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Short-Term Morphodynamics of Intertidal Bars The Case of Areão Beach (Aveiro, Northwest Portugal)

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ABSTRACT

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Intertidal bar morphodynamics were examined at Areão Beach, a mesotidal beach located in the highly energetic Northwest coast of Portugal. A field experiment was carried out in 2002 from February 5 to March 16. During this period topographic surveys were done every three days. Offshore wave data and tidal records were used to evaluate the successive morphological changes. Morphodynamics of the two intertidal bars recorded were characterized by a landward migration over a flattened profile after a previous storm event. Differences in the dimensions of the bars were related to the smaller transported volumes as the storage of sediment at lower foreshore decreased with each bar formation and migration. Intertidal bars presented the following behaviour: formation under low energy wave conditions and significant tidal ranges; stabilisation during neap tides and migration, by successive erosion/accretion series, under greater tidal ranges, while wave climate conditions experienced a progressive increasing; and welding to the beach forming a berm. Boundary conditions coupled to the significant wave height offshore were used to classify each phase of bar evolution: formation phase (1-1.5 m), evolution phase (lower than 2.5-3 m) and decay phase (>3 m). These considerations were limited to beaches in the area that present well-developed longshore bars.

ADDITIONAL INDEX WORDS: *Intertidal bars, morphological changes,hydrodynamic boundary conditions.*

INTRODUCTION

Intertidal bars are non-permanent features commonly observed at sandy coasts, mainly as a recovery response of beaches to previous storm conditions (SHORT, 1979; WRIGHT and SHORT, 1984). Low energy conditions following a storm promote the generation of intertidal bars in the lower foreshore with the sediment deposited in that area during the storm.

Several authors proposed different mechanisms of intertidal bars generation: KING and WILLIAMS (1949) proposed that ridges are formed by swash processes acting at stationary water levels, (later studies proved that swash action alone cannot generate intertidal bars); GREENWOOD and DAVIDSON-ARNOTT (1979) pointed out that formation of intertidal bars is a result of surf-swash action in the lower foreshore; KROON (1994) suggested a ridge generation due to the asymmetry between swash-backswash processes in combination with the more stationary water levels; MASSELINK and ANTHONY (2001) suggested that the bars are generated and maintained as the result of a combination of swash and surf zone processes acting across the whole intertidal zone. This hypothesis was also supported by KROON and MASSELINK (2002) for onshore bar migration.

Evolution of intertidal bars occurs if wave energy remains low to moderate after bar generation, with greater onshore migration relating to larger tidal ranges (KROON, 1994). At high water levels swash action can overtop the ridge inducing its migration. As tidal range decreases, from spring to neap tides, this overtopping by the swash ceases and the bar stabilizes. At the same time an increasing in ridge height is observed, due to swash and backswash processes acting at the seaward slope of the bar.

Intertidal bars can eventually weld to the upper beach, resulting in an increase of the berm width, if the wave energy conditions remain calm. If not, the sediment is eroded and transported offshore during storms.

CARTER (1991) described two models of intertidal bar migration, since its formation to the final welding at the upper beach: (a) at low energy mesotidal environments bars migrates as a coherent bar while, (b) under high energy conditions sediment is transported from the lower foreshore to the upper beach grain by grain. This author also observed both models existing under the same wave energy conditions.

GREENWOOD and DAVIDSON-ARNOTT (1979) and more recently WIJNBERG and KROON (2002) proposed a classification for nearshore and intertidal bars, based on location and wave and tide conditions.

Since the first studies on intertidal bars (KING and WILLIAMS, 1949; DAVIES *et al*., 1972; OWENS and FROBEL, 1977) there is a great controversy in intertidal bar morphodynamics and nomenclature, usually using terms as ridge and runnel and swash bars with different interpretations (WIJNBERG and KROON, 2002).

Intertidal bars reported in this paper are single bars developed on a mesotidal beach. They show a large migration rate from the low-tide line to the high-tide line under low to moderate wave conditions. They belong to Group II bars defined by GREENWOOD and DAVIDSON-ARNOTT (1979) and slip-face ridges of WIJNBERG and KROON (2002) classification. Their morphodynamics also correspond with the intertidal bars named as swash bars by CARTER (1991), ANFUSO *et al*. (2003) and GREENWOOD *et al*. (2003) and the bar type occurring in the Ridge and Runnel/Low Tide Terrace beach state defined by WRIGHT and SHORT (1984).

The objective of this paper is to describe intertidal bar morphodynamics observed at Areão Beach (Northwest Portugal). A monitoring program is being carried out at this beach under the project CROP (Cross-shore Processes on Contrasting Environments), which is focused on beach morphodynamics for different time scales: short-term surveys over several weeks, monthly monitoring and sporadic observations after storm events. This paper deals with short-term intertidal bar evolution over a month during moderate wave conditions.

FIELD SITE

Areão Beach is located in the Aveiro littoral on the Northwest

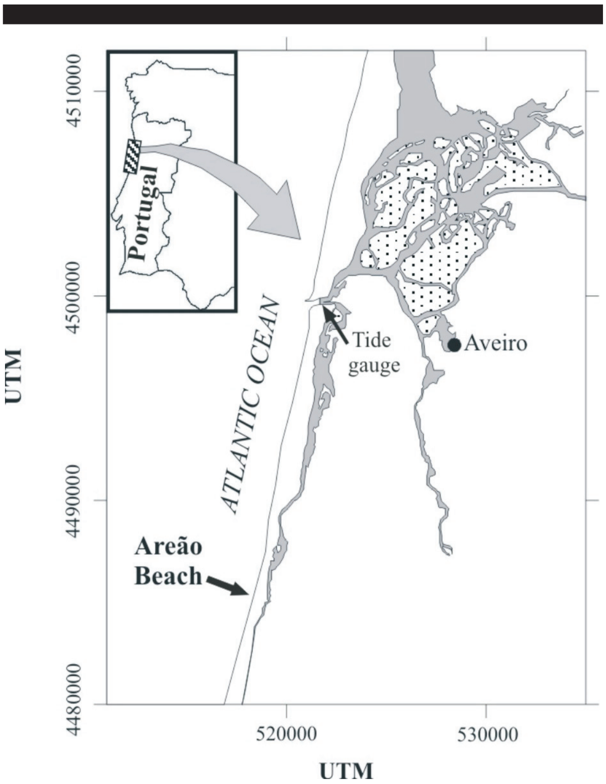

Figure 1. Location of the field experiment site. Location of the tide gauge at the artificial tidal inlet is also indicated.

coast of Portugal (Figure 1). This coastal stretch is morphologically characterized by a sandy barrier, which has been subjected to critical coastal erosion for the last decades (REY and BERNARDES, 2003).

This coast is also characterized by high-energy wave conditions. Significant waves are moderate during summer (offshore significant wave heights of 1 to 3 m; wave periods of 11 to 13 s) and large during storms (H_s often exceeds 7 m; T_s=13 s; data from COSTA, 1994). The mean wave direction is from NW (93 % of the wave direction during 2002 was between WNW-NNW) and induces an important littoral drift from north to south with an associated net transport of about 10^6 m^3/year (TABORDA, 1993). The semidiurnal mesotidal regime in the region presents a maximum tidal range of 3.2 m and a minimum tidal range of 0.9 m (predicted tidal ranges by Instituto Hidrográfico, 2002). Extreme water level fluctuations induced by storm surges usually exceed 40 cm (GAMA *et al*., 1994).

Areão Beach is backed by a dune system. This dune area is very vulnerable to coastal erosion and shows large escarpments during storm events. The nearshore exhibits a permanent longshore bar, located at 300 m offshore at a water depth of 4.5 m (REY and BERNARDES, 2002). Waves break across the longshore bar and reform in the shoreward located trough prior to successive breaking and dissipation on the beachface (CARTER and BALSILLIE, 1983; FERREIRA *et al*., 1994; AAGAARD *et al*., 1998).

The beach shows a pronounced seasonal behaviour with a wide range of morphodynamical states. This large variation in shapes reveals an important exchange of sediment between the upper and lower foreshores. During low energy conditions the beach presents a wide berm, characteristic of its reflective state, due to the onshore migration of successive intertidal bars. Under larger wave energies these features disappear, the beach flattens and a dissipative profile is developed (REY and BERNARDES, 2002). Despite this cross-shore transport, there is a significant longshore motion of sediment southwards due to the significant littoral drift.

This paper is concerned with the cross-shore movement of two subsequently developed intertidal bars migrating onshore in a post-storm recovery stage of the beach.

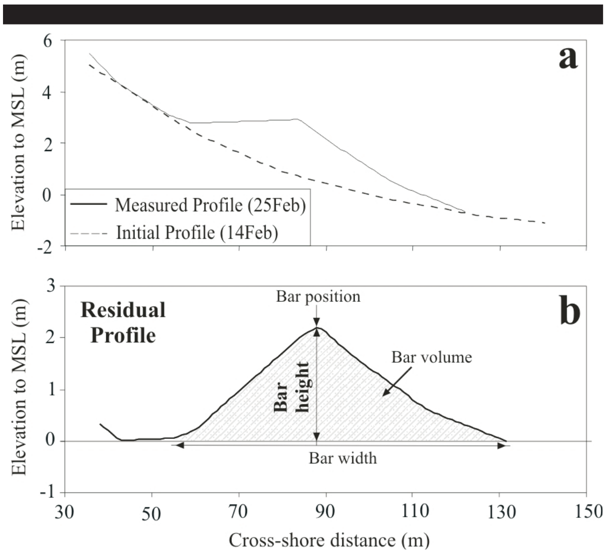

Figure 2. Calculation of intertidal bar morphometry. (a) Example of measured (February 25) and initial (February 14) cross-shore profiles. (b) Definition sketch of morphometric variables.

METHODS

Fieldwork was carried out from 5th February to 16th March 2002, in order to obtain detailed information on the beach morphology. Fourteen surveys were made with an interval of three days. Beach topography was monitored at low tide with the use of an electronic total station along six profiles with a longshore spacing of 20 m. Since the aim of this work is to evaluate just cross-shore evolution of intertidal bars, only the central profile of the study area was used for calculations.

The evolution of two intertidal bars, from their formation to their welding to the berm, was observed during the present field experiment. Bars were denominated as bar I and bar II, for the first and the second intertidal bar observed, respectively.

The intertidal profile data was used to quantify bed elevation changes between consecutive surveys. Net sediment fluxes, in m^3m^{-1}, were recorded to estimate the sediment volumes gained or lost along the profile over six tidal cycles between the surveys.

Morphometric variables of the intertidal bars were obtained by comparing the measured profiles to their initial profile surveyed just before the formation of the two bars (Figure 2a). Bar variables, i.e. height, position of bar crest and bar width, were assessed from the residual profile obtained (residual profile = measured profile initial profile). Quantification of bar volumes was also estimated with the use of the residual profiles (Figure 2b).

Hydrodynamic data consists of wave variables (significant wave height H_s and period T_s) from an offshore wave buoy located 80 Km northwards of the study site at a position of 41º19'00"N8º59'00"W and at a water depth of 83 m. Water levels presented in this paper are measured tides from the Aveiro tide gauge located at the Aveiro artificial tidal inlet (Figure 1), at a position of 40º38'30"N8º44'54"W.

RESULTS

Morphological Changes

The beach presented a dissipative state that resulted from some storm events (H_s5 m; T_s9 s) prior to the studied period. In the post-storm recovery period of the beach, a bar (bar I) was formed in the lower tide beach and migrated onshore until it welded with the upper part of the beach and created a berm (February 16-28, see Figure 3a). As this first intertidal bar merged to the berm, another bar (bar II), with smaller dimensions, was developed and also migrated shoreward

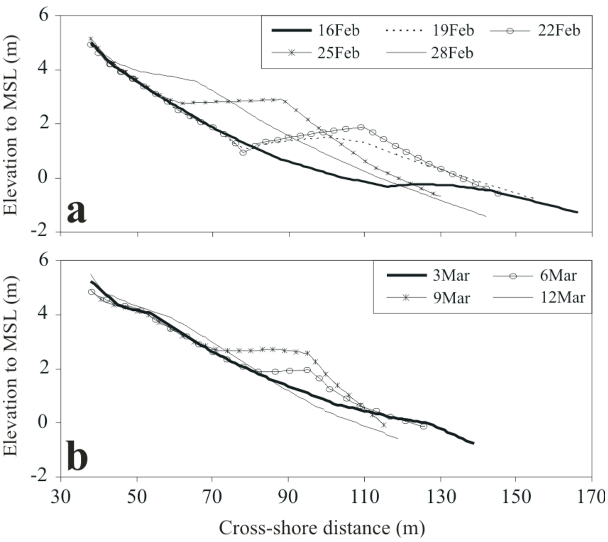

Figure 3. Morphological evolution of the intertidal bars observed. (a) Evolution of bar I. (b) Evolution of bar II.

(March 3-12, see Figure 3b). The net result of these successive bars migrating to the beach was a widening of the berm, characteristic of the reflective profile obtained.

Bed elevation changes between consecutive surveys showed a progressive displacement of the intertidal bar to the land. However, some of the cross-shore profiles were too short and calculations of morphological changes did not include the bar feature when it was in the initial stage of formation.

Morphological changes were generally not significant (0.2 m) before the generation of bar I (February 5-14). The bed elevation changes related to the incipient bar on February 16 were not detected because some of the profiles were too short. More pronounced changes were observed during the onshore bar migration (February 19-25), when the ridge reached its maximum development with a height of 2 m (Figure 4a). Important erosion was observed in the lower part of the profile (1 m) when the bar welded to the berm on February 28. This was just before the next bar started to develop.

The bar displacement in a landward direction presented a general trend of erosion in the seaward slope of the bar and accumulation to the landward slip-face due to a transference of sediment in onshore direction. This trend was only broken on February 22, when the bar remained in the same location and showed a net gain of sediment on the seaward slope. The displacement of bar I was presented by the evolution in time of the point of maximum accretion along the profile (arrows in Figure 4a).

Development of bar II showed a similar behaviour (Figure 4b). As the bar migrated landward (March 3-12) the seaward slope presented a progressive loss of sediment that was transported to the upper foreshore. This migration was also indicated by the arrows in Figure 4b. The largest sediment accumulation along the profile was again observed during maximum development of the ridge (with an associated morphological change of 1 m). However, the most significant bed elevation changes were detected later on March 12 (2 m), long after the bar welded to the berm. These changes were due to erosion of the lower part of the profile. The erosive trend continued on March 16 since no more bars were formed at the low tide line.

The differences between the intertidal bars were related to the magnitude of morphological changes. Accretional changes associated with migration of bar II were minor to those of bar I. This was in line with the smaller dimensions of bar II.

The greater erosional changes, associated to a lost of sediment in the lower part of the profile, were on both cases related to the subsequent phase of bar welding to the berm. Significant differences were also observed. The lost of sediment was larger after welding of bar II.

Volumetric Changes

Profile volumes recorded during this study reflected the variations observed in the morphological changes (Figure 4c).

From February 5 to 14 volume variations were fairly constant (10 m^3m^{-1}). The initial development of bar I was not recorded. After that, significant changes in volume variations were observed on February 19 (30.6 m^3m^{-1}) when the bar began to grow and migrated to the upper beach. On February 22 the beach continued to gain sediment, but the rate had decreased to a third of the one in the previous survey. Another important increase of volume was attained on February 25, during the maximum development of the ridge. A total accumulation of 95 m^3m^{-1} occurred. When the bar finally merged to the berm on February 28 a great loss of sediment was recorded (-11.5 m^3m^{-1}) due to erosion in the lower part of the profile.

Migration of bar II also implied a net accumulation of sediment until it reached its maximum development on February 9 (a total accumulation of 100 m^3m^{-1}). After the bar merged to the berm on March 12, an important loss of sediment was observed (-41 m^3m^{-1}). After that, the beach volume continued to decrease until the end of this study.

Differences in the behaviour of both bars were related to their dimensions, as happened with the bed elevation changes. Accumulation rates associated with bar I were larger (31 m^3m^{-1}) than that ones observed for bar II (18 m^3m^{-1}). The quantity of sediment eroded after the bar welded to the berm was smaller for bar I (-11 m^3m^{-1}) than for bar II (-41 m^3m^{-1}).

Intertidal Bar Morphometry

Intertidal bar morphometric variables were presented in Table 1. Bar height, bar crest position related to cross-shore distance, bar width and bar volume were computed for each stage of the bar.

Both bars presented the same behaviour. The height of the bars increased during their onshore movement from the lower foreshore to the upper beach. Bar I varied it height from 0.55 to 2.2 m as it moved onshore and bar II attained heights from 0.27 to 1.47 m during its landward displacement, before welding to the berm.

Migration of both bars occurred from the lower part of the profile, at a cross-shore distance of about 125 m, to the upper beach, at a cross-shore distance of about 60 m. The associated net migration rates were 4.75 and 7.55 m per day, respectively.

The larger size of bar I was evident. Its maximum width of 90 m (February 19) was far beyond the maximum width of 45 m of bar II (March 9).

Significant differences on morphometric variables were related to the different volumes of sediment transported by the intertidal bars. Maximum sediment volumes transported were 79 m^3m^{-1} for bar I and 35.5 m^3m^{-1} for bar II.

Hydrodynamic Conditions

The hydrodynamics consisted of offshore wave conditions represented by significant wave height and wave period, and measured tidal records (Figure 5).

The significant offshore wave height (Figure 5a) in this high-energetic area was scarcely under 2 m during the field experiment. Storm waves were recorded at the beginning of the study (H_s5 m). The wave height decreased during the following days, until it reached a minimum on February 17 (H_s1.3 m). After that, an increase was observed until February 28, when it reached moderate values (H_s3.51 m). Similar patterns of wave height reductions followed by increases were observed between March 4 and 13, with wave heights of 1 and 3.4 m, respectively.

The wave periods (Figure 5b) attained maximum values coincident with larger wave heights (T_s9.5 s). Minimum values were about 6.5 s. Most of the time, the waves came from westnorthwestern directions. Directions only varied slightly between March 7-13, when waves came from the northwest.

The field experiment was conducted along several spring and

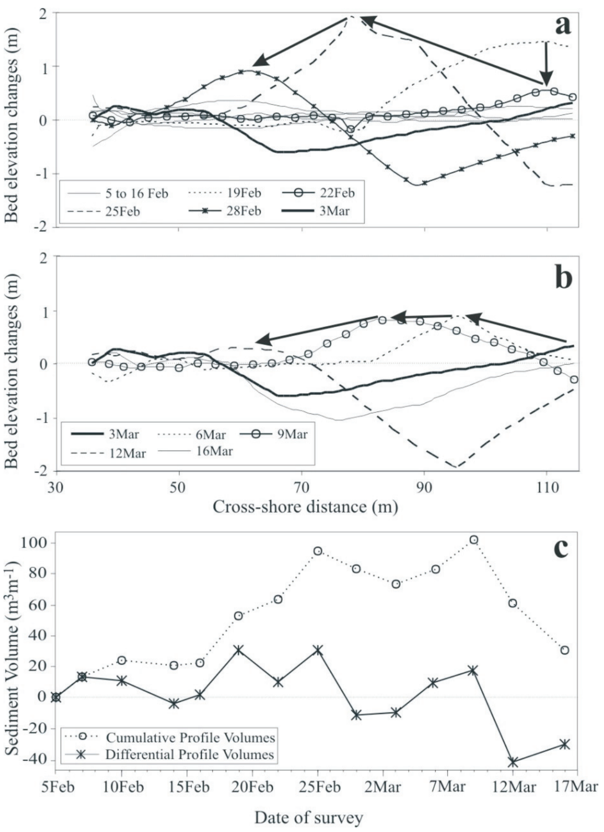

Figure 4. Bed elevation and volumetric changes between consecutive surveys. (a) Morphological changes from February 5 to March 3. (b) Morphological changes during March 3-12. Arrows indicate the displacement of the maximum accretion point along the profile. (c) Cumulative and differential profile volumes.

neap tides (Figure 5c). Maximum spring tidal ranges were recorded on the beginning of March (3.25 m) and minimum neap tidal ranges (1.04 m) during the previous neap tide at the end of February.

DISCUSSION

Morphodynamics of bars was inferred from the topographic profiles obtained. Initial formation of intertidal bars reported in this work was related to a post-storm recovery period in Areão Beach. Sediment started to be transferred from offshore to the upper beach when the wave conditions became less energetic. This transport of sediment was done by intertidal bar migration onshore, and resulted in a variation of the beach state from dissipative to reflective.

Morphological changes observed between consecutive surveys showed a general behaviour of erosion in the lower part of the profile and accretion in the upper foreshore as the bar migrated onshore. Sediment was transferred from the seaward slope of the bar to the slip face of the bar. This is obvious from the temporal and spatial displacement of the maximum accretion point in onshore direction (Figure 4a). Finally, the bar welded to the upper part of the profile and formed an incipient berm. The cycle started again due to migration of another bar (Figure 4b). This was observed only because the hydrodynamic conditions remained moderate. These series of erosion/accretion processes along the profile characterize the morphodynamics of intertidal bars (KROON and MASSELINK, 2002; GREENWOOD *et al*., 2003).

The landward transport of sediment increased with time until it reached a maximum during the maximum development stage of the bars. This situation occurred just before the bars merged to the berm (February 25 and March 9). At this stage of development, the intertidal bars attained their maximum values of morphometric variables (height and width). In the final phase of evolution, when the bars merged to the beach, volumes and morphometric variables decreased significantly.

A discrepancy in the general intertidal bar behaviour was observed on February 22. A slight gain of sediment was recorded at the seaward slope of the bar, instead of the expected erosion. Bed elevation changes were just significant at this point, indicating a stabilisation of the bar. KROON (1994) related this phase of intertidal bar behaviour to the minimum water levels attained during neap tides, because intertidal processes did not overtop the ridge and were only acting at the seaward slope, which resulted in an increase in height. This assumption explained the observed behaviour of the bar under study. Minimum tidal range was just recorded on February 22 (1.04 m). As a result, bar I stabilized and increased its height. Similar behaviour was observed for bar II as it evolution coincided with neap tides on March 9, although the stabilisation was less significant.

Differences on morphodynamics of the two bars can be explained by incorporating the bar dimensions. Volumes of sediment transported by bar II were smaller and, consequently, also the morphometric variables. The larger migration rates associated with bar II were clearly related to the smaller volume of transported sediment. But, why did the volume decrease if the wave climate conditions remained the same as both bars evolved? WOLF (1998) related the larger offshore migration of inner bars during consecutive storms to the fact that the quantities of transported sediment decreased with each storm. The same assumption might be considered in the opposite direction, since the storage of sediment in the lower foreshore decreased with each bar formation and migration.

After the bar welded to the beach, erosion recorded was larger in the case of bar II. The hydrodynamics conditions continued to increase and no more sediment was transferred from the low-tide line to the beach by means of bar migration. This increased the erosive tendency of the profile.

The prevailing hydrodynamics were closely coupled to morphodynamics. Intertidal bar generation was optimal after the post-storm recovery period at the start of the field experiments. The significant wave height decreased and the bar migrated onshore even during a slight increase in wave energy. The formation of bar II was supported by the following period characterized by a decrease in wave energy.

As a major goal to describe boundary conditions required for intertidal bar development, at the highly energetic Northwest coast of Portugal, the following considerations are proposed:

a) intertidal bar formation occurs after storm events (H_s>5 m) when significant wave height attains 1-1.5 m;

b) bar growth and migration continues, with no erosion or flattening of the ridges, while significant waves remain up to 2.5-3 m;

c) intertidal bar decay, although not observed during this field experiment, will only occur when the significant wave heights exceed 3 m.

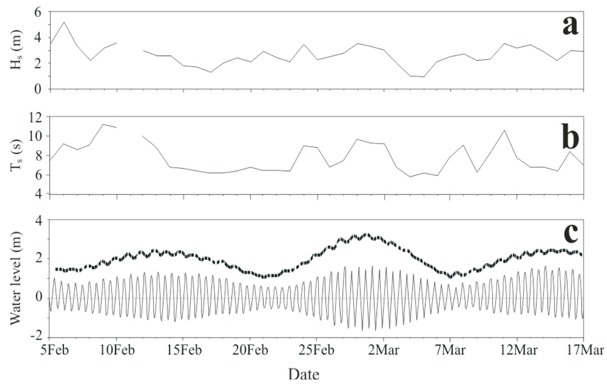

Figure 5. Hydrodynamic conditions during the experiment. (a) Offshore significant wave height. (b) Offshore wave period. (c) Measured tides and tidal range (thick line).

Table 1. *Morphometric variables of intertidal bars at Areão Beach.*

Variable	Evolution of bar I					Evolution of bar II			
	16/Feb	19/Feb	22/Feb	25/Feb	28/Feb	3/March	6/March	9/March	12/March
Bar height (m)	0.55	1.47	2.03	2.20	1.44	0.27	0.87	1.47	0.37
Bar crest position (m)	123	100	109	88	66	127	95	88	59
Bar width (m)	56	90	74	75	82	34	43	45	34
Bar volume (m^3m^{-1})	19.27	74.81	79.05	76.32	25.91	4.39	14.31	33.5	7.9
Migration rates (m/day)	---	7.5	-3	7.1	7.6	---	10.2	2.2	10.7

Significant wave heights presented here are offshore values. Neither parameterization nor assessment of local wave heights was done in this study.

The nearshore morphology with the existence of a well developed longshore bar at the study site, which acts as a natural breakwater modifying offshore waves before reaching the beach face, do influence the boundary conditions for the intertidal bar evolution. No intertidal bar development occurred, during the same period, at northern areas of Areão Beach, where nearshore bars are smaller or even absent due to the presence of transversal coastal engineering structures. Thus, the wave boundary conditions as proposed for this Portuguese site can only be considered if a well-developed nearshore bar is present.

Variations in water levels were also closely related to intertidal bar morphodynamics. Both bars were generated and started to migrate at medium tidal ranges, as tide decreased from spring to neap, recording considerable migration rates (see Table 1: 7.5 m/day on February 16 and 10.2 m/day on March 3). As the bars grew and migrated onshore a stage of relative stabilisation was observed (February 22-3 m/day and March 92.2 m/day), when minimum tidal ranges were reached during neap tides. Onshore migration rates increased again as tides went from neap to spring. As pointed out before, this behaviour is in agreement with that reported by Kroon (1994) under similar conditions, i.e., mesotidal environments and intertidal bars with comparable morphometric variables, volumes and migration rates.

CONCLUSIONS

During the field experiment carried out at Areão Beach from 5th February to 16th March 2002, migration of two intertidal bars was observed.

Some general trends, characteristic of intertidal bars similar to those ones reported here, were founded. Morphodynamics of bars were mainly characterized by an onshore migration related to a post-storm recovery of the beach. This migration occurred under successive erosion/accretion series. A continuous transference of sediment from the seaward slope of the bar (under erosion) to the slip face (under accretion) was observed as bars moved landward.

Differences between the two bars observed were referred to bar dimensions. Since bar II presented smaller volumes its morphometric variables were also smaller and migration rates were larger. The decrease in volume between bars was associated with a decrease in the storage of sediment at the lower foreshore as continuous bars migrated onshore.

Different phases of development were related to the prevailing hydrodynamics. Formation of the first bar, at the low tide beach, occurred under low energy conditions and migration onshore was observed since the wave height remained moderate. After this first ridge welded to the beach, creating an incipient berm, another bar migration was observed as the wave height decreased again until attaining favorable conditions for bar generation. However, if the wave height continued to increase no development of bars were observed. It is quite probable that if the wave height had kept constant after bar formation, another ridge could be generated at the low tide mark and migrates onshore. Larger migration rates were attained at larger tidal ranges and minimum migration rates were observed during neap tides.

Relations between offshore wave height and morphodynamical response of the beach profile were done to try to establish an approach to the wave boundary conditions required, at the study site, for each phase of bar behaviour:

a) bar generation is related to wave heights of 1-1.5 m;
b) bar evolution continues as waves do not exceed 2.5-3 m;
c) bar decay occurs at wave heights larger than 3 m.

These considerations are defined for the highly hydrodynamic Northwest coast of Portugal at beaches with well-developed longshore bars.

Hydrodynamic measurements in the site of the experiment and daily or tidal morphological profiles should be collected to improve the knowledge of intertidal bar morphodynamics at Areão Beach.

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