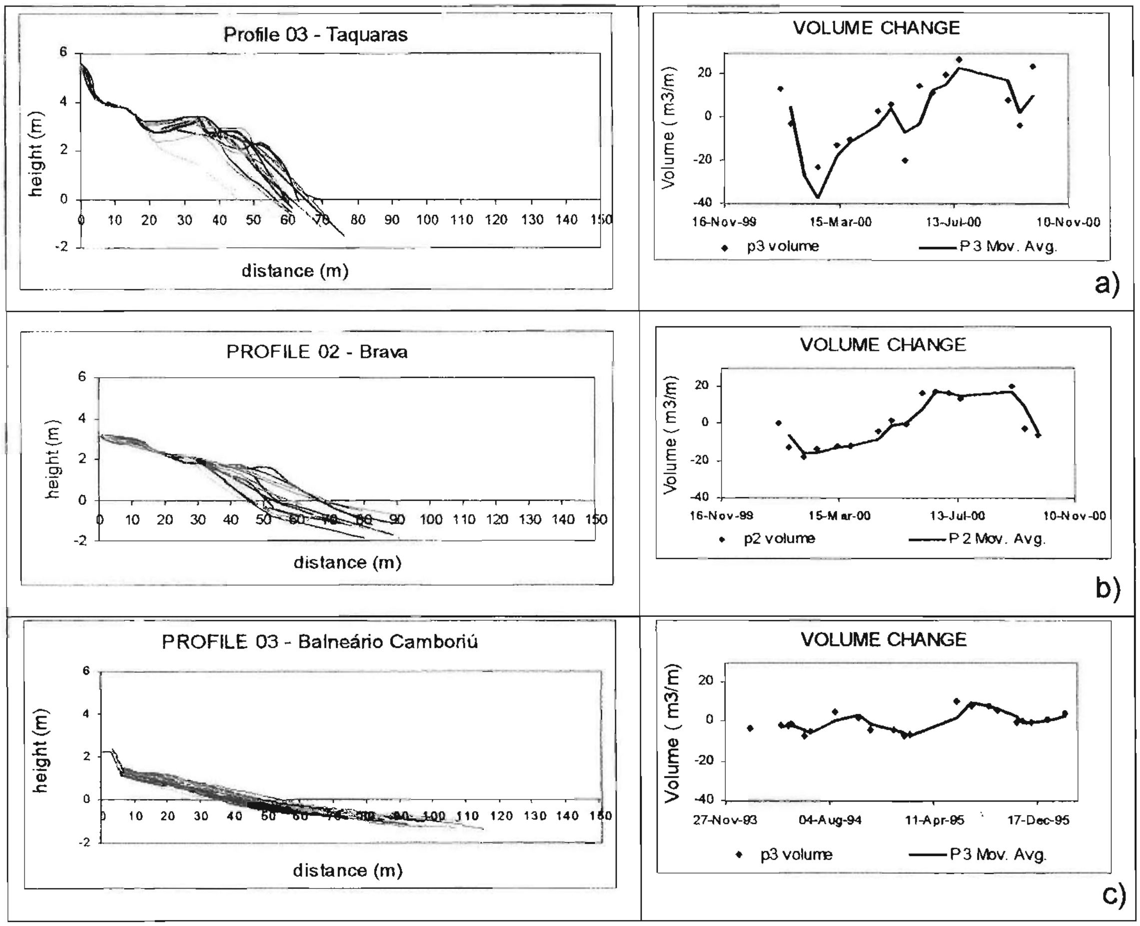


Figure 15. Beach profile envelopes with greater mobility, and volume variations for: a) the reflective beach of Taquaras/Taquarinhas, b) the intermediate beach of Brava beach, and c) the dissipative beach of Balneário Camboriu.

they are directly exposed to incident waves. The parameters a/Ro and SL/CL shows similar results, but the SL/CL parameter does not provide the point of greater indentation of the beach, which would be a hypothetical limit of the shadow zone.

2) Occurrence of submerged bars, rip currents, and cellular circulation: These factors play an important role in determining the morphodynamic behavior of beach systems being studied, as they will directly impact magnitudes of sediment exchanges between subaerial and submerged beach.
3) Shoreline length also influences the amplitude of beach rotation, and the time the whole beach takes to readjust to new wave conditions.
4) Beach Type: Short-term beach rotation processes were evident in the exposed reflective beach at Taquaras/Taquarinhas, and on the exposed dissipative northern sector of Balneário Camboriu. The process probably occurs on other headland bay beaches along our coastline, in response to waves from varying angles of incidence.

Table 2. *Beach shoreline length, amplitude of beach rotation predicted according to* Cowell et al. *(1996) and the amplitude of beach rotation observed in field during the period of monitoring.*

Beach	L(m)	Ax(m) (predicted)	Ax(m) (observed)
Balneário Camboriú (north sector)	2050	28	21
Taquaras/Taquarinhas	1582	22	22

Previous studies of beach rotation phenomena as developed by Short *et al.* (2000), detected a pivotal point with minimal variation, about which the beach rotates. In this study we did not detect a pivotal point, but rather a transitional zone.

Cycles of erosion and deposition in different sectors of the beach were detected during the same study period, suggesting complex behavior of headland bay beaches. In order to analyze temporal cycles of sediment mobility in headland bay beaches, it is necessary to monitor several profiles along the beach shoreline. If only one profile on the headland bay beach is monitored, observed beach behavior will not be representative of the whole headland bay beach. As demonstrated in this study, when one sector of the headland bay beach is erod-

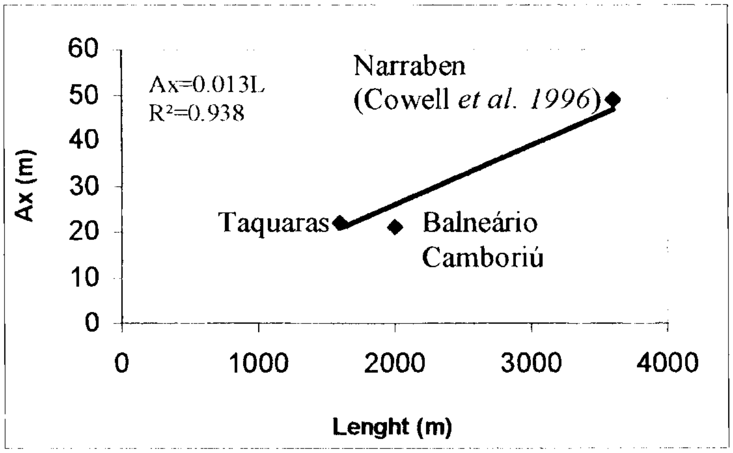


Figure 16. Simple linear regression with the values of amplitude of beach rotation observed versus the beach shoreline length, values from the present study and from COWELL *et al.* (1996).

ing, another sector might be accreting, stable, or eroding at different rates. In this way, headland bay beaches require spatio-temporal analysis, in order to properly understand its behavioral trends. Headlands interrupt littoral drift and block approaching incident waves, therefore influencing on the morphodynamic behavior of the beach.

The occurrence of sediment exchanges between opposite ends of headland bay beaches has many implications for beach management. Coastal engineers and planners should carefully analyze the implementation of hard structures such as groins, on the shore of headland bay beaches. These structures block the free sediment exchange between opposite extremities of the beach, and do not permit an important mechanism of self regulation to develop in these beach systems. Another aspect that should be considered by coastal planners is beach mobility, together with the delimitation of the rotation zone. On the zone where maximum amplitude of beach rotation occurs, the beach is more susceptible to erosion and to seasonal and long-term variations in width than in sheltered zones, and the urbanization of these zones should be carefully planned in order to avoid damages and risks.

Investigations of headland bay beach response to wave incidence should not be limited to cross-shore analysis, which typically shows sediment exchange between submerged bars and the subaerial beach, as a function of fluctuations in wave energy. The mechanism needs to be analyzed both cross-shore and alongshore, as a function of fluctuations in wave energy and direction, especially when oblique waves and longshore drift is interrupted by headlands.

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