Beach response to high energy wave climate. A case study in the portuguese west coast

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BEACH RESPONSE TO HIGH ENERGY WAVE CLIMATE. A CASE STUDY IN THE PORTUGUESE WEST COAST

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ABSTRACT: Portugal's western coast is a wave-dominated rocky coast with a semidiurnal mesotidal regime. The wave climate is highly conditioned by the Atlantic Ocean's atmospheric circulation, which results in a seasonal change in wave patterns. Storms are frequent during winter and can reach 10-m wave heights with a 5-year recurrence period. Four profile monitoring campaigns were carried out in December 2005, January and May 2006 using a dGPS and a total station to evaluate the response of three different beach systems to high wave climate events, comparing pre-storm wave, morphology and sediment characteristics with the modifications induced in the system after the storm event. A series of 64 beach profiles is analysed in terms of sediment textural properties, volume, slope, surf similarity index and dimensionless fall velocity parameters' variability. Each beach system's modal and limit morphological behaviours are established according to Wright and Short's morphodynamic model.
KEY WORDS: Beach profile, storm event, system morphodynamic range.

RESUMEN: La costa oeste de Portugal es una costa rocosa dominada por olas y con un régimen mesomareal semidiurno. El clima marítimo está altamente condicionado por la circulación atmosférica del océano Atlántico y presenta una variabilidad estacional en el régimen de oleaje. Las tormentas son frecuentes durante el invierno y pueden alanzar alturas de ola de 10 m con una recurrencia de 5 años. Se han hecho cuatro campañas de control en tres playas, mediante el uso de GPS diferencial y estación total con el objetivo de evaluar su respuesta a sendos episodios de alta energía. Se comparan los cambios en la morfología y en la textura sedimentaria antes y después de cada temporal. Para ello se realizaron 64 perfiles de playa y se han analizado las variaciones en la textura del sedimento, el volumen, la pendiente, el índice de surf similarity y el parámetro adimensional de caída del sedimento. Con todo ello ha podido establecerse el comportamiento morfológico modal y extremo de dichas playas según el modelo de Wright y Short.
PALABRAS CLAVE: Perfiles de playa, temporales, variaciones del sistema morfodinámico.

1. Introduction

Beach environments are the result of several forcing factors which act permanently changing profile morphology and beach shape. Waves, tides and sediment properties are amongst the main factors that explain those changes. Whilst beach mophodynamics can be defined through seasonal cycles, the dramatic changes occur frequently during high energy events. These changes are very significant for local communities because of the important damage costs, namely in beach facilities.

The magnitude of morphological changes in wave dominated exposed beach systems are closely related to the capacity of the outer bar sub-system to absorb and dissipate wave energy before it reaches beach face. This capacity can be exceeded if the frequency of storm occurrence overcomes the time needed for the system recovery.

The aim of this work is to evaluate the response of Sta. Rita, Azul and Foz do Lizandro beaches to high wave climate events through morphosedimentary variability analysis and to establish modal and limit morphological behaviours of this systems.

2. Study site framework

The western coast of Portugal, between Peniche and Cascais, is a wave dominated rocky coast with a semi-diurnal mesotidal regime. Tidal wave propagates northwards and reaches its maximum amplitude at *circa* 4m. The Cascais tidal gauge data shows that in 1998 the extreme water levels reached 4,030m and the mean spring tide amplitude was 3,075m (Fig. 1). Wave climate is highly conditioned by the Atlantic Ocean atmospheric circulation resulting in a seasonal change of the wave patterns. Northwest dominant wave patterns along the coast occur in 265 days of the year (Costa, 1994) and the mean offshore significant wave height is 2,5m in winter and 1,0m in summer (Oliveira Pires, 1989). Carvalho (2004), used the wave numeric model MAR3G (Oliveira Pires & Carvalho, 1996) and applied it to a 1998/2001 ocean-atmospheric climate data series. He estimated 8 storms/year in the west-central coast of Portugal with wave heights above 4m, mostly between October and April. The main directions of high wave climate found by Carvalho (2004) were W (67,3%) and NW (27,4%). Considering storms with wave heights over 6m, the W direction was found in 89,3% of the occurrences. However, storm waves from SW are less frequent but they usually have a higher magnitude and can reach heights of 10 – 12m (Pereira, 1999; Taborda *et al*, 1992). Extreme wave heights above 10m can be reached with a recurrence period of 5 years (Carvalho, 1992).

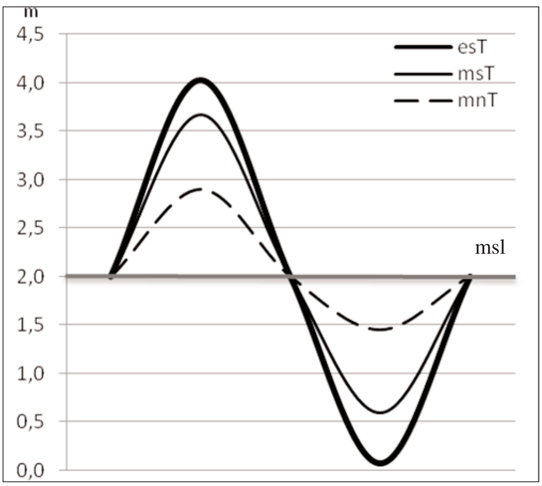
Coastal drift is usually directed to the south along the West coast, although Pereira (1991) refers that in cases of strong SW wave climate the southwards coastal drift may invert locally its direction. Several field and numerical based estimates of longshore transport rate in the western coast of Portugal have been made a range between 1,0 x10^6 and 2,3x10^6 m^3/year (Oliveira *et al*, 1982; Bettencourt, P. & Ângelo, C., 1992; Taborda, 1993; Vidinha *et al*, 1997; Larangeiro, 2002). Most of those estimates are related to the central-northern sector of the Portuguese coast, between Nazaré and Oporto (Fig. 2).

The coastline between Peniche and Cascais is a limestone cliff dominant with a lack of sediment supply from local sources and from longshore drift sediment dynamics. Southwards longshore drift is interrupted by the submerged Nazaré canyon and by the Peniche headland (Fig. 2).

The Peniche – Cascais continental shelf, between 0m and -50m, is mainly composed of rock outcrops and coarse sediment deposits with high levels of biogenic remains. Fine sands and muds are found in very confined and sheltered areas in the Ericeira sea. Therefore, local sediment sources are scarce due to (i) continental shelf morphology and deposits, (ii) little contribution from the small river basins (Pereira, 1987) and (iii) the carbonate nature of the rocks that constitute the cliff systems (Neves, 2004).

The exposed beach systems are narrow, embayed or associated with small infilled valleys as a result of the Holocene sea level rise, and their importance in the overall costal systems of the study area decrease southwards.

Three beach-dune systems, different in size and shape, but similar in the exposure to W stormy wave climate, were chosen to illustrate the beach-systems' morpho-dynamics. They are also included in a monthly monitoring programme being held at the «Centro de Estudos Geográficos» for over two years.



	High (m)	**Low** (m)
esT	4,030	0,070
msT	3,672	0,597
mnT	2,902	1,447

Figure 1. Tidal range in the Cascais tide gauge (38º41'39,171''N; 09º25'05,229''W – heights above chart datum), 01-01-1998 / 31-12-1998. *esT* – extreme spring tide; *msT* – mean spring tide; *mnT* – mean neap tide; *msl* – mean sea level.

The Sta. Rita beach is a mixed beach-dune/beach-cliff system (Fig. 2-a). The beach-dune component of the system is 550m long and 150-200m wide, while the beach-cliff part is 1000m long and 100m wide. Foz do Lizandro beach (Fig. 2-c) is a beach-dune system 600m in length and 200m in width and has a very small dune field, highly damaged by human trampling. Azul beach (Fig. 2-b) is the largest beach-dune system, 1900m long and 975m wide and is the only one of the three affected by overwashes.

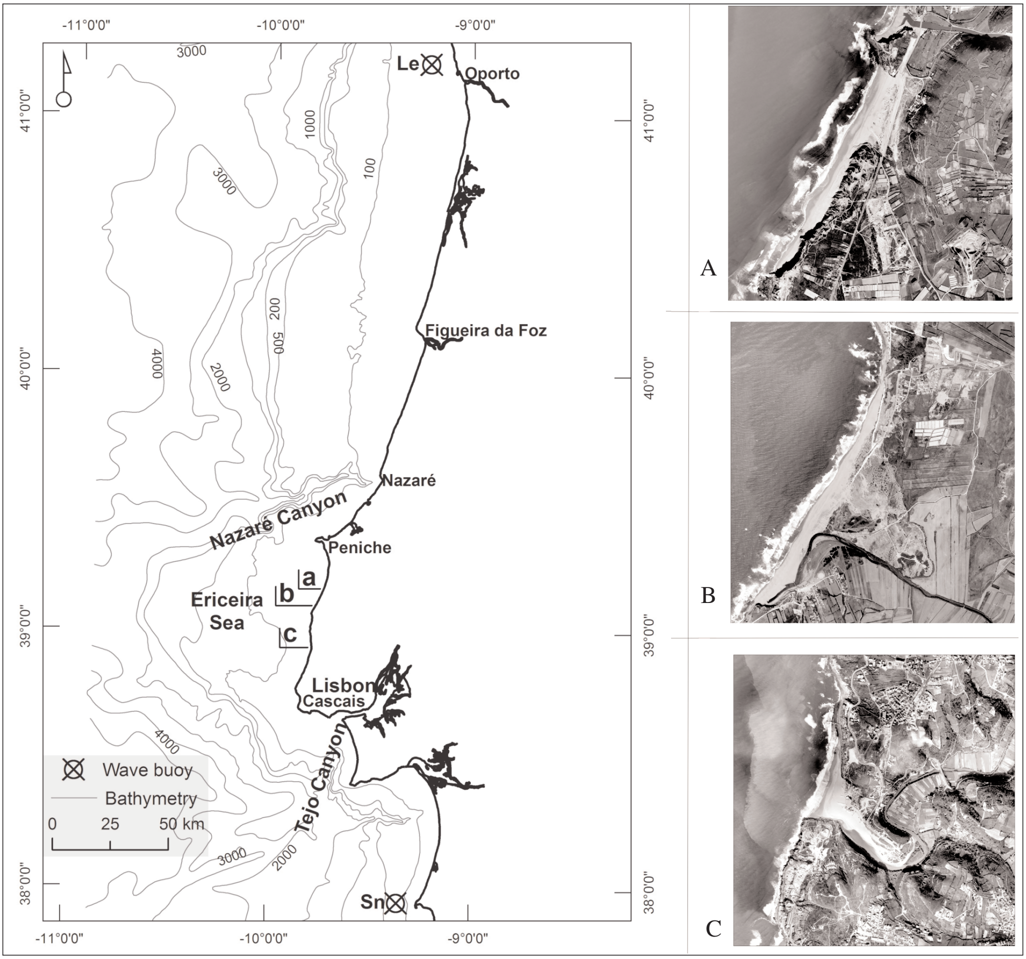


Figure 2. The study area. a – Sta. Rita beach; b – Azul beach; c – Foz do Lizandro beach; Le – Leixões offshore wave buoy; Sn – Sines offshore wave buoy.

3. Methodology

Four monitoring campaigns were carried out in pre-storm and right after storm conditions (December of 2005, January and May of 2006) on the tree beach systems, resulting in 64 survey profiles (table 1). The storm morphological and sediment parameters measured 3 or 4 days after storm peaks in early January and late May are considered representative of the local hydrodynamic influence in sediment transport during the high wave climate event.

Total station and dGPS units were used to measure emerged beach volumetric and morphometric changes. The differences between the two techniques prove to be negligible in this dynamic context (Trindade *et al*, 2007). As part of a beach monitoring programme, beach profile number and spacing were initially defined to record data from the beach face and berm morphodynamics.

Beach profiles are anchored in fixed points away from the hydrodynamic area, ensuring overlapping between campaigns (Trindade *et al*, 2006).

Beach morphodynamics was accessed by volume variability along each profile with an assumed width of 0,1m. The volume of each profile was calculated above mean sea level (msl) and below the point of no relative hydrodynamic sand movement, usually associated with the inland backshore or backshore/foredune limit (Ferreira, 1998; Baptista, 2006). The inland beach profile limits is not easy to establish and often it corresponds to a boundary between marine and aeolian dynamics. This boundary point, that we can call a knick point, was accessed by the direct overlap of all the obtained beach profiles.

Several interpolation methods were tested with the field data of May campaign in order to calculate beach profile volume, namely inverse distance to a power of two, kriging, nearest neighbour and moving average. Test results expressed in Table 2 revealed that Kriging is the most accurate technique, with the lowest residual values both in height and volume calculations (ARH = 0,300m; ARV = -1,685m^3) and therefore the most suitable for this campaigns profile volumetry.

Table 1. Monitoring campaigns.

S^{ta}. Rita beach			Azul beach			Foz do Lizandro beach		
Date	**Profiles**	**Sediment Samples**	**Date**	**Profiles**	**Sediment Samples**	**Date**	**Profiles**	**Sediment Samples**
17.12.05 (Pre-storm)	5	4	16.12.05	6	4	15.12.05	5	4
04.01.06 (Storm)	5	3	02.01.06	6	3	03.01.06	5	4
14.05.06 (Pre-storm)	5	4	15.05.06	6	4	12.05.06	5	4
28.05.06 (Storm)	5	4	26.05.06	6	3	25.05.06	5	3

Table 2. Residual values of height and volume. ARH – Average residual height; ARV – Average residual volume.

	ARH height (m)	**ARV (m^3)**
Inverse distance	0,069	-2,716
Kriging	0,030	-1,685
Nearest neighbour	0,048	-3,308
Moving average	0,965	-74,352

Sedimentological analyses of beach sands were carried out with 44 samples (Table 1) taken from the berm, beach face, base of the beach face and low tide terrace (when existent) during each campaign, in order to evaluate grain size distribution and statistical parameters. Approximately 60g from each sample were washed, without calcium carbonate destruction, and dry sieved between -2,0ϕ (4,0mm) and 4,5ϕ (0,044mm), in 0,5ϕ intervals, and weighed with a 0,01g accuracy. The SEDMAC/-SEDPC worksheet (Henriques, 2004) was used to calculate the mean, standard deviation and skewness of each sample, according to the Method of Moments of Friedman and Sanders (1978).

Offshore wave significant (H_s) and maximum (H_{max}) height, expressed in meters above chart datum (*cd ≈ -2m msl*), period (*T*) and wave direction (H_{dir}) were provided by the Leixões buoy, one of the two offshore wave buoys available on the west coast of Portugal (Fig. 2).

Wave breaker type and morphodynamic classification was accessed with widely used parameters, namely the surf similarity parameter or Iribarren Number (ξ_b) for breaker wave conditions and the dimensionless fall velocity (Ω) (Masselink & Hegge, 1995; Benavente et al, 2002; Benedet, Finkl & Klein, 2004; Benedet, Finkl, Campbell & Klein, 2004; Goodfellow & Stephenson, 2005; Anfuso & Benavente, 2006).

The surf similarity parameter was calculated according to Battjes, 1974:

$$\xi_b = \frac{\tan\beta}{(H_b / L_0)^{1/2}} \qquad (1)$$

Where:

$\tan\beta$ is the beach slope calculated from the average slope of the beach profiles, between the berm crest and the seaward limit of the surveyed profile, in each campaign;

H_b is the breaker wave significant height, expressed in meters above *cd*, obtained from the Komar and Gaughan (1972) expression based on the Leixões offshore wave data:

$$H_b = 0{,}39 g^{0,2} (T * H_o^{2})^{0,4} \qquad (2)$$

Where:

H_0 is the offshore wave significant height, expressed in meters above cd;

0,39 is the empirical coefficient based on laboratory and field data from Munk (1949) and confirmed later as a good predictive coefficient by Weishar and Byrne (1978);

L_0 is the deep water wave-length which, based on linear wave theory, can be calculated as:

$$L_0 = \frac{gT^2}{2\pi} \qquad (3)$$

The Dimensionless fall velocity parameter (Ω) was calculated according to the Wright and Short (1984) formula:

$$\Omega = \frac{H_b}{w_s g T} \qquad (4)$$

Where:

w_s is the sediment fall velocity, expressed in m/s. Hallermeier (1981a,b) empirical formulas for w_s were used to obtain the fall velocity of the sediment samples:

$$W_s = \left[\frac{(\rho_s - \rho)\, g}{\rho} \right]^{0,7} D_{50}^{1.1}, \text{ for } 39<A<10^4 \qquad (5)$$

$$A = \frac{(\rho_s - \rho)\, g D_{50}^3}{\rho \upsilon^2} \qquad (6)$$

Where:

ρ_s is the sediment density (≈2,648 g/cm^3 for quartz grains and ≈2,8 for shell material),

ρ is the density of the seawater (≈1,026 g/cm^3 at 15ªC – 33 ppt), υ is the seawater kinematic viscosity (≈0,0119 cm2/s at 15ªC – 33 ppt), g is gravity acceleration (981cm/s) and D_{50} is the Passega (1957) sediment median size, in centimetres. The Hallermeier formulation for w_s (eq. 5) was tested on previously published settling velocity measurements of sands with a diameter range between 0,125mm and 1.0mm.

The quartz/shell content of the samples was used to calculate the final result for the weighted arithmetical mean of W_s, concerning the different values of ρ_s.

These types of dimensionless parameterizations are fully related to beach behavior and are useful tools to first access the range of beach morphodynamic states, but choosing the right parameters to calculate formulae is difficult due to the irregular nature of the beach system dynamics.

The range of values assumed for Ω in one system depend on the measured range of sediment size, which usually controls the intertidal slope, and on characteristics of incident waves which are the main driving factor of beach dynamics.

Incident wave can be described by the range of breaker types (ξ_b) that can occur within a beach system, which are controlled by beach slope and wave height and length (Komar, 1998; Masselink & Hughes, 2003). However, the beach is composed of several constant slope angles associated to the different dynamic subunits of the beach. Because the submerged profile is absent in this study, mean beach slope is calculated for the most dynamic areas of the beach profile, including berm crest, beach face and low tide terrace, when present.

4. Results

January and May campaigns were preceded by two high wave climate events recorded entirely or partially in the two existing wave buoys (Leixões and Sines). Despite the proximity to the study area, it was impossible to use data from the Sines buoy because of the several gaps registered in the January and late May records. This made it unable to correlate and interpolate the Sines data with the Leixões buoy to fulfil data loss.

The Leixões offshore wave data before the January 2006 monitoring campaigns was very similar to the May 2006 (Fig. 3). Mean H_s values was 3,89m in January and 3,67m in May. T registered a range of 16,3s in January and 14,6s in May, reaching T_{max} 21,10s and 18,80s at the maximum storm strength (Table 3). H_{dir} was predominantly from the NW quadrant with resultant vectors

Table 3. High wave climate event data from Leixões wave buoy.

	30-12-2005 – 16h to 01-01-2006 – 21h	**21-05-2006 – 06h to 23-05-2006 – 12h**
Time (h)	53	54
$\bar{H}_s$ (m – *cd*)	3,89	3,67
H_{max} (m – *cd*)	9,77	10,77
$\bar{T}$ (s)	8,54	8,38
T_{max} (s)	21,10	18,80

of 310º in January and 309º in May (Fig. 3) which usually means a strong southwards longshore drift in the western coast of Portugal. The registered H_{dir} is also perpendicular to the S^{ta}. Rita and Azul beach systems. The two high wave climate events lasted 53h (January) and 54h (May) and H_{max} reached 9,77m and 10,77m, respectively (Table 3).

The morphodynamics of a beach system can be expressed in terms of the mean sediment budget (SB_m in Table 4) which, in this study, is assumed to be the arithmetic mean of the differences between the volumes of all emerged beach profiles in each system and in two sequential campaigns. Mean volumes and the sediment budget variability (mean and maximum) between campaigns are expressed in Table 4.

Values of mean sediment budget variability between campaigns range from a maximum erosive sediment dynamics (-39,952 m/m^3) in Foz do Lizandro beach to a maximum accretionary behaviour in S^{ta}. Rita beach (34,981m/m^3), both registered in January data.

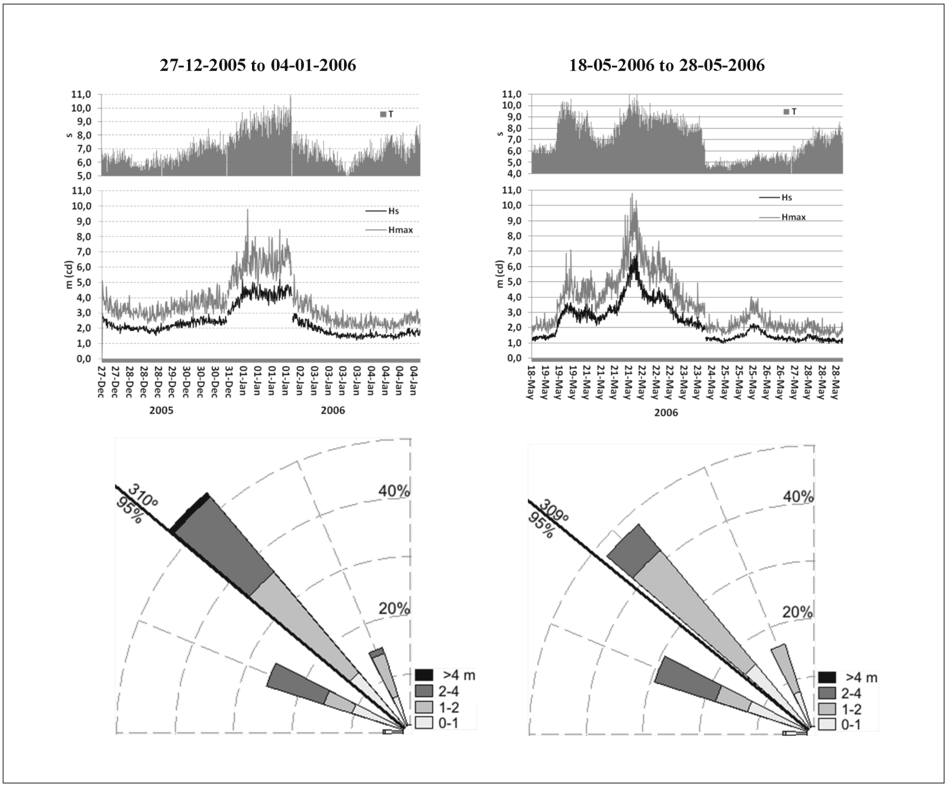


Figure 3. Wave parameters from Leixões wave buoy preceding monitoring campaigns.

Table 4. Slope, volume and mean sediment size in the three beach systems. Sm – slope (x 102 = %); Vm – mean volume (m/m^3); SBm – mean sediment budget (m/m^3); SBmax – maximum variability of sediment budget (m/m^3); TTsed – mean sediment size of the tidal terrace (mm); BBFsed – mean sediment size of the base of the beach face (mm); BFsed – mean sediment size of the beach face (mm); Bsed – mean sediment size of the berm (mm); Csed – campaign average sediment size (mm); Np – not present.

	Date	S_m	V_m	SB_m	SB_{max}	TT_{sed}	BBF_{sed}	BF_{sed}	B_{sed}	C_{sed}
Sta. Rita Beach	17.12.2005 (pre-storm)	0,0512	80,613	34,981	109,326	Np	0,370	0,348	0,602	0,440
	04.01.2006 (storm)	0,0472	115,595			Np	0,537	0,363	0,400	0,433
	14.05.2006 (pre-storm)	0,0988	164,887	-14,904	29,810	0,466	0,715	0,542	0,571	0,573
	28.05.2006 (storm)	0,0596	149,983			0,551	0,475	0,517	0,484	0,507
Azul Beach	16.12.2005 (pre-storm)	0,0514	139,185	-10,150	50,454	0,417	0,549	0,580	Np	0,515
	02.01.2006 (storm)	0,0567	129,035			0,473	0,434	0,428	Np	0,445
	15.05.2006 (pre-storm)	0,0711	103,367	8,977	12,221	0,746	0,742	0,437	Np	0,642
	26.05.2006 (storm)	0,0340	112,344			0,525	0,855	0,506	Np	0,628
Foz do Lizandro Beach	15.12.2005 (pre-storm)	0,0725	278,298	-39,952	128,950	0,714	0,443	0,498	0,544	0,550
	03.01.2006 (storm)	0,0444	238,346			0,400	0,410	0,426	0,398	0,409
	12.05.2006 (pre-storm)	0,0826	234,424	-9,059	152,313	Np	0,544	0,428	0,458	0,477
	25.05.2006 (storm)	0,0601	225,365			Np	0,536	0,364	0,395	0,431
					Sta. Rita Beach	0,509	0,524	0,443	0,514	
					Azul Beach	0,540	0,645	0,488	Np	
					Foz do Lizandro Beach	0,557	0,483	0,429	0,449	

Azul beach have the smallest variation in sediment budget variability. January erosion (-10,150 m/m^3) is almost equivalent to May accretion (8,977 m/m^3).

Differences in systems responses to the same energetic event can be measured also with maximum sediment budget variability (Table 4). The highest maximum budget value in January (128,950 m/m^3 in Foz do Lizandro beach) was 2,5 times higher than the value of Azul beach (50,454 m/m^3). In May this relation rose to 12,5 times showing the extreme differences in the morphodynamic responses of this systems.

Mean beach slope variability (Table 4) is lower in Azul beach (3,71%), similar in Foz do Lizandro beach (3,82%) and higher in Sta. Rita beach (5,16%).

The sediment collected during the four campaigns is characterised by middle medium to middle coarse sands (Table 4) with sizes that range from 0,348mm to 0,855mm. The low range of mean sand sizes, approximately 1,25Ø, may be associated to the high selectivity of the transport agent and to the homogeneity of the sediment source.

The December-January sediments are in average lower when compared to average sediment size from the May campaigns, exception made for Foz do Lizandro where overall mean sand size is slightly higher in December-January campaigns (Table 4).

Superior values of mean sand sizes can also be found in the tidal terrace (0,540mm in Azul beach and 0,557mm in Foz do Lizandro beach) and in the base of the beach face (0,524mm in S[ta]. Rita, 0,645mm in Azul beach and 0,483mm in Foz do Lizandro beach). These morphological elements are placed were the wave breaker point moves back and forward during the high tide cycle, resulting in higher concentration of turbulence and wave energy dissipation. This differentiation is not clear in the beach face and in the berm where it would be expected a gradual decrease in the sediment size (Table 4).

Sand samples are moderately well sorted according to Friedman (1962) classification. Standard deviation shows little variation when all campaigns are analysed (0,616 – 0,779). Foz do Lizandro beach has the wider range in the sample dispersion measure (0,616 in the tidal terrace; 0,739 in the base of the beach face; 0,755 in the beach face; 0,733 in the berm) in contrast with Sta. Rita which reveals the highest homogeneity both in mean (Table 4) and standard deviation measures (0,695 in the tidal terrace; 0,722 in the base of the beach face; 0,745 in the beach face; 0,733 in the berm).

5. Discussion

Although a wave breaker type and beach profile continuum occur in natural beaches, accessing wave breaker conditions and morphodynamic state of the beach by formula and models is essential in order to compare the systems response to high energy input during one or several episodes.

According to Wright and Short (1984) _ classification (<1Ω reflective; 2Ω – 5Ω intermediate; >6Ω dissipative), the three beach systems lie between the dissipative and intermediate systems. The high wave climate events that occurred in January and May of 2006 (Fig. 4) are responsible for a general change in S[ta]. Rita, Azul and Foz do Lizandro beach systems towards dissipative morphology (Fig. 4, Tables 5 and 6).

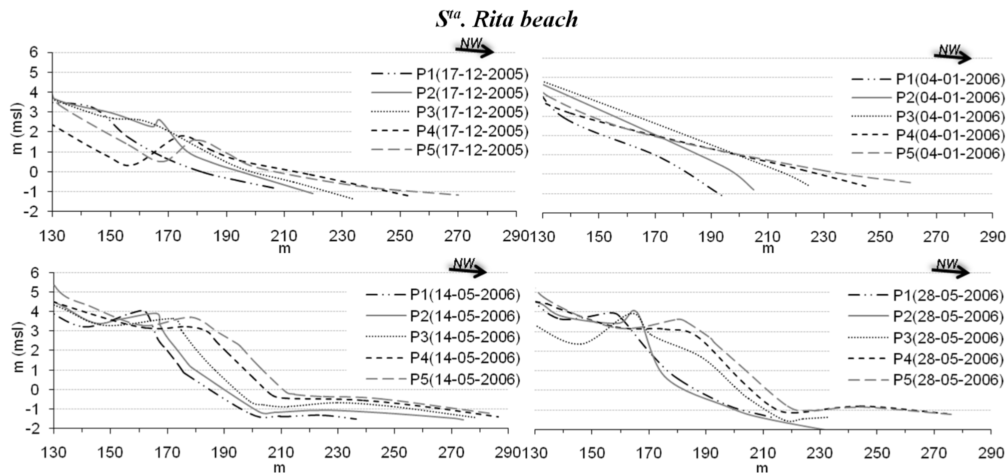
December – January results show that Sta. Rita evolved from low tide terrace with berm formation to quasi-dissipative behaviour. The general decrease in ξ_b values (Table 5) from the pre-storm to storm conditions, especially due to H_b and L_0 increase, reflects an amplification of wave energy dissipation along submerged profiles and an decrease in the energy's reflection over the beach system, as closure depth moves away from the shoreline.

The same response was not observed in May campaigns (Fig. 4) as beach profile reached only rhythmic bar and beach behaviour. In fact, for similar offshore storm values (Fig. 3) Ω is much lower in May.

Table 5. Surf similarity index parameterization (ξ_b), based on wave data from Leixões buoy. SP – spilling breakers; SG – surging breakers.

		S[ta]. Rita beach				**Azul beach**				**Foz do Lizandro beach**			
		S	H_b	L_0	ξ_b	S	H_b	L_0	ξ_b	S	H_b	L_0	ξ_b
January	**Pre-storm**	0,0512	0,74	42,15	**0,3864** SP	0,0514	0,74	42,15	**0,3879** SP	0,0725	0,74	42,15	**0,5472** SG
	Storm	0,0472	2,02	71,51	**0,2808** SP	0,0567	2,02	71,51	**0,3373** SP	0,0444	2,02	71,51	**0,2641** SP
May	**Pre-storm**	0,0988	1,09	46,74	**0,6470** SG	0,0711	1,09	46,74	**0,4656** SG	0,0826	1,09	46,74	**0,5409** SG
	Storm	0,0596	1,62	55,26	**0,3480** SP	0,0340	1,62	55,26	**0,1985** SP	0,0601	1,62	55,26	**0,3510** SP

Field observations revealed the presence of one longshore bar in January whilst in May there were at least two bars present. According to Battjes (1974) classification, the wave type for the two high wave climate conditions was the spilling breaker, given as storm in Table 5. Spilling breakers are usually associated with steep incident waves ($\approx H_b \geq L_b$) and low gradient beach profiles that play a significant role in wave energy dissipation. The presence of multi-barred submerged profile and very well defined crescentic berms in S[ta]. Rita pre-storm May morphology (Fig. 4) acted as a buffer to wave energy and to onshore sediment transport, restricting beach profile progression towards fully dissipative behaviour. The differentiated Ω values for January and May storm events are consistent with the maximum sediment budget variability expressed in Table 4, where higher variability of January storm (109,326m/m^3) is contrasting with lower May value (29,810m/m^3). Further more, sediment size variations across beach profile confirm this tendency. An increase in January mean sediment size between pre-storm and storm data (Table 4) is noted on the base of the beach face and on the beach face (BBF – 0,370mm to 0,527mm; BF – 0,348mm to 0,363mm), which directly reflects a rise in the energetic levels. May results reveal the opposite tendency, with a decrease in mean sand size between pre-storm and storm conditions.



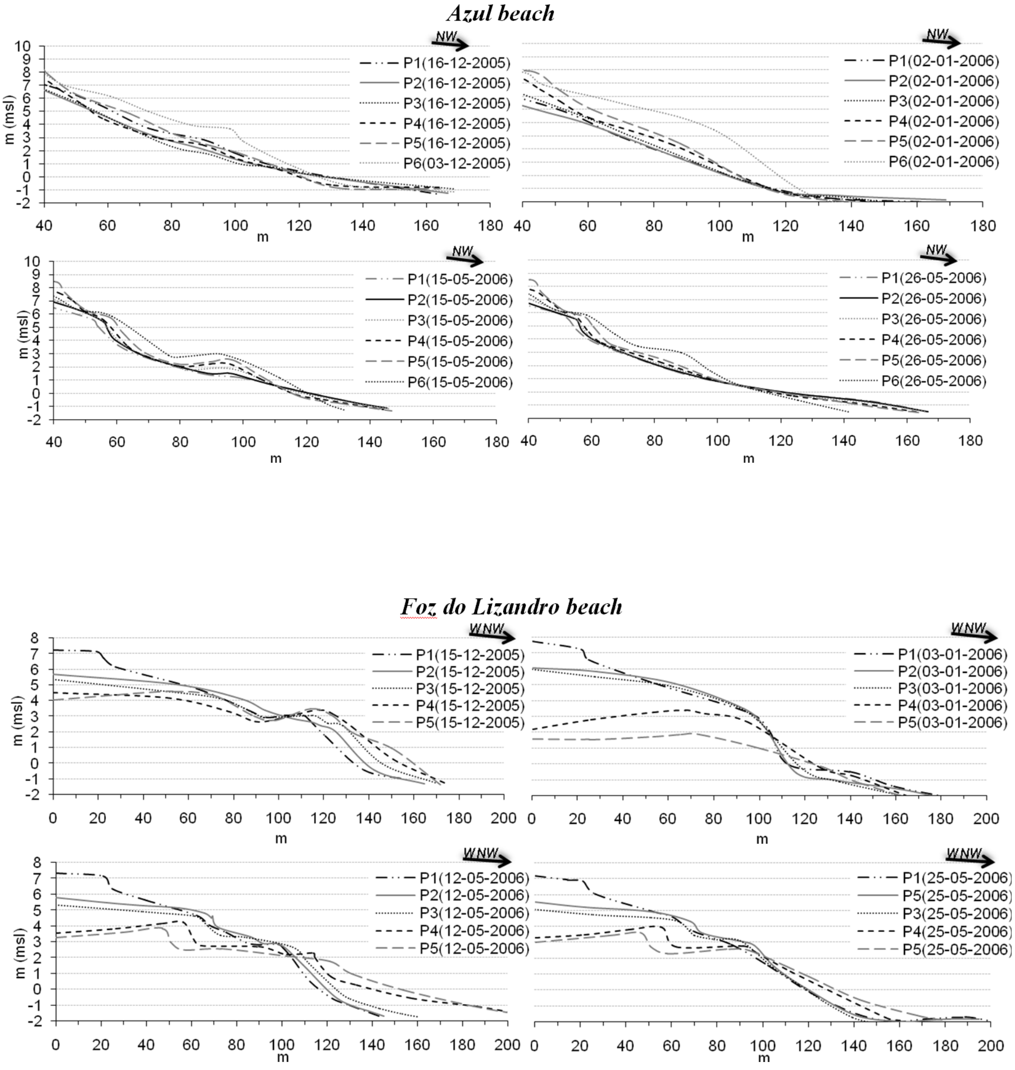


Figure 4. Beach profile sequence in Sta. Rita, Azul and Foz do Lizandro.

Exception made for more energetic and/or durable storms it can be assumed that the intermediate morphodynamic state of longshore bar-trough is the limit response to high hydrodynamic events. The modal state of morphodynamic behaviour during low-energy wave climate was found to be the low tide terrace.

Azul beach morphology ranged from low tide terrace in pre-storm measurements to longshore bar-trough in January and transverse bar and rip in May, as a response to the respective storm events (Table 6). Field observations revealed a decrease in the number of bars from pre-storm to storm morphology. In December, the pre-storm submerged morphology included one bar indirectly observed through the number of consistent breaker lines present during low tide. This bar disappeared after January storm. A two bar system was also found in May pre-storm conditions. This bar system was reduced to one transversal bar after late May high wave event.

The existence of a barred system in May observations along with low values of ξ_b (0,3373 – January storm; 0,1985 – May storm) indicate high dissipative behaviour of the submerged beach and was a major contribution to the lowest mean variability of January (-101,497m/m^3) and May (89,769m/m^3) sediment budgets (Table 4).

This fact doesn't necessary mean a less dynamic system when compared to the other two beaches. Dimensionless fall velocity parameter values and it's correspondent classification (Wright and Short, 1984) and the observed bar number along the four campaigns denote high morphological dynamics of the submerged beach profile.

Azul beach modal state of morphodynamic behaviour (low tide terrace) and limit conditions under storm influence (longshore bar-trough) can be assumed as being similar to Sta. Rita beach.

Unlike S^{ta}. Rita and Azul beach, Foz do Lizandro beach reached the fully dissipative morphodynamic behaviour in January storm event and the range of Ω values indicate the full spectrum of intermediate types are present (Table 6).

Table 6. Dimensionless fall velocity parameterization (Ω). D – dissipative; LBT – longshore bar-trough; RBB – rhythmic bar and beach; TBR – transverse bar and rip; LTT – low tide terrace.

		S^{ta}. Rita beach				**Azul beach**				**Foz do Lizandro beach**			
		H_b	T	W_s	Ω	H_b	T	W_s	Ω	H_b	T	W_s	Ω
January	**Pre-Storm**	0,74	5,17	0,071	**2,0160** LTT	0,74	5,17	0,076	**1,8833** LTT	0,74	5,17	0,069	**2,0744** LTT
	Storm	2,02	6,73	0,055	**5,4572** LBT	2,02	6,73	0,061	**4,9205** LBT	2,02	6,73	0,051	**5,8853** D
May	**Pre-Storm**	1,09	5,44	0,075	**2,6716** LTT	1,09	5,44	0,082	**2,4435** LTT	1,09	5,44	0,064	**3,1307** TBR
	Storm	1,62	5,86	0,066	**4,1886** RBB	1,62	5,86	0,083	**3,3307** TBR	1,62	5,86	0,054	**5,1195** LBT

At Foz do Lizandro, the high variability in morphodynamic states is consistent with the higher values of maximum sediment budget changes over the four campaigns (128,950m/m^3 in January and 152,312m/m^3 in May, (Table 4). This system is smaller and, unlike the other beach systems, beach morphology is conditioned not only by wave climate but also by direct river hydrodynamics during winter. The Lizandro river flows in the southernmost sector of the beach (Fig. 2) and in high water episodes can flood and erode the beach and the backshore profile. This combined fluvial and marine hydrodynamics probably explain the higher volume and parameter variability recorded in this system.

Because of this high variability in the beach profile it was not possible to characterize modal behaviour of Foz do Lizandro beach. More wave, morphologic and sediment data is needed to fully understand this system dynamics.

6. Conclusion

Beach morphology dynamics depends, in the first place, on the variations of wave energy reaching the coast, namely during storms, and secondly on sediment availability to fulfill loss from high hydrodynamic events.

Parameterization of data collected with regular beach profile monitoring campaigns is a useful tool to predict and validate beach behaviour. The use of the surf similarity index (ξ_b) and the dimensionless fall velocity (ξ_b) parameters allowed differentiating between the three beach systems' behaviour before and right after two high wave events that occurred in January and May 2006. Field data parameterization allowed establishing modal behaviour and limit response to high wave climate within Wright and Short morphodynamic model. Sta. Rita and Azul beach have the same modal morphodynamic behaviour (low tide terrace) as well as the similar response limit to storm conditions (longshore bar-trough). Foz do Lizandro revealed no modal morphodynamic behaviour and reached fully dissipative conditions during January storm event.

The Ω parameter showed good predictive results when compared to the observed beach morphology.

Results reveal the high potential of beach monitoring programmes in the prediction of local system behaviours under high wave events and, therefore, in potential beach damage by storms.

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