Journal of Coastal Research	SI 39	542 - 546	ICS 2004 (Proceedings)	Brazil	ISSN 0749-0208

Small Scale Beach Rotation Process on a Reflective Beach

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ABSTRACT

MARTINS, C. C. and MAHIQUES, M. M., 2006. Small scale beach rotation process in a reflective beach. Journal of Coastal Research, SI 39 (Proceedings of the 8th International Coastal Symposium), 542 - 546. Itajaí, SC, Brazil, ISSN 0749-0208.

The beach rotation process has been described on different annual and decadal time scales (Short et al., 1995; Klein et al., 2002). In all cases there is a clear relationship between beach rotation and changes in the wave regime, mainly wave direction, associated with a succession of antagonic meteorological conditions. It was possible to identify a very sort (daily) beach rotation process measured during a survey carried out on Sununga beach, southeastern Brazil, between May 14 and May 27, 2002. During the survey period it was possible to observe a succession of four distinct morphodynamic conditions identified mainly by the reorientation of the coastline. During the first rotation event there was erosion of the southwestern sector and, during the second, erosion in the southeastern sector. Application of the linear correlation analysis method indicated a significant negative correlation between the profiles located at the extreme ends of the beach near the headlands. It was concluded that the same meteorological agent, a cold front, was responsible for initiating both processes of reorientation of the coastline by virtue of distinct patterns of development and intensity giving rise to different wave regimes. It was, further, observed that, due to geomorphological characteristics of the beach, as well as the direction of waves, energy was the determining factor in the initiation of the beach rotation process.

ADDITIONAL INDEX WORDS: *Beach morphodynamics, Cold front, Semi-enclosed beach system.*

INTRODUCTION

Beach rotation is a natural phenomenon which occurs on beaches the extremities of which are limited by headlands and which corresponds to the periodical lateral movement of sand, its direction alternating as between the two extremities of the beach. In most cases it is due to the seasonal or periodic wave regime, in particular to the direction of the waves (SHORT *et al*., 2000; KLEIN *et al*., 2002). According to SHORT & MASSELINK (1999) the beach rotation process may occur within a varied range of time scales, leading to great variation and movement of the coastline, without necessarily meaning any gain or loss of sediment within the system.

ENVIRONMENTAL SETTING

The climatic dynamic of southern Brazil results mainly from the advance of the Migratory Polar Anticyclone (MPA), brought about by the displacement and weakening of the Tropical Atlantic Anticyclone (TAA), which predominates in the region during the better part of the year. During these events the winds alternate from the northeast and east to the southeast and southwest, preceded by cold fronts. It is to the incursion of the MPAs that the events of greatest energy of the southern and southeastern coasts of Brazil are to be attributed (MONTEIRO, 1969; SANT'ANNA NETO, 1990).

Systematic data on waves off the Brazilian coast are few, the only existing records being associated with the intervention by engineering projects of great impact in the coastal region.

Despite this situation, the main wave systems present a close relationship with the climatic rhythm as determined either by the prevalence of the TAA or the MPA which, generally speaking, give rise to waves from the northeast-east quarter or from the southeast and northeast quarter, respectively. As regards wave height, there is predominance of the range from 0.5 and 2.0 m, the lesser heights coming from the east and southeast while the values above 2.0 m come from the south and southwest. It is to this dynamic behaviour, arising from the advance of the MPA towards the tropical regions, together with the general lie of the coastline, that inversion of the coastal currents is due. These present a shift to the southwest under the influence of the tropical system and a shift to the northeast on the advance of the polar system (PONÇANO *et al*., 1999).

The main morphological characteristic of this sector of the Brazilian coast is the presence of the crystalline massif of the coastal range (Serra do Mar), the greater or lesser approach of which to the coastline confers peculiar physiographical characteristics to de coastal region. The closest approach to the coastline occurs in the north portion of the littoral of state of São Paulo and results in a highly broken coast with numerous bays typical of the sector as a whole.

It is in this geomorphological context that the Sununga beach (from 23º29'30” S to 23º32'30” S and from 45º06'30” W to 45º10'30” W) is located. The beach, 50 meters wide and 250 meters long, lies in a general northwest-southeast direction, which means that it faces south-southwest, the direction from which the fronts advance on the region. Its location on the Fortaleza bay means that it is semi-enclosed as regards the direct incidence on it of the series of waves which thus undergo the effects of diffraction and refraction (Figure 1A). The Sununga beach presents a well developed berm crest, limiting its beach face on the upper side, and cusps of 30 m amplitude, extending along the whole arc of the beach. There is no river, which means that all its morphodynamic behaviour is submitted exclusively to the dynamics of marine origin. According to the criteria of morphodynamic classification established by WRIGHT *et al.* (1979), it may be classified as a beach of reflective type, with no surf zone. The waves break near the beach face with a predominance of waves of the plumging type, with strong control by the runup and backwash on the beach face dynamic to the detriment of the setup. The average diameter of the sediment corresponds to that of medium to coarse quartz, 1.8 to 0.6, from moderately to poorly sorted (0.55 to 1.05).

METHODS

The topographical survey was undertaken daily using GPS Trimble 4700/4800 equipment, during the period from 14 to 27

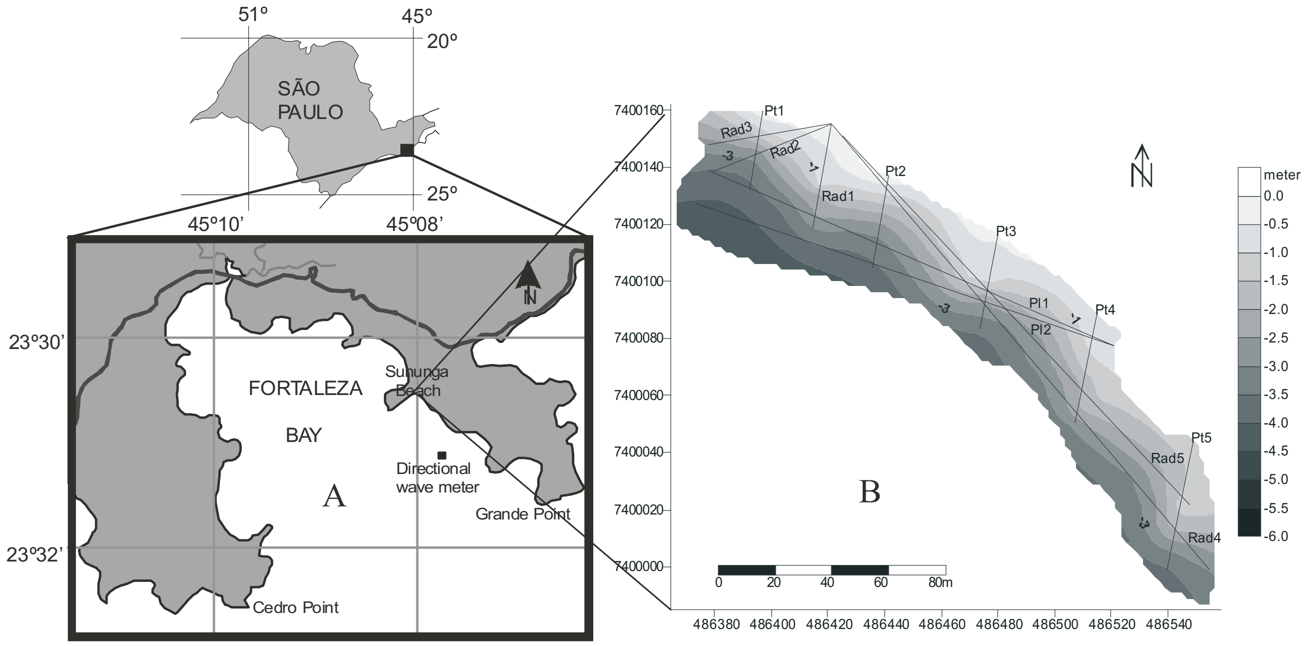

Figure 1. **A.** Localization of the study area and position of the directional wave meter in relation to Sununga beach. **B**. Detail of the Sununga beach showing the positioning of the topographical profiles: transverse (PT), radial (PR) and longitudinal (LP).

May, 2002. The acquisition of the topographical data was undertaken by the real time kinematic (RTK) mode, accurate to the nearest centimeter, related to the WGS-84 global *datum*, so that all the altitudes are geometric and related to the ellipsoid. Profiles transversal, radial and longitudinal to the coastline were surveyed as well as random walks at the end of each daily survey (Figure 1B). The calculations of volume for the profiles and for the surfaces were performed by the respective BMAP and SURFER programmes, taking the level -3 m as the lower limit for the calculations. After this limit was established, the 17 and 23 May, with reference to the PT1 and PT5 profiles, were not taken into consideration in the analysis; the other profiles which did not reach the level of reference but which on being prolonged did not present a variation in volume above 6% that initially determined, were maintained.

A Valeport 730D directional wave meter was moored near the mouth of Fortaleza bay, at the beginning of the study at a depth of 10 m (Figure 1A), so as continuously to register data related to waves and tides. The equipment was calibrated in subjected to various mechanisms of deposition, while on 23 May it was clearly being eroded, very much like the dynamic behavior presented by PT5 (Figure 2A and B and Table 1).

The wave regime acting on the beach sector (Figures 3 A to E), presented considerable modification over the period of the study. The interval between 14 to 16 May was characterized by an average significant wave height of 0.5 m, significant average periods of the 14 s, with peaks of up to 19 s, average direction peak of N147º, associated with energy levels below 200 $N.m^2.m^3$.

The wave regime change between 17 and 19 May, the average significant height becoming 1.0 m accompanied by an increase in average energy, 964.0 $N.m^2$.m3. The average values for direction (Figure 3C) show an increase in the southerly component, to be observed in the increase in the frequency of the peak values in that direction (Figure 3D), though the average of the peaks remains unaltered, N145º. On 18 May the such way that the wave data could be obtained at 3-hour intervals. Wave data made available by the Directory of Hydrography and Navigation (DHN) and the forecasts produced by the National Institute of Space Research (INPE) were also used. Data on the tides were registered by the same equipment at 30-minute intervals, the data on forecasts of tides were produced by MapLab Oceanographic Institute of the Universite of São Paulo.

The data for the analysis of meteorological change were obtained from the automatic meteorological station of the northern base of the Oceanographic Institute, 5 kilometers from Sununga beach, which registers wind speed and direction, atmospheric pressure and temperature at 30-minute intervals. Together with all the above data, those made available by the DHN in the shape of synoptic charts and daily summaries of meteorological change, as well as those by INPE, as daily maps of the wind forecasts, were also adopted.

RESULTS AND DISCUSSION

The daily variation of volume for the profiles (Figure 2) indicated the occurrence of two changes in the lie of the coastline, thus allowing the period to be subdivided into four episodes. The first occurred between 14 and 17 May, when the profiles presented low sedimentary mobility. The second began on 18 May, when the first beach rotation occurred. On this occasion there was erosion of the northwest portion of the beach prism and deposition to the southeast; a movement which was observed by the behaviour of the PT1 and PT5 profiles, positioned at the extremes of the beach near the headland. In the period between 18 and 21 May the profiles once again presented low sedimentary mobility, followed by a new reorientation of the coastline on 23 May. On this occasion, there occurred the inversion of the mechanism described initially, this time with erosion in the southeast and deposition to the northwest, the rotation process being very clear also near the PT4 profile. The data concerning the variation in surface volume show that during the event on 18 May the beach was greatest values for height and energy were registered with respective values of 1.79 m e 2000 $N.m^2.m^3$.

After a short interval of diminished energy which occurred on 20 and 21 May, when the average significant height was of 0.8 m, energy was of 400.0 $N.m^2.m^3$ and the average of the direction peaks continued to be N147º, there occurred, on 22 and 23 May, a renewed intensification of the hydrodynamic regime. On this occasion, the average wave height was of 1.6 m attaining a maximum of 2.6 m, while the average energy for the period was of 1724.0 $N.m^2.m^3$, with values of up to 4000.0 $N.m^2.m^3$. There was an increase in the wave period to 11 s. The daily average of directions peaks remained south-southeast, N150º (Figure 3D).

In the period from 24 to 27 May, this situation was attenuated

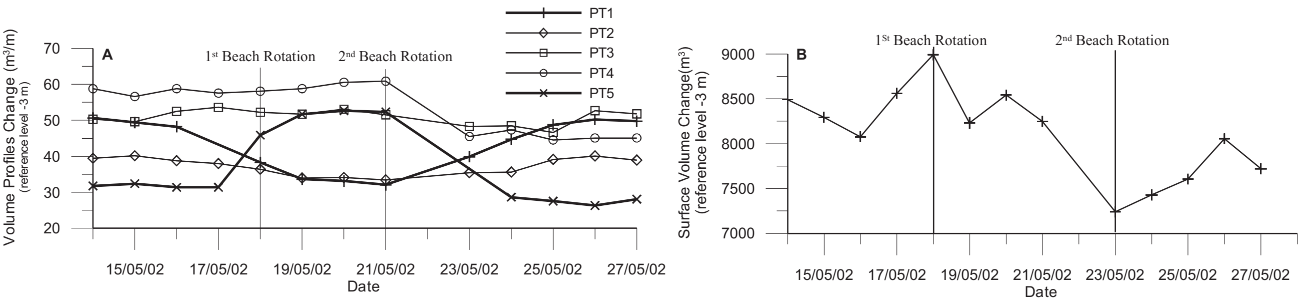

Figure 2. (A) Inverse variation of the daily volume as between the PT1 and PT5 profiles, with behaviour similar to the PT2 and PT4 profiles, especially in the second beach rotation process. (B) Variation of the surface volume similar to the PT5 profile.

with average values for the peaks of height, direction, period and energy of 0.9 m, 10.7 s, N144º and 604.0 $N.m^2.m^3$, respectively.

The variations observed in the wave regime, may be correlated with the passage of two front systems close to the coast of state of São Paulo. The first cold front occurred on 16 May, associated with winds from southeast and northeast of velocity varying from 4.0 to 6.0 m/s and waves with a significant height of 1.5 m and period of between 10.0 and 12.0 s. The second front began on 21 May under the influence of an extratropical cyclone with advanced over the southwest Atlantic Ocean. Under these circumstances, the wind pattern of winds from the east-northeast, became northwest-southwest, attaining on 21 May the maximum velocity of 14 m/s to 10.0 m/s (DHN, May/02; Atlasul-INPE, May/02).

Figure 3. (A to E) Wave data parameters. (F) Tidal observed and forecast range (the squares show storm surge events).

The waves, which had been coming from the east-northeast quarter, now came from the south with a height forecast of between 3.0 and 4.0 and period of between 8.0 and 10.0 s, from 22 to 24 May, 2002. This meteorological event took place during a neap-tide cycle, which must have contributed to the storm surge event's not having been more marked and presenting values close to 0.5 m (Figure 3F).

The climatic parameters obtained from Ubatuba meteorological station give the intensity with which the two front systems and de MPAs developed over the region, thus permitting their differentiation. There was an increase in wind strength between 14 and 16 May from 0.6 to 1.0 m/s. The wind veering to the east-southeast quarter (N140º), accompanied by a fall in atmospheric pressure of from 1016 to 1010 hPa and a 2ºC rise in temperature, from 24 to 26 ºC. After 16 May the velocity of the wind diminished to 0.2 m/s, blowing from the south-southwest (N200º), atmospheric pressure underwent a slight rise to 1014 hPa and the temperature a slight decline to 24 ºC. This situation continued relatively stable until 21 May, when the meteorological conditions changed completely, with wind velocity of 1.6 m/s from the southwest-west/northwest (N290º), an increase in pressure which reached a peak on 23 May (1022 hPa) and a considerable fall in temperature of from 25ºC to 16ºC. After that episode the conditions tended become gradually attenuated until the end of the study period on 27 May.

The application of the linear correlation analysis as between all the profiles and the wave parameters showed that there was a negative correlation between the PT1 and PT5 and also between the PT2 and PT5 profiles and a positive correlation between the PT1 and PT2 and between the PT4 and PT5 profiles, while the PT3 profile presented no significant correlation with any of the other profiles. The wave data presented low correlation both with regard to the variations of the sedimentary volumes as also between them, there being significant correlation only between the period and PT5and between the wave height and energy (Table 2).

The rotation pattern identified on the Sununga beach may be attributed to morphological modifications which have occurred within a short time scale in response to the change in the regime of the incidence of the waves by virtue of incursion of extratropical cyclones over the region. As is described by SHORT *et. al.* (2000) and KLEIN *et al.* (2002) the correlation of the variation in volume between the PT1 and PT5 profiles, for May 2002, demonstrates clearly the mechanism of the rotation of beach by the reorientation of the coastline (Table1).

KLEIN *et al.* (2002) in their analysis of the Taquaras/Taquarinhas beach on the coast of Santa Catarina (southern Brazil), found a significant correlation between the periods of erosion at one of the extremes and depositional the other, while the central portion did not present any significant correlation with either of the extremes. The pattern of rotation of the Sununga beach is fully compatible with the model described above, with a well defined alternation between de PT1 and PT5 profiles and an absence of any correlation with the PT3 profile located in the central section of the beach.

The fact that the rotation processes were set in motion by the same atmospheric mechanism, the advance of the MPA over the region, may be explained by the peculiar change which they ....

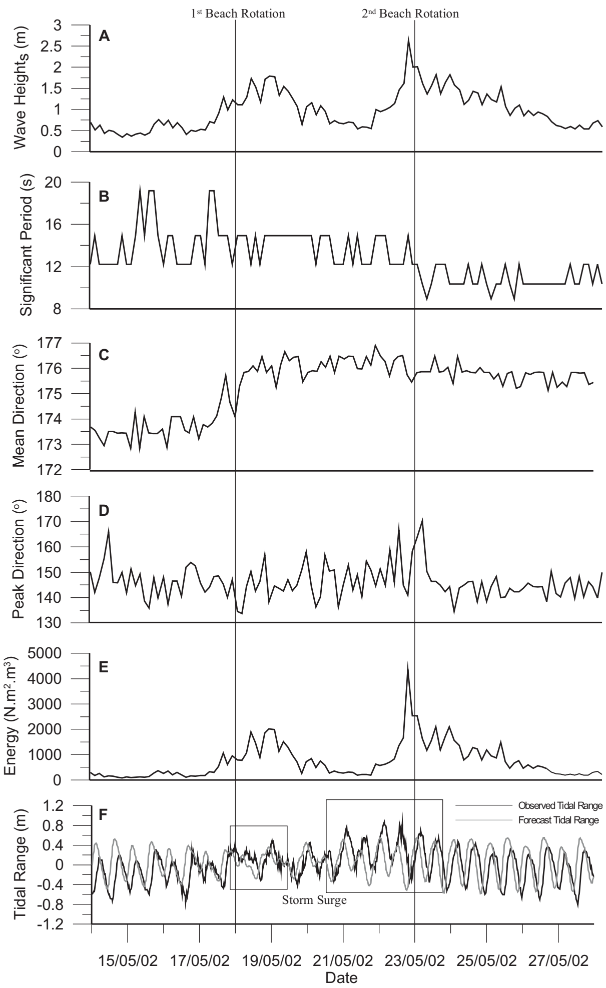

Figure 3. (A to E) Wave data parameters. (F) Tidal observed and forecast range (the squares show storm surge events).

Table 1.*Comparative Volume change and budget for all profiles and surfaces during the period.*

Time Interval	PT1	PT2	**PT3**	PT4	PT5	Volume Surface
14 to 18	-12.3	-3.0	**2.0**	-0.7	+14.1	+501
18 to 21	-6.2	-3.0	**-0.8**	+2.8	+6.5	-743
21 to 24	+12.7	+2.2	**-3.0**	-13.6	-23.7	-820
24 to 27	+5.0	+3.3	**3.3**	-2.2	-0.6	+291
Budget	-0.9	-0.5	**1.5**	-13.7	-3.7	-770

presented. The first MPA, responsible for the rotation observed on 18 May was associated with the rapid displacement of a MPA of low intensity (1020 hPa), close to the southeastern Brazilian coast, with limited fetch. Even though the wave had come from the south quarter, the process did not alter the prevailing southeasterly direction from which the waves had been reaching the beach. Despite there being no change in the direction of the incident waves, the process of erosion of the extreme southwest of the beach may be explained by the fact the beach is limited at its extremes by headlands. The headland which limits this sector of the beach produces a considerable reflexive effect on the waves which arise from the south-southeastern and which then move along parallel to the coastline, giving rise to flow currents in the same direction, i.e. towards the southeast. With the increase in the energy of waves from the south-southeast this process may have been intensified, carrying the erosion to the northwest sector (PT1), while the headland situated at the extreme southeast served as a barrier to the sediment transported by this flow leading to its deposition near the PT5 profile.

The following event, responsible for the second reorientation of the coastline, may be related to the effective change in atmospheric pressure and the fall in the temperature. The MPA was further from the coast, and the dynamic process continued for three days, thus permitting the formation of larger waves from the southwest. Waves from this direction strike the southeastern headland first thus leading to the inversion of the currents to the southwest, prevailing against the reflection mechanisms of the headland at the opposite extremity which even under these conditions continue to have their effect.

When the variation in the volume of sediment in relation to the surface area is considered a close correlation between its behaviour and the prevailing dynamic, independent of the beach rotation, is noted. During the first event when waves from the south-southeast quarter, with smaller amplitude and energy predominated, even though the PT1 profile may have undergone a process of erosion, the balance of beach prism shows a clear depositional tendency, the same thing happening when the beach was undergoing a regime of waves of greater energy, when it showed that the whole system was undergoing clearly erosive processes.

The low correlation between the variation in the volume of the profile and the wave parameters, mainly as regards direction and energy, is to be explained by the increase in wave energy's not being accompanied by the alteration in the direction of the incident waves during the first event as it was in the following event.

CONCLUSIONS

The data of the wave regime and the climatic dynamic used in the analysis of the process of the beach rotation in a short period showed that the same climatic agent may set in motion inverse dynamics by virtue of their inherent characteristics in association with the morphology of the beach. The fact that Sununga beach is situated within a semi-enclosed bay exercises great influence on the direction of the wave which reach the beach and which thus present considerable influence of the southeasterly component, the direction towards which the mouth of the bay faces.

This behaviour became evident in the attenuation of the wave systems generated by anticyclones of low intensity which entered the area from the south-southeast, exercising their influence on the southwesterly sector, responsible for the erosion of this sector of the beach, and the deposits made in the southeast. This mechanism is possibly intensified by the reflection of the waves by headland and which in consequence sweep the lower beach face; often reaching the southeastern sector at the other extreme.

Table 2. *Correlation coefficients between all profiles and wave parameters (gray values p<0.05)*

Variable	PT2	PT3	PT4	PT5	Surf	Hs	T1/3	Dir º	Energy
PT1	0.95	-0.37	-0.60	-0.96	-0.42	-0.45	-0.45	-0.16	-0.43
PT2	-	-0.25	-0.49	-0.86	-0.20	-0.50	-0.29	-0.19	-0.47
PT3	-	-	-0.45	-0.45	0.57	-0.17	0.30	0.23	-0.15
PT4	-	-	-	0.75	0.75	-0.11	0.83	0.60	-0.56
PT5	-	-	-	-	0.61	0.30	0.62	0.29	0.31
Surf. Vol.	-	-	-	-	-	0.19	0.69	0.27	0.88
Hs	-	-	-	-	-	-	-0.75	-0.43	0.99
T 1/3	-	-	-	-	-	-	-	0.27	0.05
Dir º	-	-	-	-	-	-	-	-	-0.40
Energy	-	-	-	-	-	-	-	-	-

Even though the alternation in the direction of the waves be the determining factor for the occurrence of the rotation of the beach prism, the energy with which the waves reach the coast and the increase in the swash process which is associated with them, must explain the volume of sediment made available and the velocity with which the process take place. Further, on a pocket beach, as is the present study area, the wave reflection process, caused by the impact on the adjacent headland, may create an additional component responsible for the longitudinal transport, remobilizing sediments and acting as one more factor in setting the rotation process in motion.

In the corresponding variations in volume of the beach as a whole, a sedimentary dynamic corresponding to the morphodynamic processes of erosion or deposition prevalent at the moment is to be observed. In view of this fact, it is important to emphasis the overlapping of the longshore rotation dynamic on the processes onshore-offshore of the gain or loss of sediments by the beach prism, without leading to the suppression of the latter, but to its attenuation.

ACKNOWLEDGEMENTS

We wish to thank Fapesp for its financial support of the Projects 00/009364-5 and 00/10298-7 which have made this research project possible.

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