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Comparison of long-, medium- and short-term variations of beach profiles with and without submerged geological control

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ABSTRACT

Victoria Beach (Cadiz, Spain) comprises a rocky flat outcrop in its northern zone and a sand-rich southern zone. These natural features allowed for a 5-year monitoring period and subsequent analysis of two different profiles (one in each zone) based on differences in bottom contours. Topo-bathymetric data were analysed using empirical orthogonal functions (EOFs) to determine changes over the short-, medium- and long-term. Several morphologic phenomena were identified (generalised erosion, seasonal or summer–winter tilting of the profile around different hinge points, berm development and its posterior destruction, etc.) in terms of their importance in explaining the variability of the collected data for both profiles. It is worth mentioning that both profiles undergo parallel regression in the medium-term. Thus, the 1st eigenfunction enabled us to identify the true regression of the beach shoreline, independent of seasonal or summer–winter slope changes. Reconstruction of profiles using EOF components demonstrated that though accretion periods in the medium-term were similar for both types of profiles, the accretion speed was much faster in the sand-rich profile than in the reef-protected profile (1.01 m^3/day versus 0.33 m^3/day). Moreover, the seasonal erosion rate and the subsequent shoreline retreat for the sand-rich profile were much larger than for the reef-protected profile (121 m^3/year versus 29 m^3/year). Analysis in the short-term (changes induced by a single day's storm) showed an instantaneous tilting of the profile, with the mobilised sand volume being much greater for the sand-rich than for the reef-protected profile (68 m^3/m versus 12 m^3/m).
In brief, we can assume that the wave energy attenuation provoked by the existence of a reef flat acted as a geological control for profile evolution, which is essentially different for both profiles. Among the most important differences, special attention should be given to the larger slope, smaller mobilised sand volume and slower accretion rate of the reef-flat profile versus the non-protected profile.

1. Introduction

Most coastlines are in recession, and coastal researchers and engineers consider beach nourishment to be the most natural way to counteract the effects of coastal erosion when properly designed ([U.S.] National Research Council, 1995). Improving knowledge of beach-nourishment behaviour still requires a better understanding of complex shoreline processes and, in particular, the role of geological factors and the fill responses to the force of waves.

In the design and evaluation of beach fills, both short- and long-term modes of variability must be considered (Larson et al., 1999). As a matter of fact, according to Van Rijn et al. (2003), the time scales of relevance for profile models are: the storm time scale (hours to days), the seasonal time scale (months to years) and the decadal time scale (up to 10 years). Long-term trends are relevant for the evaluation of final beach width or the rate of erosion and, therefore, for the determination of future use and the suitability of the areas adjacent to the beach. Medium-term responses, with their seasonal winter–summer profile oscillations, provide information about the across-shore dimension of the berm and may play an important role in the location of beach services like showers, litter bins, toilets, foot bridges for disabled people, etc. Moreover, short-term changes (e.g., following an extreme storm) may determine the maximum retreat of the shoreline and, consequently, where seaside promenades or buildings and their appropriate types of foundations should be placed.

A great number of investigators have pointed out that beach variability is also affected by the underlying shoreface geology (e.g., Pilkey et al., 1993). It is not unusual to find areas of hard bottom or mud at many beaches for which the entire profile is not sand-rich. For instance, Larson and Kraus (2000) modified the SBEACH numerical model to allow calculation of the response to storm waves and changes in the water level of a sand-beach profile with arbitrary configurations of hard bottom. Building artificial reefs to improve

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surfing conditions or retain the beach in a perched position is one engineering practice (Lamberti et al., 2005).

Many characteristics and informative details about these reef-protected beaches have been discussed previously, including wave breaking and wave attenuation (Horikawa and Kuo, 1966; Gourlay, 1994; Nelson, 1994; Hardy and Young, 1996; and more recently Johnson et al., 2005); wave-setup and water-level fluctuations (Symonds et al., 1995; Karunarathana and Tanimoto, 1995); sediment flux (Roberts, 1980; Massel and Gourlay, 2000); annual and interannual changes in beach morphology (Norcross et al., 2002); and the influence of the reef on the *A* parameter of Dean's (1977) formula (Muñoz-Pérez et al., 1999).

Nevertheless, differences in the short- and long-term modes of variability between sand-rich and reef-protected profiles have received less attention in the scientific literature. Van Rijn et al. (2003) stated that profile models cannot simulate beach-recovery processes on a post-storm time scale because these processes are not known well enough to be included in the models. Similarly, there is still no universal model for analysing and predicting coastal evolution and its governing processes on annual to decadal time scales. Thus, available numerical model types were discussed by Hanson et al. (2003) in terms of their general assumptions, approaches and applicability. Some techniques for nonlinear analysis of time data over the same time scale were reviewed by Southgate et al. (2003).

Beach profiles have been observed to change over a range of temporal scales. However, according to Li et al. (2005), techniques for quantifying this variability have not been fully established.

Victoria Beach on the SW coast of Spain (Fig. 1) can be divided in two different zones owing to the existence of a transverse fault (Bernabeu et al., 2002). The northernmost zone presents a rocky platform that emerges during low tide and acts as a geological boundary for profile development, whereas the southern zone has no such platform. This natural feature makes it possible to compare the behaviour of a reef-protected profile to a complete profile under the same external conditions (waves, tide, currents, wind, etc.). Because of the retreat of this coastline and its economic importance due to tourism (Muñoz-Pérez et al., 2001a), the Spanish Coastal Authority decided to carry out a 2 Mm^3 sand nourishment and 5-year monitoring program focused on achieving a minimum beach surface for tourism use.

The objective of this study was to compare the evolution and variability of a reef-protected profile versus a sand-rich profile in the short- (changes undergone from a storm), medium- (seasonal or winter–summer variations), long- (rates of yearly recession) and very long- (average or almost invariable profile) term. As a result, the erosion–accretion rates for both profiles have been compared in terms of sediment needs for the tourist season.

Within the scientific bibliography, short- and long-term responses for sand-rich beach profiles have been researched (Larson et al., 1999). However, these changes have not yet been documented for the reef-protected profiles that are so numerous on the world's coasts (Norcross et al., 2002; Karunarathana and Tanimoto, 1995). In a complementary way, this research aims to demonstrate how under the same climatic conditions, two profiles of the same beach (reef-flat vs. the more standard-type profile) evolve in terms of different behaviours.

2. Study area

Victoria Beach is a 3-km-long beach with a NNW–SSE orientation located on the Gulf of Cadiz, facing the Atlantic Ocean on the SW coast of Spain (Fig. 1). The beach can be divided into two different zones due to the existence of a transversal fault to the shoreline. The northern zone presents a rocky platform that is almost horizontal and coincides with sea level at spring low tides. On the other hand, the rocky stratum of the southern zone is so deep that it remains covered by sand (Figs. 2 and 3). This results in two areas with different contour conditions at the seabed but the same wave climate.

The dominant swell comes from the W, typically from the WNW. The most energetic swell occurs less frequently and is oriented WSW, while eastern swells (ESE) are moderate (the wave-chart can be seen in Fig. 4). These sea and swell conditions generate a dominant littoral drift towards the S and SE, whereas the storms proceeding from the east induce the sand to be transported northwards instead. Nevertheless, a decrease in the height of these latter waves allows for the net quantity of sediments to have a southward direction, with an average loss value of approximately 70,000 m^3/year (Muñoz-Pérez et al., 2001b).

This coast responds to mesotidal characteristics, with two alternating high and low tides separated from one other by 12.42 h. The mesotidal range has a medium neap to spring variation (1.20–3.30 m). More tidal data details of the area are documented in Aboitiz et al. (2008).

The sand is 90–95% quartz and 5–10% bioclastic material, with an average grain size of about 0.25 mm. Geologically, the rocky platform that occurs at Victoria Beach is an outcrop of the Plio–Quaternary age. Lithologically, it is a bioclastic conglomerate, composed mostly of oysters and pectin shells. This structure is fossilised by a continental glacis consisting of quartz-rich red sands with quartzite pebbles. The siliciclastic conglomerate lays in disconformity with the Pliocene rocks,

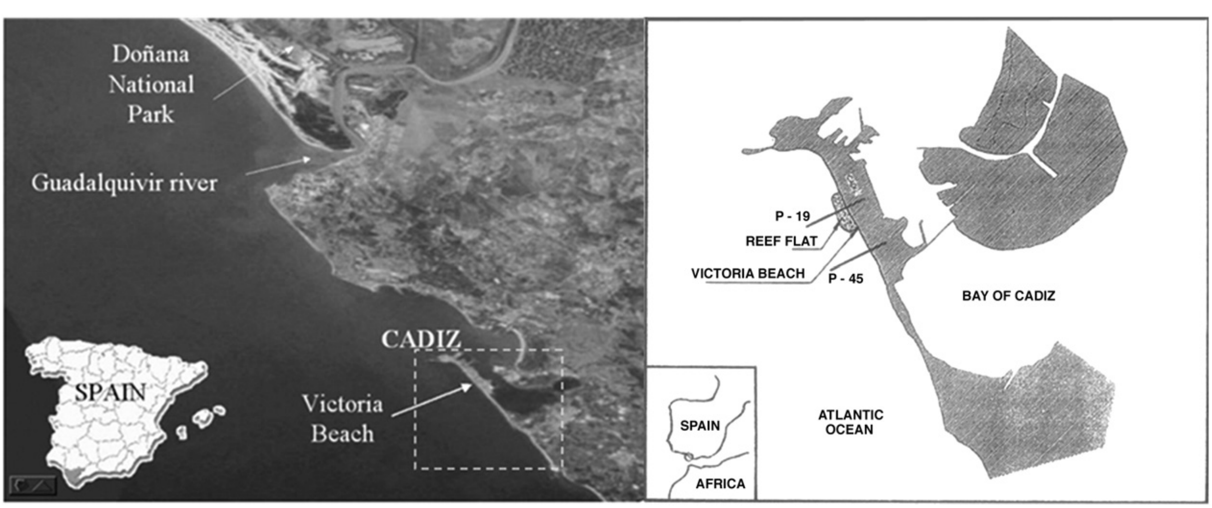

Fig. 1. Location of Victoria beach in Cadiz (SW Spain). A reef-flat profile (P19) and a standard or sand-rich profile (P45) are represented.