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Medium-term evolution of an intermediate beach with an intertidal bar (Amoreira beach, Southwest Portuguese rocky coast).

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ABSTRACT

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The subaerial beach and low tide terrace morphology of the Amoreira beach (Southwest Portuguese Coast) was assessed using a DGPS system between December 2006 and October 2008. The offshore wave conditions were described by the SWAN model, and the nearshore wave using the COULWAVE model. DEMs show significant variations on beach width and berm elevation, and intertidal bar migration. The seasonal variation of the beach width (from the 2 m contour line above the MSL to the dune baseline) is significant (88 to 66 m) indicating a subaerial beach retreat of 13 m. The berm height elevation ranges between 3.3 and 2.5 m. The obtained results also show that beach sedimentary budget results from a close relationship between the volumes of sediment retained on the subaerial beach (mainly the width variations) and the morphology of the intertidal bar. The effect of intertidal bar morphology variations on the wave height for the field surveys of 6th April and 18th October 2008 was analysed. The obtained data set indicates that: 1) the intertidal bar migrated in the landward direction welding to the beachface lower limit by infilling a runnel of -0.61 m (minimum elevation); 2) the frontal berm increased the width and elevation in 8 m and 0.7 m, respectively; 3) the intertidal bar morphology with a trough on its landward side allows the dissipation of about 0.029 kJm^{-2}/m of the wave energy along the surf zone; and 4) the wave spectrum shows a frequency band between 0.03 and 0.35 Hz.

ADDITIONAL INDEX WORDS: *beach morphodynamics, DGPS, SWAN, COULWAVE, wave breaking, digital elevation model.*

INTRODUCTION

The intertidal zone of intermediate beaches is generally characterized by the presence of one or more intertidal bars (Wright *et al*., 1985). These intertidal bars are morphological features of the sub-tidal zone. Nearshore bars can present a cyclic movement in onshore and offshore direction (Larson and Kraus, 1994) according to annual wave energy incidence. The energy dissipation rate is a crucial term in the modeling of wave propagation across the surf zone (e.g. Huang *et al*., 2009; Aagaard *et al*., 2010). Between July 1998 and October 2001, the Amoreira beach, showed a significant retreat of the subaerial beach. During the same time, a persistent intertidal bar was characterized by significant variability in morphology and volume (Gama, 2005).

In this paper, the morphological variability of the subaerial Amoreira beach is documented over two years. The intertidal bar migration and welding to the lower beachface was also followed. The sediment volume in the subaerial beach and intertidal bar welding is analyzed and related to the intertidal bar effect on wave energy decay along the surf zone.

STUDY SITE

The Amoreira beach is an embayed beach located at the Southwest Portuguese Atlantic Coast. Is an intermediate beach approximately 450 m long, backed by a dune field and bounded in the south by the Aljezur rivulet mouth (Figure 1). The subaerial beach has a maximum elevation of 5 m, the berm elevation varies between 2.5 and 3.3 m, while the berm width reaches values between 65.3 and 88.8 m.

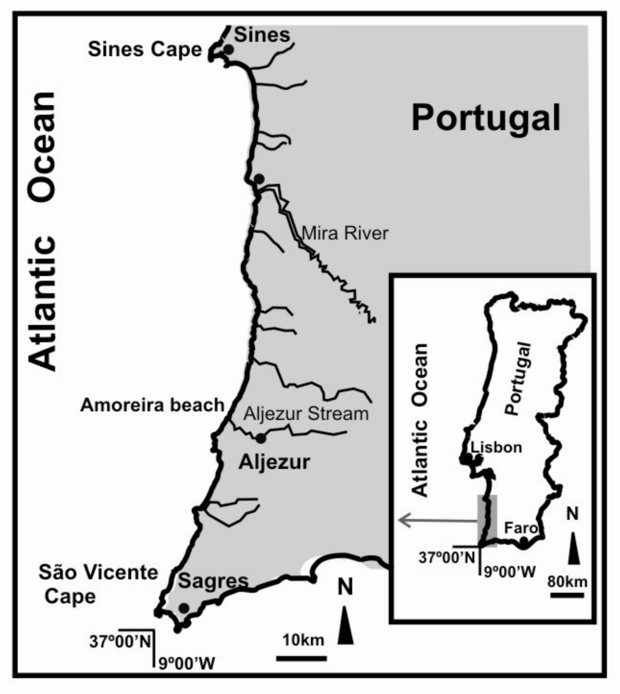

Figure 1. A - Location of the study area in the western Atlantic Coast of Portugal.(adapted from Reis and Gama, 2010).

The beachface slope (tanβ) varies between 0.02 and 0.11. The sediment size of the main beach sectors (berm, beachface and intertidal zone) corresponds to medium sand, varying between 0.26 and 0.31 mm. The calcium carbonate content in superficial sands is high (mean = 27%, Gama, 2005). The intertidal zone generally contains an intertidal bar with a maximum cross-shore width of 180 m, with a mean gentle slope that varies between 0.0073 and 0.019. The subaerial beach and low tide terrace morphologies, at the southern beach extreme, are affected by the Aljezur rivulet mouth particularly during the winter maximum fresh water flux.

METHODS

Detailed morphological data of Amoreira beach are presented between December 2006 and October of 2008 in a total of seven field surveys. The three-dimensional morphology of the subaerial beach, intertidal sector, and distal Amoreira rivulet margins, was obtained by collecting dense beach position measurements by DGPS (Differential Global Positioning System) by a multi-antenna system mounted in a four wheel quad motorcycle (Baptista *et al.*, 2008).

The 2 m (MSL) contours for each field survey were extracted from the DGPS survey grids. The beach width was defined as the horizontal distance between the 2 m contour and the dune baseline limit (Figure 2). The Digital Shoreline Analysis System (DSAS, Thieler *et al.*, 2005) was used to calculate the beach width between 2 m contour and the fixed dune baseline limit at 9 cross-shore profiles spaced at 50 m along the beach.

At the 6th April and 18th October of 2008 surveys the intertidal bar morphology was quite distinct, the reason why the sector of 40 x 125 m (Figure 2) was studied in detail. During this 6 month time period an intertidal bar migrated landward and welded to the beachface lower limit.

In order to understand the behavior of the waves parameters along the intertidal bar, the wave field in the study area was calculated with the spectral wave propagation SWAN (Simulating WAves Nearshore), Booij *et al.*, 1999, model coupled to the MesoNH (Mesoscale NonHydrostatic), Laford *et al.*,(1998), model, from 6th to 8th April and from 16th to 18th October, 2008. The use of the wave buoy measurements obtained at Sines (70 km far from this site) and the MesoNH wind field for the SWAN simulations and the tide levels calculated by Antunes (2007), permit to obtain the wave characteristics at the outer surf zone (approximately -7.7 m ZH, i.e., 2 m below the Mean Sea Level). Then, those wave parameters were used into the nonlinear wave Boussinesq–type propagation wave model COULWAVE (Cornell University Long and Intermediate Wave Modeling Package, Lynet and Liu, 2004), in order to describe the wave transformation between the outer surf zone and the swash zone as well as the energy wave dissipation along the intertidal bar.

For SWAN model, the bathymetry field used was obtained by a coupling three bathymetry sources: a) The Portuguese Hydrographic Institute chart no. 6, scale 1/150 000, April de 1979, Portuguese Coast, from Cabo de Sines to Cabo de São Vicente; b) the bathymetry survey from the BayBeach Project (PTDC/CTE-GEX/66893/2006); c) Bathymetry surveys May of 2009 and September of 2009, for the depth below 0.5 m ZH. For the COULWAVE model, along the shallow water region it was used the bathymetric profiles extracted from DGPS grid, for each survey.

The superficial beach sediments were collected at the berm, beachface and intertidal berm. The textural parameters were obtained by the logarithmic graphical method applying the software GRADISTAT® package (Blott and Pye, 2001).

RESULTS

Morphological and volumetric changes

The digital elevation model (DEM) described in detail the seasonal evolution of the subaerial beach and intertidal bar morphology. The subaerial beach width showed a decrease in width during the study period varying between a mean value of 88 m in 5th December 2006 and 75 m in 18th October 2008. The 2 m elevation used to describe the shoreline has a convex tendency. During the study period the beach width decreased and the beach configuration became more concave. Although the alongshore beach configuration changes, the frontal berm elevation varies slightly, between 2.5 and 3.3 m.

Volumetric changes were evaluated considering 10 elevation classes with 0.5 m amplitude (Table 1), and above the 0 m MSL, to guarantee the comparison between field grids with equal surveyed area. The results pointed to a decrease in the subaerial beach budget between 5th December 2006 and 18th October 2008. The analysis of the volumetric pattern between consecutive surveys and adjacent elevation classes, points to a maximum retention of sediment at the 0.5 to 1 m elevation class. The maximum sedimentary exchange occurs during the intertidal bar welding or after the beach width retreat (e.g. storm incidence), in particular between 0.5 to 1m and 2 to 2.5 m classes. After a storm period or during a retreat period the sediment volume decrease between 3.5 to 2 m increasing at the lower beach face, 0.5 to 1 m. Although after a storm period (17th January 2008) a sediment volume increase, at the berm (3.5 to 4.5 m), was recorded. When the berm width decreases the 1 to 1.5 m class is reinforced with the decrease of the 2 to 3 m or /and 3.4 to 4 m classes.

Table 1: Subaerial beach characteristics.

Date	Beach width (m)	Berm elevation (m)	Volume above 0.5m (MSL) (m^3)
5th December 06	88	3.32	1.17 x10^5
3rd Mars 07	84	2.80	1.19 x10^5
13th July 07	83	2.46	1.09 x10^5
14th October 07	81	3.15	1.04 x10^5
26th January 07	76	2.76	9.91 x10^4
6th April 08	66	2.56	8.81 x10^4
18th October 08	75	2.60	9.39 x10^4

Between 6th April and 18th October 2008 intertidal bar welded to the beach, infilling the trough. The data points to a positive correlation between the increase of the berm width extension (8 m) and the frontal berm elevation (2.0 to 2.7 m). A maximum sediment volume was also recorded between the -0.5 to 0 m and the 0 to 0.5 m elevation classes, with an increase of 5.1 and 3.3% respectively.

In the Aljezur rivulet mouth vicinity the morphological variation (beach width and frontal berm elevation) and volumetric changes are more pronounced. The maximum sediment volume occurs at 0.5 to 1.0 m elevation that contains 36.3 to 51.3 % of the total volume.

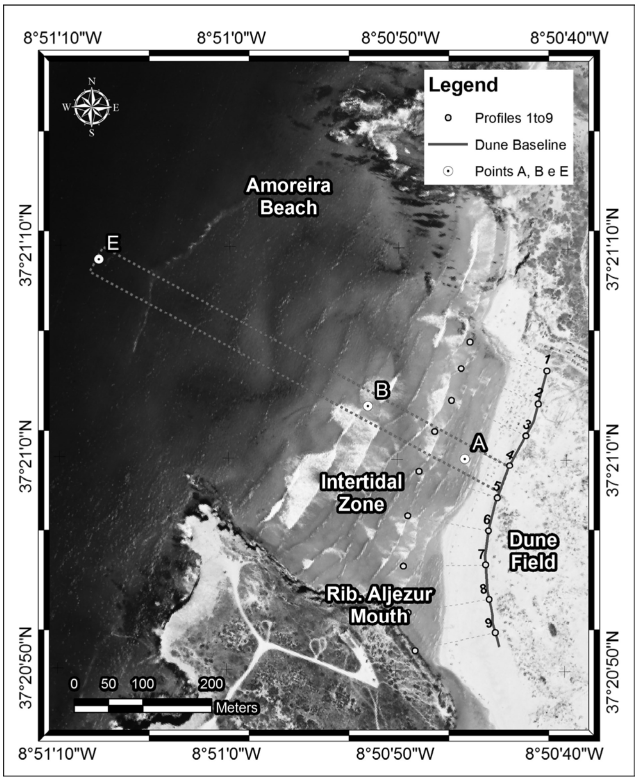

Figure 2. Amoreira beach. Cross-shore profile used in the COULWAVE simulation (A to E). Cross-shore profiles used by DSAS (1 to 9).

Table 2: COULWAVE results over a distinct intertidal bar morphology (profile A to E). tan β-beachface slope ; tan β_{intb}- seaward intertidal bar slope; H_b- breaking height; d_b – breaking depth; ξ- Iribarren number; Mz- mean grain size at intertidal bar. (1)- First breaking line; (2)- Second breaking line.

Parameters	6th April 2008	18th October 2008
tan β	0.075	0.11
tan β_{intb}	0.019	0.014
H_b (m)	1.91(1) 1.02(2)	2.0
d_b (m,ZH)	-1.23(1) +1.61(2)	1.2
Wave energy dissipation rate (kJm^{-2}/m)	0.039 (1) 0.029 (2)	0.0436
Spectrum Frequency (Hz)	0.03<f<0.35	0.03<f<0.35
ξ	0.16	0.15
Mz (mm)	0.27	0.31

Nearshore wave conditions

To assess the intertidal bar welding between 6th April and 18th October 2008 a detailed analysis of the wave characteristics was performed for the 4 days that precede each field survey, 4th to 6th April and 16th to 18th October 2008, respectively. Between these two dates the intertidal bar's seaward slope changed from 0.019 to 0.014. In the landward direction the trough was infilled by 0.95 m of sand.

For the period between 4th to 6th April, the average offshore wave characteristics were: significant wave height 0.88 m, peak wave period of 10 s and wave direction around W. For the period 16th to 18th October 2008, the offshore wave characteristics were: significant wave height 0.95 m, peak wave period of 10.0 s and wave direction 318º.

In order to analyze and compare the nearshore wave conditions and the wave energy dissipation in those two periods (April and October), offshore wave conditions were chosen that led to the same wave condition at point E (the boundary condition of COULWAVE wave model). In this way, the differences in wave propagation and dissipation due to the bottom profile between point B and A could be assessed. Offshore conditions were those corresponding to the 6th April at 0:30 h and 18th October at 15:00 h. These led at point E to wave heights of 0.77 m and 0.73 m, for 6th April and 18th October, respectively. The peak wave period, wave direction and the tide level in both cases is 10.1 s, 310º and 2.3 m.

For 6th April, the significant wave height increases as the wave propagates to shallow waters and breaks over the intertidal bar. Then, there is a decrease in wave height, followed by a slight reformation of the wave on the trough (there is almost a stabilization of the wave height) and finally a second wave breaking in the very shallow water region.

The first breaking occurs at a water depth of ~1..23 m (ZH); the wave height at breaking reaches up to 1.9 m (Figure 2, B point) at the beginning of the intertidal bar; after that, spilling wave breaking occurs and the wave energy dissipation rate is about 0.039 kJm^{-2}/m until the wave height stabilizes at the trough. Then, for water depth of ~1.6 m (ZH) a second spilling wave breaking occurs and the wave energy dissipation rate is about 0.029 kJm^{-2}/m. At the beachface the wave height reaches 1.0 m.

For 18th October, the significant wave height increases as the wave propagates to shallow waters and breaks over the intertidal

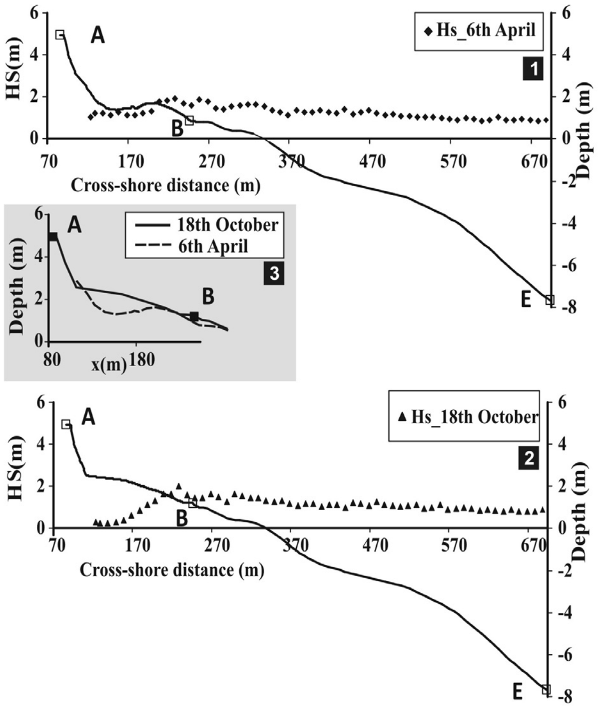

Figure 3. COULWAVE results of significant wave height across the intertidal bar morphology. 1- 6th April 2008 (Hs-0.77 m; Tp-10.1 s; TL-tide level-2.3 m), 2- 18th October 2008 (Hs-0.73 m; Tp-10.1 s; TL-tide level-2.3 m) and 3- Intertidal bar morphology.

bar. Then, there is a significant decrease of the wave height which occurs along the entire intertidal bar. Initial calculations showed that for those conditions there is only one break, which occurs at a water depth of ~1.2 m (ZH). The wave height at breaking reaches up to 2.0 m (Figure 2, B point) at the beginning of the intertidal bar after which spilling wave breaking occurs and the wave energy dissipation rate is about 0.0436 kJm^{-2}/m along the remaining intertidal bar. At the beachface the wave height reaches 0.2 m.

So, from above and considering the intertidal bar morphology (in particular de seaward slope) it was possible to evaluate the initial wave breaking point or the region of the evolving wave breaking and the wave energy dissipation along the surf zone, for medium tide conditions. For both periods, the wave starts to break at the same point (143 m from A) with almost the same wave height 1.9~2.0 m. Then for April, there is another wave breaking line at 52 m from A (with 1.0m) while for October no other wave breaking line occurs.

Considering the energy offshore (or in point E) it was possible to evaluate the energy dissipation when the waves reach the surf zone of the Amoreira beach. The total energy dissipation rate between the outer surf zone (point B) and the inner surf zone (point A) was also assessed. The distance between point B and A defines the region of the evolving wave breaking, in both periods. The results of the COULWAVE model as well as the Iribarren number (Table 2) points to the predominance of spilling waves, in high and low tide conditions, i.e. values below 0.4.

The spectral analysis also points to the importance of the nonlinear phenomena present in the wave propagation. For 6th April and 18th October, from point E to point B, the energy spectrum contains three main peak frequencies: 0.09, 0.18 and 0.28 Hz. There is clear transfer of the energy from the peak period at point E to its harmonics in point B. From point B to the beachface, wave breaking occurs, and the spectrum is characterized by a more distributed energy in the frequency band of 0.03Hz<f<0.35Hz, with less energy as expected. The main difference between April and October spectra at the beachface is the magnitude. April waves had higher energy than October.

DISCUSSION

The analysis of seven DGPS interannual field surveys at the Amoreira beach allowed the characterization of the main variations of the subaerial beach width and intertidal bar evolution. The obtained results points to a decrease in beach width, and intertidal bar migration cycle, reinforcing the results obtained by Gama (2005) for the period between July 1998 and July 2001. The subaerial beach width decrease can be significant in a 3 months period, with slight variation in berm elevation. The reduction in subaerial beach width and berm height decrease occurs after storm periods with sediment transport to the low tide terrace. The post-storm recovery period is slow and dependent on the intertidal bar morphology.

The influence of the intertidal berm morphology was studied in detail by modeling the incident waves over the intertidal bar morphology at 6th April and 18th October 2008 field surveys. The interdital bar morphologhy at 6th April 2008 (tan β_{intb}-0.019) with a well defined trough and spaced out by the beachface (lower limit), allows the dissipation of about 0.0259 kJm^{-2}/m of the wave energy along the surf zone. For the 18th October 2008 situation, characterized by an intertidal bar welded to the beachface (tan β_{intb}-0.014), the wave energy dissipation is higher (0.0436 kJm^{-2}/m).

The wave dissipation energy across the extensive surf zone of intermediate beaches is well known (Short, 1999), where the waves reform in the trough to break in the inner bar. The spectrum is characterized by a more distributed energy in the frequency band of 0.03Hz<f<0.35Hz.

COULWAVE is a depth integrated model, and so its application to very shallow waters should be made with caution, especially in regions where wave breaking occurs. Moreover, the numerical simulations considered a regular wave as offshore boundary condition, which does not fully represent field conditions.

Also, the COULWAVE analysis of the wave breaking region and the wave energy dissipation was made considering the same wave breaking parameters for the entire conditions observed from April to October 2008, which can be considered as a first approximation. So, a sensibility study of the wave breaking parameters of the model should be performed since different wave breaking characteristics from spilling waves can occur in the whole period (Okamoto *et al*., 2009).

CONCLUSION

The digital elevation model (DEM) described in detail the seasonal evolution of the Amoreira subaerial and intertidal beach morphology. The morphological and volumetric changes point to a variation of the alongshore beach configuration, characterized by a predominant convex planform and more variability at the Aljezur rivulet mouth. The mean berm elevation varies only slightly, between 2.5 and 3.3 m.

The intertidal morphology, characterized by a trough (6th April 2008) defines two wave breaking lines. The first one 143 m from the beachface ($H_b \approx 1.9$ m) and the second one near the beachface (52 m) with $H_b \approx 1.0$ m. So the intertidal bar morphology tends to decrease the wave breaking height and to increase the wave energy dissipation rate (0.039 kJm^{-2}/m, along the ~90 m of the surf zone extension). According to the field data of 18th October field survey the wave characteristics, allowed subaerial beach recovery, increasing the beach width by 8 m and frontal berm elevation by 0.7 m. The importance of sediment retention in the intertidal zone as well as the intertidal bar morphology in the surf zone energy dissipation is revealed. This pattern prevents medium-term beach indentation and dune erosion.

The intertidal zone and probably the Aljezur rivulet distal sector, work as sediment sources to the subaerial beach. Regarding the volumetric changes the Amoreira beach works as a semi-enclosed cell being, this conclusion also supported by the small variability of the beach textural sediment parameters.

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