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Characterisation of the dynamics of Figueira da foz beach, Portugal

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ABSTRACT

The characterisation of the dynamics of Figueira da Foz beach, in the West coast of Portugal, is presented based on the analysis of previous studies and results obtained from the application of a numerical model. Advances on the understanding of the beach dynamics have been achieved by the quantification of the annual and seasonal longshore transport and several beach profile parameters. An evaluation of the contribution of the wave climate components on the longshore transport was also obtained. The results allow sustaining a prediction of the effect of a future change of the wave climate on the longshore transport. Figueira da Foz shoreline change was simulated based on different conceptual scenarios and the results, although not quantitatively conclusive, allow the understanding of the influence of the neighbouring beach hard rock outcrops on the recent evolution.

ADDITIONAL INDEX WORDS: *Longshore sediment transport; mathematical modelling; beach characterisation; hard rock outcrop; West coast of Portugal.*

INTRODUCTION

This study aims at characterising the dynamics of Figueira da Foz beach, an important seaside resort in the Atlantic West coast of Portugal (Figure 1). The methodology applied was based on gathering and analysing the existent information and completing the existent studies with additional mathematical modelling. The quantification of local hydrodynamic and morphodynamic beach parameters is obtained in the present study. The influence of the hard rock outcrops of the neighbouring beach on the recent evolution of the shoreline is assessed.

The present paper is organised in three main sections. In this section, a characterisation of the study area and its morphological evolution are presented, followed by a description of the wave climate at a location opposite to the beach. In the following section the numerical model applied on the analysis of the littoral transport is briefly referred to. The results obtained for the longshore sediment transport, the beach profile characterisation parameters, and the contribution on the total longshore transport of the each directional wave sector and wave height class, are presented and discussed. A critical analysis of the numerical simulations executed aiming to understand the effect of the existent hard rock outcrops of the neighbouring northern beach on the shoreline evolution closes the section. In the last section concluding remarks on the study findings are summarised.

Study area

Figueira da Foz beach is located in the Atlantic West coast of Portugal in the north side of Mondego estuary (Figures 1 and 2). The beach has a N-S general orientation with a slightly curvilinear shape. At south is limited by the north jetty of Mondego estuary mouth and at north by Buarcos beach. Buarcos shoreline has WNW-ESE orientation until Cabo Mondego, a natural headland. Further north the shoreline presents a rectilinear shape with a NNE-SSW orientation, the same as the shoreline orientation southward of Mondego river mouth.

Figueira da Foz beach is 2km long and between 250m and 500m wide. The backshore of the beach is limited by urban infrastructures. Beach sediments are predominantly medium-sized sands. The mean sea level (MSL) is 2m above the 0m depth chart datum (CD). The local mean tidal range is 2.2m and the maximum tidal level above the CD is 3.6m. The net longshore transport is directed to the south. The longshore transport rate estimated by several authors varies between 200-1500x10³m³/year (FERREIRA *et al.*, 1961; CONSULMAR, 1988; BETTENCOURT and NGELO, 1992; ANDRADE *et al.*, 1997; CUNHA and DINIS, 1998). Such wide range of estimated values and consequent difficulty to analyse and characterise the beach dynamics, points out to the necessity to apply other means, such as mathematical modelling, to obtain a detailed description of the longshore transport.

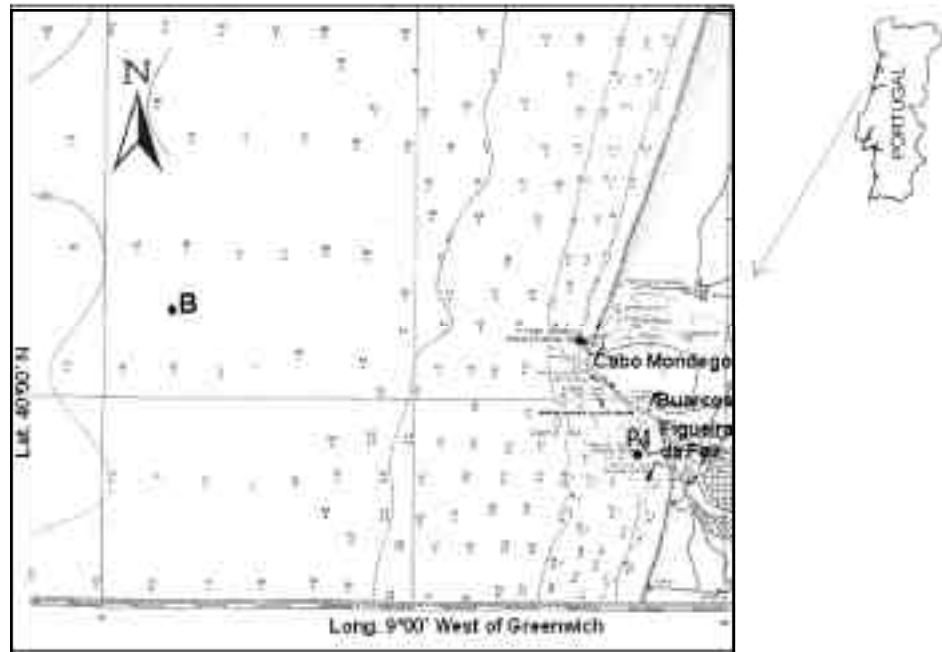


Figure 1. Location of the area of study.

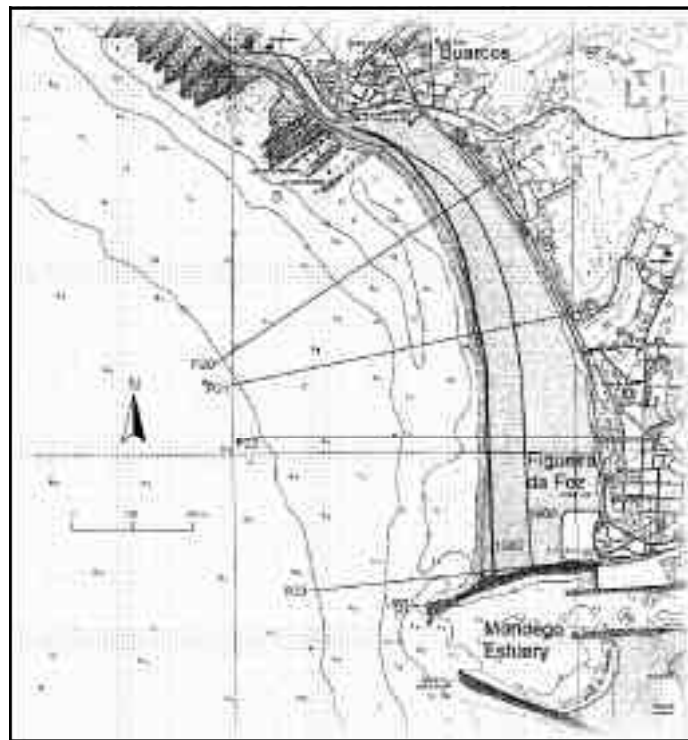


Figure 2. Figueira da Foz beach (based on IH chart no. 64, 4th edition, 1985). Cross-shore profiles. Shoreline position in 1968 and 1983.

The historical evolution analysis presented by several authors based mainly in the study of charts and aerial photographs (BETTENCOURT and NGELO, 1992; ANDRADE *et al.*, 1997; CUNHA and DINIS, 1998) shows that the morphological evolution of Figueira da Foz shoreline since 1800 is characterised by seasonal and inter-annual accentuated variations of transversal extension of the beach. Between 1800 and 1860 the shoreline showed a progradation of 100m with an average rate of accretion of +1.5m/year. During the following hundred years the beach retreated, with a maximum erosion rate of -2.3m/year in the period 1871-1947. After the end of the 50's the shoreline showed new period of progradation with an average rate of +1.8m/year, between 1958 and 1985. During this period the maximum rate of accretion (+23m/year) was observed

between 1958 and 1977. This progradation episode was promoted by the construction of the jetties in the Mondego estuary mouth, which was complete in 1965. The infilling of the beach was studied by VICENTE and CLÍMACO (1986) based on periodic surveys of the low tide and high tide shoreline positions. The authors concluded that the beach infilling was complete in 1980. After this, the shoreline has maintained general stability despite the local erosion episodes that occurred between 1982 and 1990 near the north jetty, with an average erosion rate of -3.5m/year as reported by ANDRADE *et al.* (1997). The occurrence of this erosion processes may be related, according to CUNHA (1999), with sand mining near this area. The value of sand extraction estimated by this author is $400 \times 10^3 \text{ m}^3/\text{year}$ in the period 1989-1995.

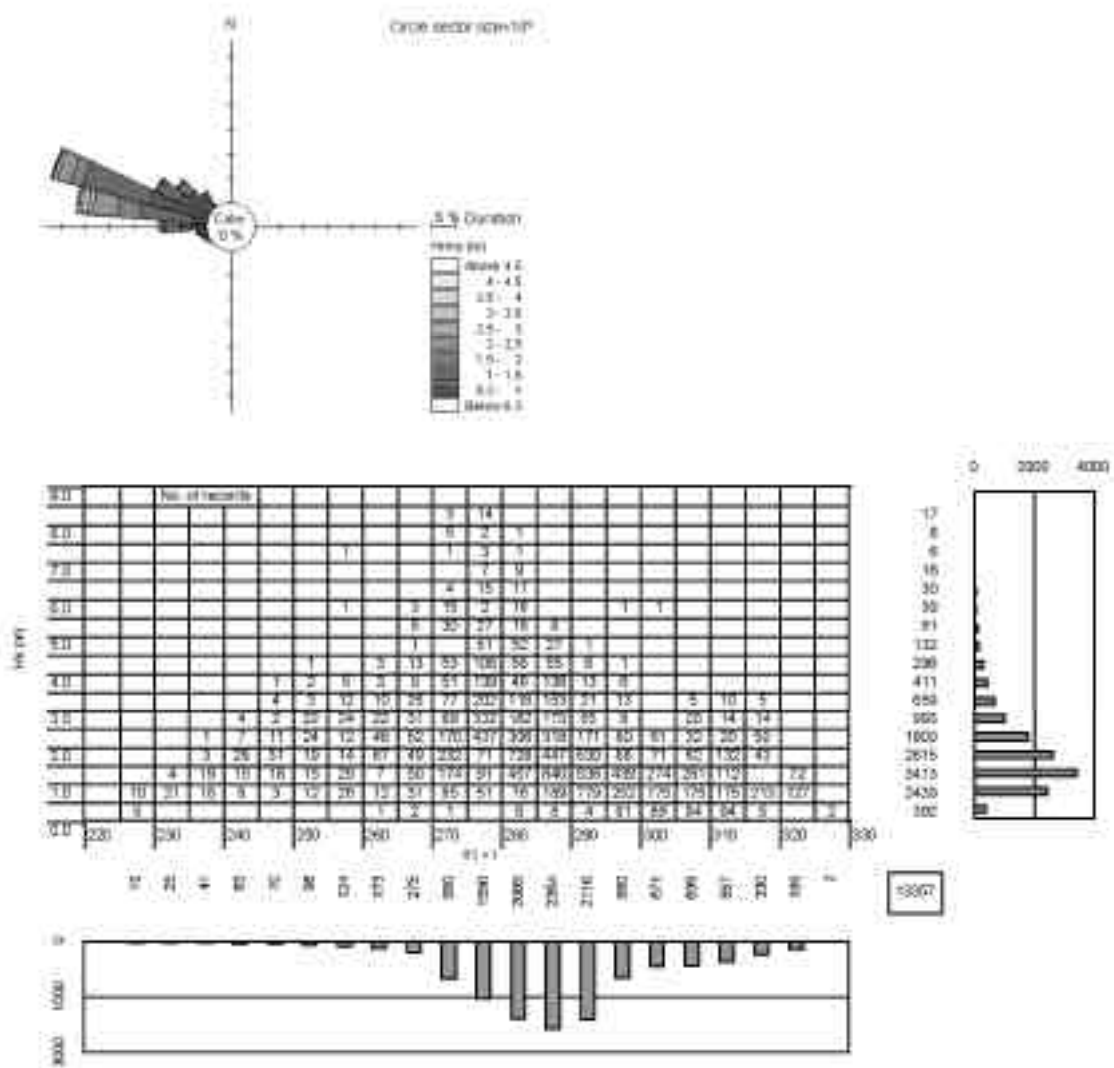


Figure 3. Total observed wave regime in P1: a) Graphical form; b) Tabular form.

The evolution of the coastline northward Figueira da Foz until Cabo Mondego is characterised by significant retreat episodes between 1996 and 1998, with a large amount of sand eroded from the beach and with the destruction of the seawall constructed in the 80's on the beach backshore. The explanations presented by several authors (ANDRADE *et al.*, 1997; CUNHA and DINIS, 1998; VICENTE and CLÍMACO, 1998) are that these occurrences are associated with extreme and unusual meteorological conditions and sediment starvation.

Wave climate

Three main previous studies that characterise the annual wave climate in the coastal zone of Figueira da Foz exist. The two first ones (CARVALHO and BARCELÓ, 1966; SANTOS *et al.*, 1991) were based on an incomplete set of wave records registered from January 1954 to December 1960. Due to buoy damage during storms and discontinuous recording of wave data, severe storm events associated to the highest values of wave heights were not registered during that period of time. The maximum significant wave height registered was 7.5m. Nevertheless, a later analysis of storm events return period offshore the Portuguese West coast (CARVALHO, 1992) showed that storms with maximum significant wave height of 9.5-10m have a return period of 5 years (Table 1).

A more recent study, based on wave records from January 1984 to December 1996, obtained from a waverider station located at 89m depth CD (location B in Figure 1), allowed to estimate the annual wave climate at a location opposite to the beach, at a depth of 10m CD (location P1 in Figure 1). The transference of the wave climate to the nearshore was based on mathematical modelling of wave refraction (CAPITÃO *et al.*, 1997) and was done for three periods of time: total regime observed, in Figure 3; maritime Winter regime observed (includes months from October to March), in Figure 4; and maritime Summer regime observed (includes months from April to September), in Figure 5. The still water level considered was the MSL.

From the study developed by CAPITÃO *et al.* (1997) and considering the relation $H_s = 1.55 H_{rms}$, where H_s is the significant wave height and H_{rms} is the root-mean-square wave height, the wave regime in P1 can be characterised as follows:

- The average offshore spectral wave directions within the range N200-349° rotate to the average spectral wave directions within the range N227-326°.
- The most frequent wave directions occur within the range N270-300° and are mostly associated to values of H_{rms} between 0.35 and 2.12m. Waves with longer duration occur within the directional sector N285-290°.
- The values of H_{rms} vary between 0.11 and 5.93m, being the maximum value limited due to the process of wave breaking. The corresponding offshore values are 0.18 and 6.5m, respectively.
- The most frequent H_{rms} occurs within the range 0.35-2.12m.
- T_z , where T_z is the zero crossing period, was derived based on the observed wave regime. A linear regression fitting has been made to obtain the relationship between T_z and H_s .
- T_z varies within the range 5-15s and was assumed constant from offshore to P1 in the calculations.
- Generally, for T_z between 5 and 9s, the values of H_{rms} are smaller in P1 than offshore. However for values of T_z higher than 10s, H_{rms} is higher at P1 than offshore for directions between WSW and WNW. For the remaining wave directions, the values of H_{rms} do not reveal such regular behaviour.
- Wave heights are higher in Winter than in Summer. The number of wave records with H_{rms} higher than 2.82m are 606 in Winter whereas in Summer are only 29. In Winter the most frequent H_{rms} varies between 0.35 and 1.77m whereas in Summer varies between 0.35 and 1.41m.
- The most frequent directions in Summer occur within the range N280-295°, being waves with longer duration within the directional sector N290-295°. The most frequent directions in Winter occur within the range N275-295°, being waves with longer duration within the directional sector N285-290°.

NUMERICAL MODELLING OF LITTORAL SEDIMENT TRANSPORT. RESULTS AND DISCUSSION

Two modules of a commercial integrated modelling system for littoral processes and coastal kinetics (DHI, 2000a; DHI, 2000b) have been applied to calculate the cross-shore distribution of the longshore sediment transport and the coastline evolution over a period of time. Since the

Table 1. Significant wave heights associated to storm events return period at Figueira da Foz.

Return period (years)	H_s (m) offshore Figueira da Foz
5	9.50-10.00
50	11.50-13.60
100	12.40-15.50

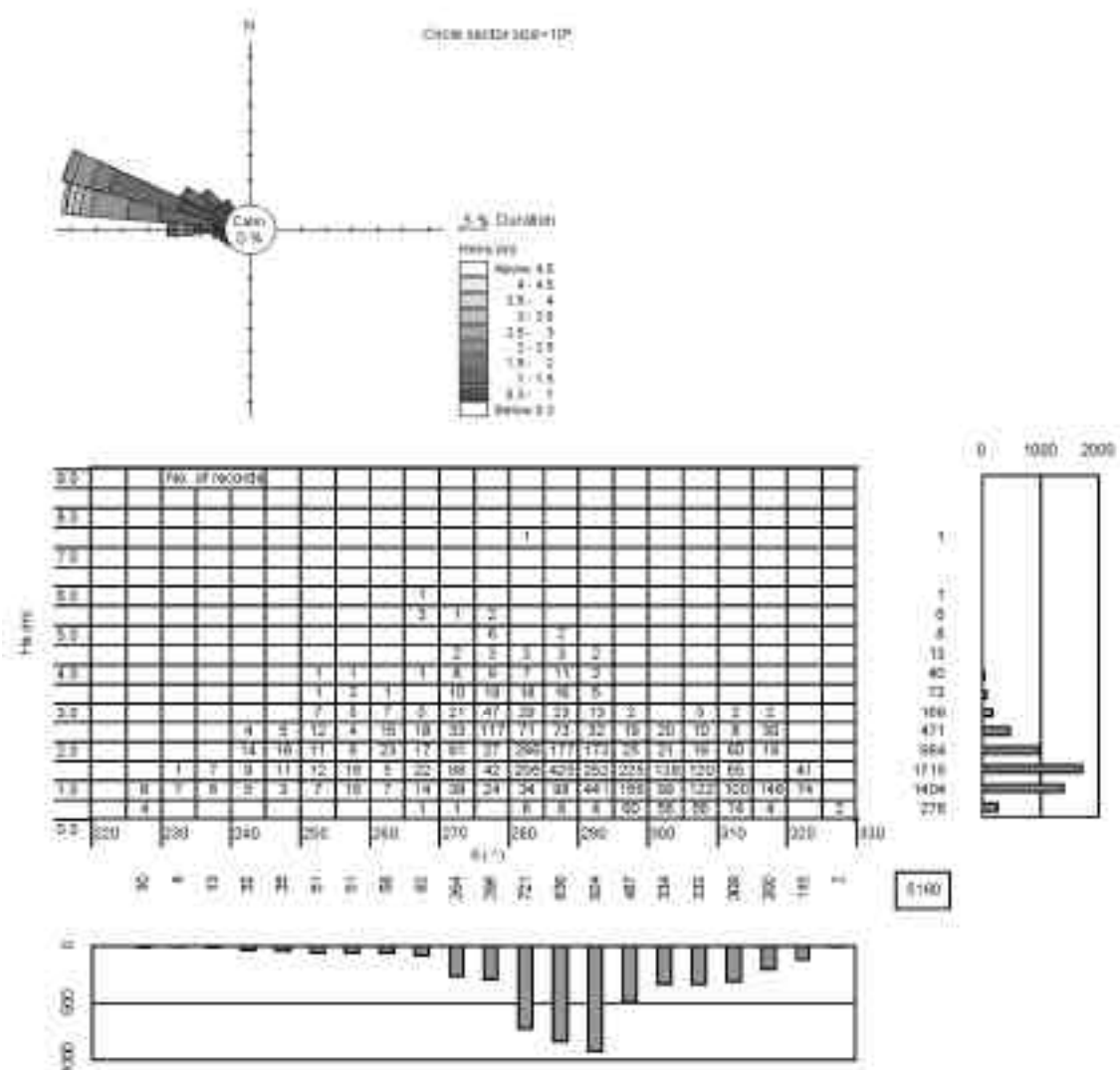


Figure 4. Maritime Winter observed wave regime in P1: a) Graphical form; b) Tabular form.

description of the modules, of their formulation and validation, and of their successful application in several study areas worldwide, has been vastly reported and therefore is well known, a repetition of the subject is avoided here.

Longshore sediment transport and beach profile characterisation

Four cross-shore beach profiles were extracted from a chart at scale 1:10 000, dated of 1985, date when the beach had already achieved stability (Figure 2). They have been used to estimate the cross-shore distribution of the longshore sediment transport due to wave-induced currents. At each grid node of each profile the suspended and bed load were integrated to obtain the longshore drift and the

annual sediment budget. The numerical results obtained can be seen in Figures 6-9 for profiles P20-P23, respectively.

The existence of a longshore bar located southward of the cross-shore aligned hard rock outcrops of Buarcos (Figure 2) might be an indicator of the deposition of sand transported by the predominant littoral current instead of the result of onshore-offshore sand movement, since its extension is confined to the northern sector of Figueira da Foz beach. Such sea bed shape influences the cross-shore distribution of the longshore transport by generating a peak in the drift, which is higher in P21 (Figure 7), where the bar is steeper, than in P20 (Figure 6). The shape variation of this longshore bar results in a different degree of protection of the shoreline: the transport drift at the shoreline is strongly reduced in P21.

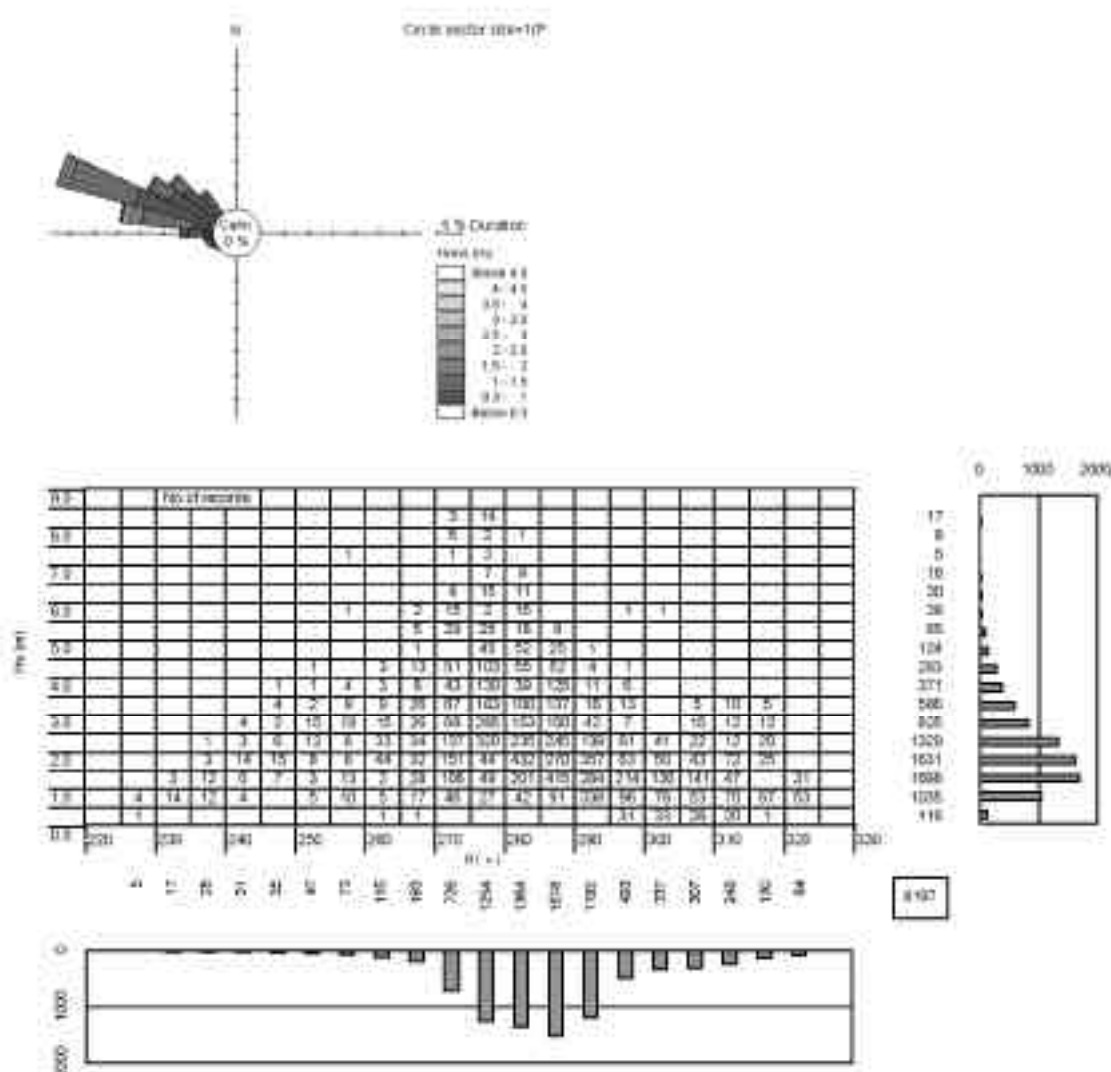


Figure 5. Maritime Summer observed wave regime in P1: a) Graphical form; b) Tabular form.

In the model results for P22 (Figure 8), where the longshore bar is absent, the peak of the transport drift is located at the shoreline. Approaching the southern limit of the beach, (northern jetty of Figueira da Foz harbour) the shape of the profile is highly influenced by the local hydrodynamics of the inlet, where other currents different from wave induced ones may play a dominant role in the process of sediment transport. The sand bank which surrounds the tip of the north jetty does not have a relevant influence on longshore transport due to wave induced currents exclusively, as can be observed in the results obtained for P23 (Figure 9).

Profile P21, has the higher transport capacity in terms of total transport and net longshore transport. As expected, based on the observation of the coastline change of

direction, the southern half of Figueira da Foz beach is characterised by a decrease of the southwards longshore transport and an increase of the northwards longshore transport.

Most of the annual longshore transport, 83%, occurs during the maritime Winter regime. The northwards annual longshore transport for Figueira da Foz beach is only about 3% of the total annual longshore transport. The southwards transport is about five times higher in Winter than in Summer. The northwards transport is about two times higher in Winter than in Summer. The average northwards and southwards annual longshore transport rate was found to be approximately $30 \times 10^3 \text{ m}^3/\text{year}$ and $893 \times 10^3 \text{ m}^3/\text{year}$, respectively.

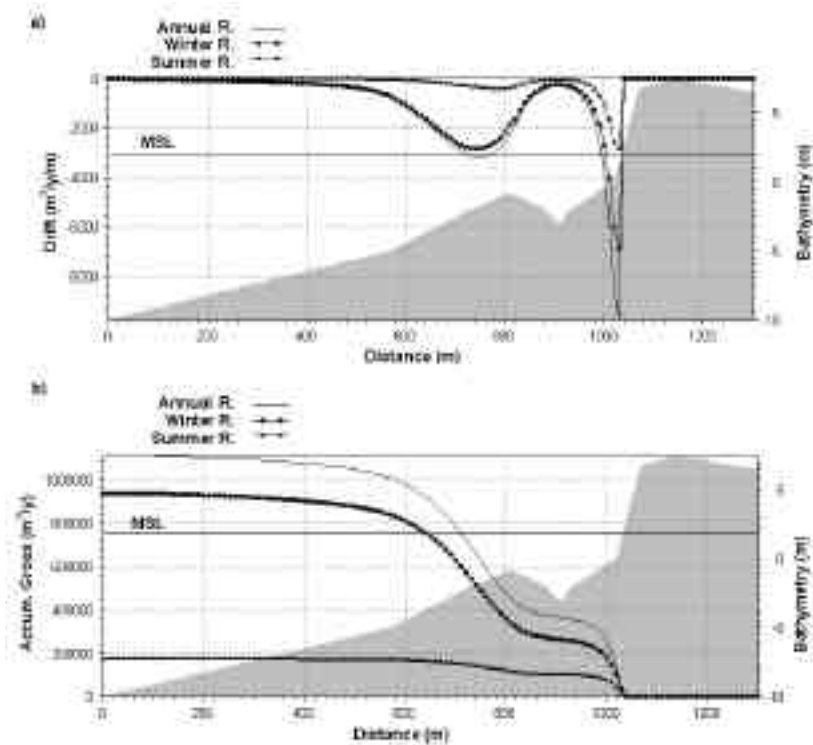


Figure 6. Numerical results for P20: a) Southward longshore drift; b) Accumulated longshore annual transport.

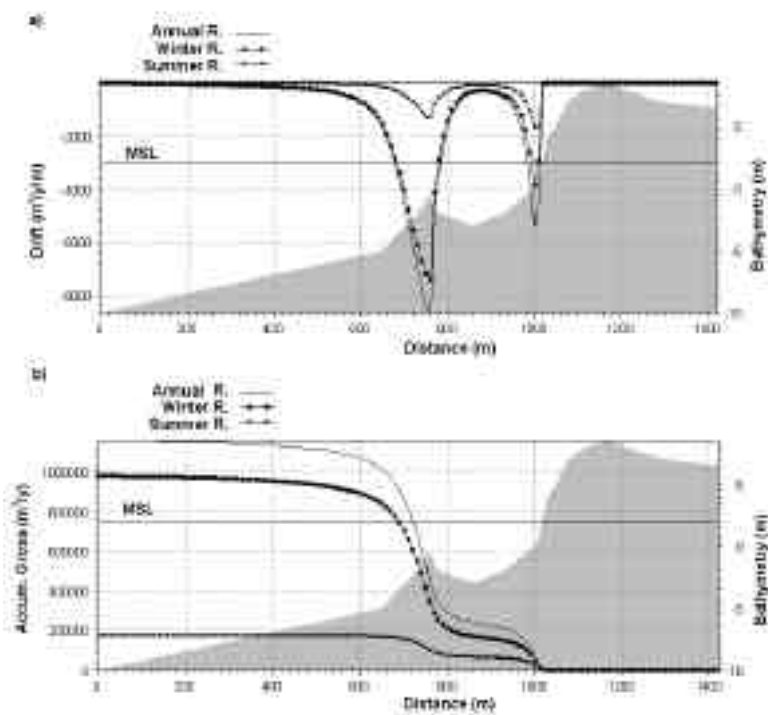


Figure 7. Numerical results for P21: a) Southward longshore drift; b) Accumulated longshore annual transport.

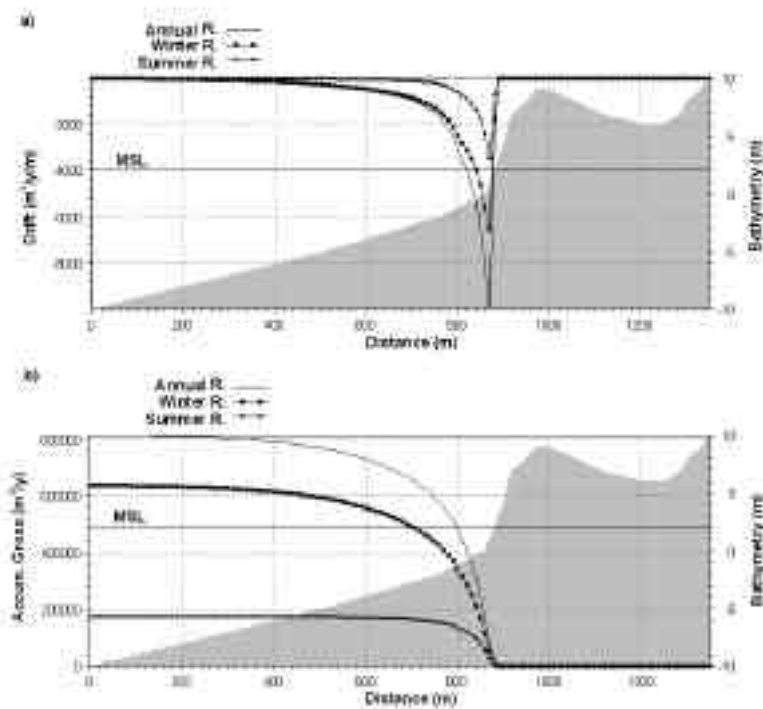


Figure 8. Numerical results for P22: a) Southward longshore drift; b) Accumulated longshore annual transport.

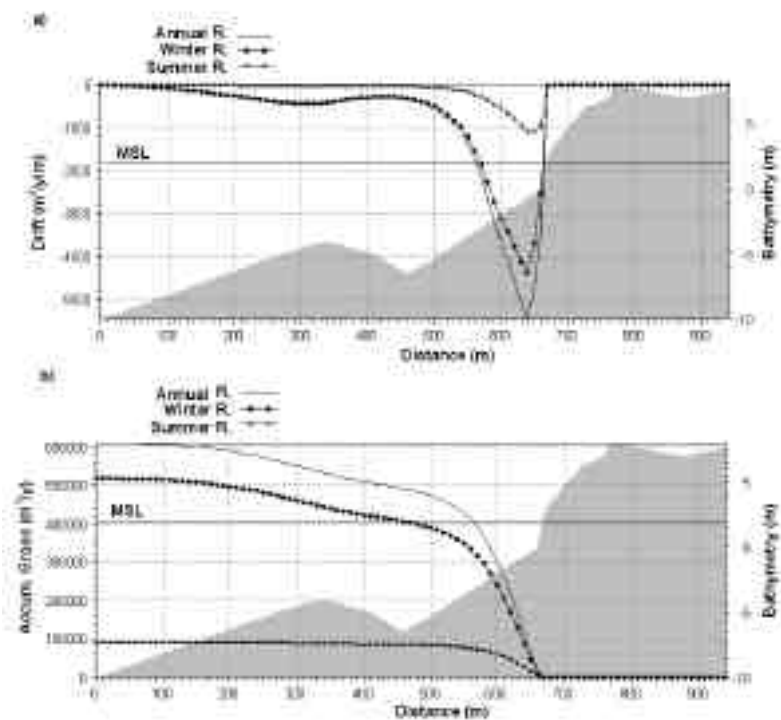


Figure 9. Numerical results for P23: a) Southward longshore drift; b) Accumulated longshore annual transport.

Table 1. Significant wave heights associated to storm events return period at Figueira da Foz.

	Cross shore profile	Active depth (m)	Active length (m)	Sediment transport (m ³ /year)	
				Southwards	Northwards
Annual Regime	P20	11.91	1 050.00	1 108 658	170
	P21	11.77	1 010.00	1 141 852	17 490
	P22	11.71	870.00	740 349	73 297
	P23	11.81	680.00	582 046	27 596
	Average	11.80	902.50	893 226	29 638
Maritime Winter Regime	P20	11.91	1 050.00	935 340	105
	P21	11.62	990.00	968 340	10 860
	P22	11.80	880.00	587 993	49 002
	P23	11.81	680.00	498 115	19 351
	Average	11.79	900.00	747 447	19 830
Maritime Summer Regime	P20	9.37	750.00	173 294	65
	P21	9.15	670.00	173 497	6 622
	P22	9.35	630.00	152 362	24 257
	P23	9.78	570.00	83 928	8 236
	Average	9.41	655.00	145 770	9 795

Parameters like active depth and active length, which indicate how much of the profile below MSL is subject to erosion and accretion, in the vertical and normal directions to the coastline respectively, allow a better characterisation of the beach dynamics. They have been summarised in Table 2 for the four cross-shore profiles. It was assumed that the offshore limit of the longshore sediment transport occurs at a grid node of a profile, for which, the transport between the two consecutive inner grid nodes, distant 10m, is less or equal than 50m³/y.

The analysis of the parameters active length and active depth allow one to quantify the onshore-offshore extension of the area subject to erosion and accretion due to longshore transport. Such extension has tendency to decrease as one travels southwards along the beach. During the Winter regime, in average, the longshore transport occurs within an area of about 900m width, which extends from the shoreline up to a depth of about 11.8m below the MSL. During the Summer regime, in average, the offshore limit of the longshore transport occurs closer to the shoreline at a depth of about 9.4m below MSL.

The annual gross sediment transport can be investigated as a function of the wave height and the wave angle. Such allows an assessment of the contribution of each directional wave sector and associated wave heights to the annual longshore transport. Model results for profiles P20-P23 are shown in Figures 10-13, and Table 3. About 80% of the total annual longshore sediment transport is generated by incoming waves from the directional sector N275-295°. More than 50% of the total annual longshore transport

results from the contribution of waves with Hrms within the range 1.00-2.50m.

Incoming waves from direction N285-295° have a duration slightly higher than those from N275-285°, but the highest percentage of waves with Hrms above 1.50m is associated to the sector N275-285° (Figure 3). Incoming waves from direction N275-285° are the ones that generate more longshore transport along the total extension of the beach, particularly at the northern zone due to the coastline orientation. Such was expected since the sediment transport increases with the increase of the wave height, and the increase of the angle between the wave direction and the profile orientation up to the value of 45°.

Influence of the hard rock outcrops of Buarcos beach

As referred above, Figueira da Foz beach is bounded northwards by Buarcos beach. Buarcos beach, with a shoreline of 2.8km long and an exposure WNW-ESE, is characterised by the existence of several hard rock outcrops (Figures 2 and 14) with an onshore-offshore orientation and a maximum length of 200m. These natural structures, which are totally submerged during high tide, cover the total extension of the beach since the northern limit of Figueira da Foz up to Cabo Mondego, with only two small discontinuities.

In order to evaluate the influence of the hard rock outcrops of Buarcos beach, the evolution of Figueira da Foz shoreline was simulated from 1968, after the conclusion of the harbour jetties, until 1983, when the advance of the

Table 3. H_{rms} contribution to the total annual longshore transport.

Hrms (m)	% of total annual longshore transport			
	P20	P21	P22	P23
< 0.30	1.0	1.0	1.0	0.0
0.30 - 1.00	2.0	2.0	3.0	2.0
1.00 - 1.50	18.0	17.0	29.0	15.0
1.50 - 2.00	12.0	13.0	16.0	14.0
2.00 - 2.50	22.0	25.0	24.0	27.0
2.50 - 3.00	11.5	12.0	9.0	13.0
3.00 - 3.50	9.0	9.0	6.5	9.0
3.50 - 4.00	11.5	10.0	6.0	11.0
4.00 - 4.50	3.0	3.0	1.5	2.5
> 4.50	10.0	7.0	4.0	6.5

shoreline had finished and the beach was considered stable. Two shoreline positions were obtained from local measurements (VICENTE and CLÍMACO, 1986). Two different scenarios were established to simulate numerically the northern conditions of Figueira da Foz beach. In the first scenario it was assumed that the northern boundary for the numerical model was an open boundary, which is the same as if the hard rock outcrops would not cause any influence on the total longshore transport and on its distribution along the northern profile of Figueira da Foz beach. The results obtained did not agree with the shoreline position in 1983 (Figure 2). The northern sector of the beach presented a higher rate of shoreline advance than the southern sector, which does not correspond to the real evolution. Based on the results of the first scenario a second scenario was established: it was assumed that the northern boundary of the numerical domain was partly closed. Such was achieved

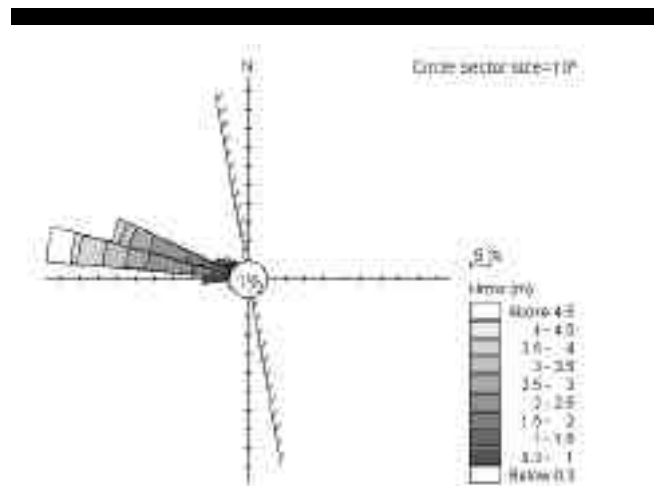


Figure 11. Annual gross sediment transport in profile P21.

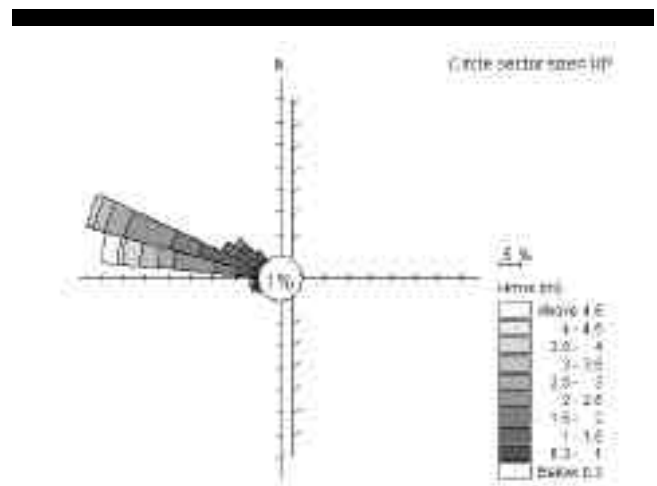


Figure 12. Annual gross sediment transport in profile P22.

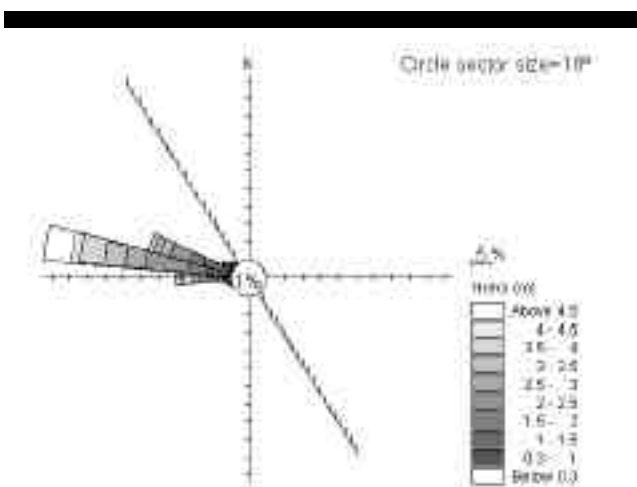


Figure 10. Annual gross sediment transport in profile P20.

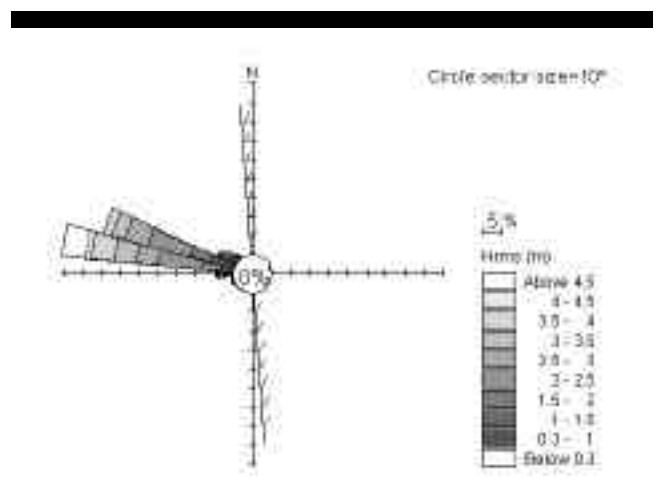


Figure 13 - Annual gross sediment transport in profile P23.

through the implementation of a groyne that interrupts the continuous passage of sediment in the nearshore part of the northern profile of Figueira da Foz beach. The results obtained from this simulation did not show a good agreement with the existent data. However, an important remark is that the implementation of the groyne, which objective was to simulate an obstacle to the longshore sediment transport, produced the real tendency of the beach evolution. It had exactly the opposite effect of the first scenario on the advance of the shoreline position: the rate of shoreline advance was lower at the northern sector than at the southern sector of the beach.

CONCLUSIONS

The historical evolution of Figueira da Foz beach showed important seasonal and inter-annual variation of the cross-shore extension of the beach. After 1960, as consequence of the construction of the jetties at the mouth of Mondego estuary, the beach experimented intense progradation. This infilling process was accomplished in 1980 and after this the shoreline showed stabilisation despite some local erosion episodes that seemed to be related with sand mining.

The wave regime at Figueira da Foz is characterised by waves with most frequent incident direction within the range N270-300° and Hrms between 0.35 and 2.12m. During the maritime Winter regime, which includes months from April to September, the most frequent Hrms varies between 0.35 and 1.77m, whereas during the maritime Summer regime, which includes months from October to March, varies between 0.35 and 1.41m. The most frequent directions during the maritime Summer regime occur within the range N280-295°, being waves with longer duration within the directional sector N290-295°. The most frequent directions during the maritime Winter regime occur within the range N275-295°, being waves with longer duration within the directional sector N285-290°.

The results obtained in this study allowed to quantify for the first time the seasonal variations of the longshore transport and its cross-shore distribution along the beach profiles. Analysis based on numerical modelling of the average longshore littoral transport at Figueira da Foz beach shows that 97% of the total annual transport, about $893 \times 10^3 \text{ m}^3/\text{year}$, is directed southwards. Most of the annual longshore transport, 83%, occurs during the maritime Winter regime, when wave heights are higher and the most frequent associated incident wave directions occur within



Figure 14. Hard rock outcrops of Buarcos beach.

the range N275-295°. The nearshore area where the longshore sediment transport occurs was identified based on the parameters active length and depth. On average, the active length and active depth are: 900m and 11.8m respectively, during the maritime Winter regime; and 655m and 9.4m respectively, during the maritime Summer regime.

The investigation of the annual gross sediment transport as a function of the wave height and the wave angle was another novelty to the existent knowledge achieved with the present study. This type of analysis allows sustaining a prediction of the effect of a future change of the wave climate on the longshore transport. The results show that about 80% of the total annual longshore sediment transport is generated by incoming waves from the directional sector N275-295° and more than 50% of the total annual longshore transport results from the contribution of waves with Hrms within the range 1.00-2.50m. Incoming waves from direction N275-285°, which is the directional sector with a higher percentage of waves with Hrms above 1.50m, are the ones that generate more longshore transport along the total extension of the beach, particularly at the northern zone due to the coastline orientation.

The numerical simulation, based on two different scenarios, of Figueira da Foz shoreline change from 1968 until 1983, despite not being quantitatively conclusive, shows that the hard rock outcrops of Buarcos beach, acting as a natural obstacle to part of the longshore transport, influenced the variation of the shoreline rate of advance along the beach extension.

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