EVALUATION OF SEDIMENTOLOGICAL AND MORPHOLOGICAL CHANGES INDUCED BY THE REHABILITATION OF SANDY BEACHES FROM THE RIA FORMOSA BARRIER ISLAND SYSTEM (SOUTH PORTUGAL)

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ABSTRACT
The Ria Formosa barrier island system is the most remarkable physiographic unit of the Algarve, south Portugal. This system composed of sand spits, beaches and dunes constitutes a Natural Park that has undergone artificial nourishment under the project “Rehabilitation of the lagoon system of Ria Formosa”. The main objective of this study is to evaluate the effects of a beach and dune rehabilitation program in particle size and morphology in two contrasting sites of the system (Ancão Peninsula and Tavira Island). A monitoring program was performed from June 1999 until September 2000, in order to determine the morphological and grain size changes along these beaches, before and after nourishment. The results of particle size analysis show the predominance of coarse sand at Ancão Peninsula and medium sands in Tavira Island. Nourished beaches presented coarser sands and bimodality, due to the heterogeneity of the dredged sediment used for nourishment. The nourished profiles, with increased sand stock, quickly developed natural profile morphology and proved to be able to decrease the effects of acting storms, namely avoiding dune erosion and overwashes. The soft interventions conducted at Ria Formosa proved to be useful on protecting the natural system, being a positive indication for future interventions at sensitive areas prone to marine erosion.

Key words: Sandy beaches, barrier islands, grain size, morphodynamic evolution, rehabilitation, Ria Formosa, Portugal.

RESUMEN
El sistema isla barrera de la Ría Formosa es la unidad fisiográfica más notable del Algarve, al sur de Portugal. Este sistema compuesto por pozos arenosos, playas y dunas constituye un Parque Natural que se ha alimentado artificialmente en el marco del proyecto “Rehabilitación del sistema lagunar de Ría Formosa.” El objetivo principal de este estudio es evaluar los efectos de un programa de rehabilitación de playas y dunas sobre la granulometría y la morfología en dos sitios contrastantes del sistema (Península Ancão y Tavira Island). Se llevó a cabo un programa de monitorización entre junio de 1999 y septiembre de 2000, con el fin de determinar los cambios en morfología y tamaño de grano a lo largo de estas playas, antes y después de la intervención. Los resultados del análisis de tamaño de partículas muestran el predominio de arena gruesa en la península Ancão y arenas medias en la isla de Tavira. Las playas en las que se ha aportado artificialmente áridos presentan arenas más gruesas y bimodalidad, debido a la heterogeneidad de los sedimentos dragados utilizados para los aportes. Los perfiles de las playas artificialmente alimentadas, partiendo de una mayor cantidad de arena disponible, desarrollaron rápidamente el perfil morfológico natural de la playa y demostró ser capaz de disminuir los efectos producidos por las tormentas, en concreto evitando la erosión dunar y los lavados excesivos. Se demuestra que las intervenciones suaves realizadas en Ría Formosa fueron útiles en la protección del sistema natural, siendo prometedoras para futuras intervenciones en zonas sensibles propensas a la erosión marina.

Palabras clave: playas arenosas, sistemas isla barrera, granulometría, evolución morfodinámica, rehabilitación ecológica, Ría Formosa, Portugal.
INTRODUCTION AND OBJECTIVE

The coastal zone is characterized by its extreme diversity and rapid evolution, and it can be considered able to accommodate various activities. The evolution of the coastline does not depend solely upon natural processes (wind, waves and currents) but also upon the type of intervention and land use by man. The majority of beaches are generally in balance with the natural dynamic conditions of a given site. Coastal interventions (e.g. coastal protection works) disrupt the natural balance and a new equilibrium tends to be created resulting in a further evolution of the coastline (Paskoff, 1998; Komar, 1998; Doody, 2001; Finkl & Walker 2002).

Coastal defense is a general term that refers to any activity taking place in the coastal zone, which has a protection purpose (Mangor, 2004). There are many techniques of coastal protection including “hard” and “soft” construction and planning approaches. Hard construction (e.g. groynes, breakwaters) is the more traditional response to shoreline erosion problems and involves the construction of structures that stop, absorb or reflect the wave energy reaching the shore (Ferreira et al., 2006). These have often caused problems themselves, such as increasing erosion elsewhere (Mangor, 1998; Inman, 1978). Soft engineering techniques (e.g. beach nourishment and beach replenishment) have become more popular and widely used as an alternative to traditional hard defenses. These techniques involve promoting natural systems such as beaches, dunes and salt marshes which protect the coast, and are usually cheaper to construct and maintain than hard construction techniques (Basco, 1998; Griggs, 1999). Soft protection techniques

Figure 1:
Location map of the study area (upper image), including a wave rose with annual average conditions, and approximate location of the sites where beach profiles were carried out at the Ancão Peninsula and Tavira Island.
also have fewer environmental impacts and, therefore, are a better solution for sensitive areas, such as barrier island systems (Dias et al., 2003).

In the Ria Formosa system (south Portugal, Fig. 1), there are several social and economic conflicts. The level of conflict increases when we consider that the system is a Natural Park, where economic interests and diverse human activities must be compatible with the preservation of the natural environment. In a very sensitive system such as Ria Formosa, already heavily impacted by human activities, it is only possible to preserve the natural environment through interventions aimed to minimize negative impacts induced by human activities (Ramos & Dias, 2000). On the basis of this philosophy, the Natural Park of Ria Formosa (NPRF-Portugal) implemented over the past 15 years, several soft interventions to improve the functioning of the system and at the same time reduce its vulnerability to overwashes (Dias et al., 2004).

This paper aims to better understand and evaluate the beach naturalisation process after replenishment, using particle size analysis and morphological data from Ria Formosa (South Portugal). A monitoring program was designed to determine morphological and volumetric changes, as well as particle size evolution along these two sites. The monitoring has been established by a network of profiles in both replenished and natural sites.

**THE STUDY AREA**

**Geomorphological setting**

Ria Formosa is a tidal lagoon located in the South coast of Portugal, consisting of salt-marshes, tidal flats and channels separated from the Atlantic by a belt of barrier islands and peninsulas that extend for 55 km along the coast (Fig. 1). It covers an area of about 170 km², most of it submerged at high tide, and communicates with the sea through inlets (presently six), two of which are stabilized by breakwaters. Along the Ria Formosa barrier-island system, sediments located at 0-5 m depth are very homogenous, with quartz having 80-90%. Other terrigenous particles are practically absent and bioclasts represent almost 20% of the sand composition (Rosa et al., 2013). The lagoon comprises a complex network of natural channels, partially dredged, that are increasingly narrow and shallow in the upper regions of the system (Salles, 2001). The inner coastline, along the backbarrier islands and peninsulas, is characterised by low, narrow sandy beaches alternating with portions of salt marsh, and washover plains (Andrade et al. 1998). The barrier islands are dominated by dune formations and sand plains presenting exposed oceanic sandy beaches with reflective to intermediate behaviour at the west flank, and intermediate towards dissipative at the east flank (Martins et al., 1996; Ferreira et al., 1997; Matias et al., 1998). This study will focus on one of the peninsulas (Ancão Peninsula, west flank, Fig. 1) and one of the islands (Tavira Island, east flank, Fig. 1).

Ancão Peninsula shows a general NW-SE direction and has undergone considerable morphological changes in recent decades, due to shoreline retreat, inlet relocation or beach nourishment (Vila-Concejo et al., 2002; Dias et al., 2004; Ferreira et al., 2006; Matias et al., 2008, Cela, 2009; Rodrigues et al., 2012). Its natural length ranged from 8,500 m in 1947 to 10,000 m in 2007, depending on the Ancão Inlet position and migration. In order to improve its hydraulic efficiency, the Ancão Inlet was artificially relocated at a western position in July 1997 and afterwards evolved naturally. The width of the peninsula varies between 65 m and 280 m. The dune crest is generally single with high peaks of 9.3 m above mean sea level (MSL) to the east, near the mainland attachment, decreasing to 6.5 m above MSL, near Ancão Inlet. The western part is characterized by a stable foredune and

![Figure 2: Average grain size distribution on different geomorphological units of the Ancão Peninsula beach, before (3rd February 2000) and after (2nd August 2000) nourishment. The solid line represents the average of all samples.](image-url)
Tavira Island shows a SW-NE orientation and is moderately sheltered from the W-SW oceanic swells that dominate the wave climate along the southern coast of Portugal (Vila-Concejo et al., 2002). Its length depends on the position and migration of the Fuzeta Inlet, being in average around 11 km. The island width varies between 200 m and 900 m, being the widest of the entire system. The island is characterized by a single continuous and well-developed foredune with a mean elevation of 5.8 m above MSL (Garcia et al., 2005). In front of the foredune, sand fences were installed by the Natural Park authority in order to prevent and reduce the vulnerability and the occurrence of overwash processes (Gomes et al., 2003). At the backbarrier, dunes, marshes and tidal creeks form a complex three-dimensional pattern. The eastern end of the island undergoes accretion process due to sediment retention promoted by the Tavira Inlet jetties. The central sector presents an average shoreline retreat rate of 0.4 m/year (Garcia et al., 2005).

Oceanographic setting

Tides in the area are semi-diurnal, with a mean tidal range of 2 m, and a maximum range of 3.5 m during spring tides, reaching maximum levels of 1.8 m above MSL. The projected levels for 10 and 100 year return periods, taking into consideration tide, storm surge, and sea level rise, and using 2010 as baseline, are 2.39 and 2.84 m above MSL (Carrasco et al., 2012). Wave energy is moderate (Ciavola et al., 1997) with an average annual significant offshore wave height of 1.0 m and average peak period of 8.2 s (Costa et al., 2001). Storm conditions (offshore wave height > 3 m; Pessanha & Pires, 1981) correspond to 1% of the offshore wave climate regime (Costa, 1994). The dominant and the more energetic waves (Fig. 1) come from west-southwest (71% of the time), while the “Levante” events (east-southeast waves) represent 29% of the occurrences (Costa et al., 2001). Net littoral drift in the area is typically from west to east with variable values according to authors (Vila-Concejo et al., 2006), ranging from 6x10^3 (Andrade, 1990) up to 3x10^5 m/year (Bettencourt, 1994). The cuspatate shape of the Ria Formosa lagoon system produces two different areas in terms of exposure to wave action. The west flank is more energetic, being under the direct influence of the prevailing west-southwest waves and is protected from “Levante” waves. On the other hand, the eastern flank is directly exposed to the less frequent and less energetic “Levante” conditions.

Management operations

Storm action, overwashes and shoreline retreat often cause property damage and barrier breaching along Ria Formosa (e.g., Pilkey et al., 1989; Andrade et al., 1998; Ferreira et al., 2006; Carrasco et al., 2009; Matias et al., 2007, 2008; Garcia et al., 2010) affecting both ecosystems and the resident population. The Park Authority has put into practice several management plans in order to diminish the vulnerability of the frontal dune.

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**Figure 3:**

Average grain size distributions and statistic parameters for Ancão Peninsula at natural (An1) and replenished (An2, An3) sites. The asterisk stands for surveys after nourishment, at replenished sites.
MATERIALS AND METHODS

A monitoring program was designed to determine the morphological and volumetric changes induced by beach nourishment along the Ria Formosa coastal area. In order to characterize beach morphology, a network of topographic profiles has been established including both replenished and natural sites. The beach topography was surveyed at selected sites using a Total Station. For the purposes of this study a set of profiles from Ancão Peninsula and Tavira Island were analysed (Fig. 1). The sites at which topographic surveys were performed, were numbered from west to east in both studied barriers and spaced by a distance ranging from 500 to 1000 m. Three sites were surveyed in Ancão Peninsula for three different times (3rd February 2000, 4th and 13th April 2000), including two sites within the replenished area (An2 and An3) and one (An1) in a natural area. In Tavira Island, four sites have been surveyed also at three different periods (7th July 1999, 5th November 1999 and 12th April 2000). One of them is located at a replenished area (Ta2) and the rest on natural areas (Ta3, Ta4 and Ta6).

The grain size characterisation of the Ria Formosa beaches was carried out using samples taken along the surveyed sites (cross-shore profiles). Those samples represent the upper 5 mm of the surficial sediment, and were collected at low spring tides from the four main beach geomorphological units: dune, backshore (beach berms), foreshore (beach face) and upper shoreface (tidal terrace when present). A total of 67 samples were collected and analysed for the 7 sites. In the Ancão Peninsula, 29 samples were taken in two campaigns. The first one was conducted in 3rd February 2000, before dredging operations (March 2000) and 14 samples were collected along sites An1 to An3. The second campaign was conducted in 2nd August 2000 with 15 samples obtained...
for natural (An1) and nourished (An2 and An3) sites. For Tavira Island, the two sampling campaigns were carried out after beach nourishment (September-October 1999), however only site Ta2 was nourished with the others remaining natural. A total of 38 samples were collected along four sites (Ta2, Ta3, Ta4 and Ta6), of which 18 samples in 11th April 2000 and the rest (20 samples) in 25th July 2000. Grain size was determined by dry sieving, using a ½ phi sieve interval ranging from 4 phi (0.063 mm) to -2 phi (4mm) or coarser when necessary. Grain size data were processed using GRADISTAT software (Blott & Pye, 2001).

RESULTS

Ancão Peninsula

Grain size

The results of the grain size analysis of the Ancão Peninsula sediments show that the particle size increased significantly between the two sampling periods (Fig. 2). The mean size increased from 0.74 phi (0.59 mm) in February to 0.33 phi (0.79 mm) in August 2000. The average grain size distribution of samples taken during August 2000 shows that few months after replenishment operations (March 2000) the percentage of coarse and very coarse sand increased 10% and 18%, respectively. The modal class varied from medium sand (1.25 phi, 35%) to very coarse sand (-0.25 phi, 41%). A comparative study between grain size of natural and artificial dunes was also conducted. The results also show an increase of grain size in the replenished area. The modal class varied from coarse (28%) to very coarse sand (26%). The samples from August 2000 show moderately sorted and negatively skewed distributions due to the heterogeneity of the dredged material used for dune replenishment. The grain size analysis at the backshore indicates the predominance of coarse sand before replenishment, while after intervention the modal class tends to be very coarse sand (Fig. 2). Regarding the foreshore, the modal class increased from medium (45%) to coarse sand (56%). A significant increase of grain size was also observed at the shoreface, characterized by a polymodal and very poorly sorted distribution (Fig. 2). The main modal class obtained for both sampling periods corresponds to very coarse sand, but showing an increase of 25% during the second sampling period.

The variation of particle size characteristics for the three sites from Ancão Peninsula, between February and August 2000 (Fig. 3), show that for profile An1 (natural), the average grain size of sand increases slightly. The modal class varies from medium (0.83 phi, 0.56 mm) to coarse sand (0.62 phi, 0.65 mm) and the coarse fraction increases by 10%. Profiles An2 and An3 shown unimodal grain size distributions before the intervention, with modal classes ranging from medium (28%) to coarse sand (18%). After nourishment, the average particle size increased significantly, from 0.43 to 0.76 mm and from 0.84 to 1.03 mm for An2 and An3, respectively. The average grain size distributions were found to be heterogeneous and poorly sorted; the modal classes correspond to very coarse sand.

Morphology

Site An1 is located at the west of the peninsula in an unreplenished area. The February 2000 profile is a pre-storm condition (Fig. 4) while the subsequent profiles were obtained after storms. The profile is reflective, with a steep dominant beach face slope (tanb ≈ 0.14). The general shape of these profiles shows a similar morphology at the dune front, but also relevant erosion induced by storm effect at the entire profile, characterized by a concavity and loss of sediment. The beach face slope diminishes to values on the order of 0.06-0.07 after the storm. The eroded volume of sediment was about 68 m³/m, with the erosion affecting part of the backshore and foreshore, while the upper part of the profile (dune)
remained more or less stable. The recovery is in general quite rapid at these beaches and the erosive profile only stays for few days (Vousdoukas et al., 2012).

Sites An2 and An3 have pre-storm profiles with small berms and similar characteristics to An1 pre-storm profile. The beach face slope had values of 0.13 (An3) and 0.15 (An2) before storm. The post-storm profiles were also obtained after nourishment and a considerable increase of sediment volume is observed, about 105 m$^3$/m were also obtained after nourishment and a considerable and 0.15 (An2) before storm. The post-storm profiles present a significant volumetric increase and the erosive profile only stays for few days (Vousdoukas et al., 2012).

The beach Profile at Ta2 had a regular shape (tanb $\approx$0.07-0.1) and a slightly convex form (tanb $\approx$0.08), with a wide berm and no dune, in July 1999, and 0.15 (An2) before storm. The post-storm profiles presented a significant volumetric increase and the erosive profile only stays for few days (Vousdoukas et al., 2012).

Tavira island

Grain size

The grain sizes of Tavira Island sediments show small variations within each analysed period (April and July 2000; Fig. 5). The average grain size distributions are relatively homogeneous for each period, both moderately sorted and coarse skewed. The modal class corresponds to medium sand (1.75 phi, 28%); the average particle size increased from 1.34 phi (0.39 mm) in April to 1.18 phi (0.44 mm) in July and the percentage of coarse fraction also increased by 8%. The results of the comparative study between natural and artificial dune also show an increase of grain size in the replenished area (from 1.78 phi, 0.29 mm, to 0.94 phi, 0.54 mm). The coarse fraction increased by 38% (coarse sand: 23% and very coarse sand: 15%) compared to the natural dune.

When considering different geomorphological units, the grain size analysis shows relatively heterogeneous distributions (Fig. 5) and some variability between sampling periods. In the backshore, the percentage of medium sand (modal class) decreased by 12%, while the coarse fraction increased 10%. The increase of particle size was also observed in the foreshore sediments, with the modal class varying from medium (35%) to coarse sand (36%). The grain size analysis of shoreface sediments indicates the predominance of medium sand (35-38%), and a significant decrease of coarse fractions (about 9%).

The comparative study of the particle size variation for different sites in Tavira beach between April and July 2000 (Fig. 6) shows that for site Ta2 (replenished), no significant grain size change was observed. The average frequency curves indicate a heterogeneous and poorly sorted distribution. The main mode corresponds to medium sand (25%), and the secondary is represented by very coarse sand (11%). The natural beaches show important particle size variations, especially Ta6 which evolved from a well sorted distribution with predominance of medium sand (53%) to a bimodal and moderately sorted distribution. Between sampling periods, the percentage of coarse sand increased by 22%, while medium sand decreased 23%. For Ta3, the observed changes were not so significant and showed moderately sorted distributions with predominance of medium sand.

Morphology

The beach Profile at Ta2 had a regular shape (tanb $\approx$0.08), with a wide berm and no dune, in July 1999, three months before the soft intervention (Fig. 7). One month after the intervention (November 1999), this profile presented a significant volumetric increase and morphological changes, especially at the dune and
Figure 7:
Morphological variation of cross-shore profiles surveyed at Tavira Island.
Underlined indicates post-nourishment surveys at replenished areas. MSL: Mean Sea Level

backshore. The profile shape was convex due to the creation of a large sand dune, and to the increase of sediment volume (more than 70 m³/m, tanb≈0.06). The profile obtained after the storm period (April 2000) shows that the dune was still present, even if part of it and the foreshore suffered from the erosive effects of the storm, reflected in a decrease of the sediment volume without significant decrease of the beach slope (tanb≈0.06). The topographic profiles (Ta3, Ta4, and Ta6) conducted in natural areas (tanb≈0.05-0.1) present the expected evolution after storm, with dominant berm erosion, sometimes balanced by accumulation at the beach face, accompanied by a decrease on the beach face slope (tanb=0.04-0.07) (Fig. 7).

DISCUSSION

The results obtained from the average grain size distributions of beach sediments (including replenished areas), show the predominance of coarse sand in the Ancão Peninsula, while medium sand prevails in Tavira Island. This grain size variation, observed on beaches prior to any intervention, results from differences in the hydrodynamic regime (wave energy and exposure). The results are consistent with previous conclusions from Bettencourt (1988), Teixeira (1989), Andrade (1990) and Rosa et al. (2013). The grain size differences are associated with the decreasing wave energy along the Ria Formosa system while moving from west to east which depends on the coastline configuration and orientation. The Ancão Peninsula occupies the western flank of the system and is exposed to the direct influence of the dominant and more energetic WSW waves. Those waves and the associated longshore transport promote the transport of finer sand fractions and only allow the deposition of coarse sediments. Tavira Island is protected from the energetic storm waves from WSW. The island is exposed to moderate to low energy waves from SE direction, which generates a medium to low energy regime.

The observed natural grain size variability can be related to the nature of the main sources of sediment supply, especially at the Ancão Peninsula that receives sediments from the erosion of sandy cliffs located to the west, which have been facing intensive erosion since the 1970’s (Correia et al., 1997; Oliveira et al., 2008). Longshore currents and littoral drift generated by southwest waves are responsible for the longshore transport of these eroded materials towards the southeast, i.e. to the Ancão Peninsula (Dias, 1988; Bettencourt, 1989).

The nourishment operations conducted at these areas produced a remarkable change in particle size, manifested by an increase on bi-modality and heterogeneity. This granulometric variation is typical of sediments coming from various sources and could be related to the diversity of the dredged lagoon channels used for nourishment, which produced bimodal, poorly sorted and very coarse skewed sediments.

Morphodynamic (morphological and volumetric) variations have been widely used to quantify beach volume changes and to understand the beach response to coastal process. The morphological and volumetric changes
recorded in different beach profiles at Ancão Peninsula and Tavira Island highlight the importance of soft intervention (nourishment) operations in the maintenance of the beach dynamic balance, based on the sedimentary exchanges that occur from the dune and berm to the shoreface, during erosive episodes. The analysis of the topographic profiles showed that the dredged sediments deposited in the eastern part of the Ancão beach served to minimize the impact of storm waves. In the Tavira beach that fact is manifested by the presence of a large amount of sediments available at dune and backshore of site Ta2, constituting an important sedimentary reserve capable to moderate and reduce the erosive effect of storm waves. Therefore, the additional sand replenished acted as a source of extra sediments during storm conditions, which can be particularly relevant to the protection of sensitive areas such as barrier islands.

In general, the results of volumetric and morphological analysis obtained in the study area show a variation of the topographic surface before and after the soft intervention (see Fig.4 and Fig. 7). Before artificial recharge, overwashes were frequent in the study area, being the main cause of dune destruction, also contributing to the silting up of some internal tidal channels. After artificial recharge, the volume of sediment at the backshore (including the dune) increased. Part of this deposited volume was lost during the readjustment process of these materials to the hydrodynamic conditions or by surface erosion or direct transport by storm waves. It was however verified that the profile adjustment after nourishment operations was almost immediate, and that beaches evolved naturally, the main difference being an increased availability of sediment. The injection of sands from the lagoon channels to the oceanic beaches, in order to reduce the effects of overwashes and assist in the recovery of the beach after storm erosion, is therefore a possible and positive coastal management approach for this natural park area, confirming the findings of Ramos & Dias (2000), Dias et al. (2003), Matias et al. (2004) and Achab et al. (2009).

Currently existing indicators related to dredging operations performed in the study area show that they have improved the functioning of the ecological system of the Ria Formosa, the renewal of water in the lagoon system, and that they also induced positive effects on different economic activities (Dias et al., 2003; Dias et al., 2004; Ceia, 2009; Ceia et al., 2010). These authors also suggest that natural systems of high socio-economic and environmental importance, such as Ria Formosa, can be managed using these types of techniques, while taking advantage of the use of existing resources. This information, jointly with the results of this work, suggests that soft interventions are well suited for this type of coastal systems. On the one hand, they allow the continuation and maintenance of the natural processes and allow a rapid naturalization of the managed area; moreover they tend to preserve and/or improve the aesthetic values of the area, at same time that they provide additional protection to storm action and a quicker recovery after high energy events.

CONCLUSIONS

The Tavira Island, located at the east flank of the Ria Formosa system, shows intermediate beaches. The Ancão Peninsula, at the western flank, is in average more reflective. That is mostly related with a natural difference in grain size, with Ancão having a coarser sand and therefore a higher slope and more reflective behaviour. The artificial nourishment conducted at these areas produced a significant change in particle size, due to heterogeneity of the dredged marine sediments used for artificial recharge. These changes did not cause, however, significant changes on the beach profile behaviour since a rapid beach profile adjustment was observed at the managed areas. These results proved the importance of soft interventions in reducing vulnerability related to overwash events and the risks associated to coastal erosion, which have particular relevance at natural preservation areas as it is the case of the Ria Formosa coastal system or other barrier island systems.

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