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Shoreline dynamics and beach rotation of artificial embayed beaches

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ABSTRACT

Artificially embayed beaches are an increasingly common environment in retreating and urban coasts. The study of embayed beaches usually focuses on the concept of some equilibrium configuration of the shoreline caused by the wave approach and the location of protection structures, but detailed studies of their shoreline dynamics are scarce. The study reported herein monitored the shoreline dynamics of three artificial embayed beaches in Barcelona City during a three-year period using an Argus video system to examine the behaviour of the emerged beach in order to assess the main factors affecting the shoreline, and to analyze the processes causing beach rotation at different time-scales. The length and degree of protection of the three beaches were different and so were their morphological behaviours. Two of the beaches presented a general retreating trend with rapid/abrupt displacements of the shoreline caused by oblique wave incidence during storm events and to the effects of beach nourishment. After nourishment, slower changes at the beaches determined beach evolution which was also influenced by the formation of long-lasting megacusps. The third beach, the most protected one, showed an accretionary trend, no formation of megacusps and episodes of beach rotation related to the gradual recovery of the beach after storm events.

It is concluded that factors controlling the evolution of Barcelona City beaches are associated with both natural processes and man-induced actions, resulting in a more complex pattern than would be expected for small embayed beaches. Beach rotation appears as a key process for understanding the morphodynamics of embayed beaches. It occurs as a fast response to storms but also as a medium-term adaptation of the shoreline configuration to morphological changes in the beach or to the recovery of a more stable orientation after storm events and man-made changes in the beach orientation resulting from nourishment or sand relocation.

1. Introduction

Rocky coastal zones represent approximately 80% of the world's coast (Trenhaile, 1987). Within these zones sandy beaches bounded by rock outcrops or headlands where the shoreline takes on some form of curvature are a common occurrence. Beaches of this type are known as curved, hooked, pocket, embayed or headland-bay beaches, and have been the subject of a variety of attempts to model their equilibrium plan forms (e.g. Silvester, 1960; Gonzalez and Medina, 2001). Embayed beaches differ from long sandy beaches in the limited alongshore sediment transport, which varies according to the beach boundaries.

Artificial embayed beaches have been suggested as a means of stabilizing eroding shorelines (Klein et al., 2003). Furthermore, the number of sandy beaches enclosed by artificial structures has increased in the last few decades due to the construction of harbours and other structures aimed at stabilizing coastlines threatened with erosion. However, little research has been conducted on these non-natural systems (Gonzalez and Medina, 2001; Muller et al., 2006). The study of embayed beaches is usually based on the concept of some static or equilibrium configuration of the shoreline; three main models are used to fit this equilibrium shape: logarithmic-spiral (Silvester, 1960), parabolic (Hsu et al., 1989) and hyperbolic tangent (Moreno and Kraus, 1999). Beaches with two headlands are best described by the logarithmic-spiral model (Martino et al., 2006). These equilibrium models are applied to fit the shoreline configuration with the mean shoreline position associated with some specific wave climate, they consider a perfect adjustment of the shoreline to the incoming wave direction, in a simplification of the real morphology of the beaches. However, detailed observations of beach mobility are scarce and basic processes in embayed beaches such as beach rotation are still poorly documented.

Embayed beaches are typically affected by headland bypassing, when the sand moves subaqueously around its boundaries (Short, 2002), by the formation of rips (Holman et al., 2006), and by *beach rotation*, i.e. lateral movement of sand along the beach in response to a modification in the incident wave direction (Short and Masselink, 1999). Beach rotation causes localized retreat or advance of the shoreline along the beach, although it does not lead to a long-term loss or gain of sediment because the beach often returns to the initial location in response to a new shift in the wave direction (Klein et al.,

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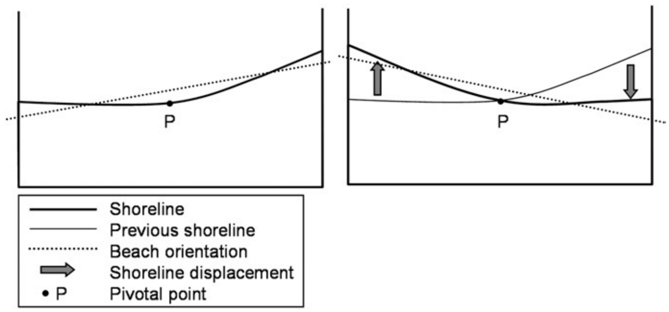

Fig. 1. Parameters used to define beach rotation.

2002). It has been described at monthly to decadal time-scales as being caused by variations in the wave direction related to the El Niño Southern Oscillation, alterations in the sediment supplied from nearby rivers, and seasonal changes in the wave climate (Anthony et al., 2002; Klein et al., 2002; Ranashinge et al., 2004).

Beach rotation is schematized in Fig. 1; the change in the shoreline from t_0 to t_1 implies an advance (retreat) of the left (right) section of the beach. One of the parameters involved in the determination of beach rotation events is this advance/retreat of the shoreline which is maxima near the limits of the beach and minima or zero at the central section represented by the pivotal point. Beach rotation can also be determined by the change in the orientation of the shoreline; however, these changes in orientation can be also related to other alterations of the shoreline such as differential erosion or accretion alongshore or beach nourishment.

The general objective of the present study was to achieve a better understanding of artificial embayed beach morphodynamics using shoreline position and beach area data from three beaches in Barcelona City during a three-year period. It analyzes the impact of natural processes and human interventions on the shoreline, focusing on mechanisms that cause beach rotation and the recovery of the former beach orientation. We first examine the dynamics of the shoreline of the three beaches and their changes in the emerged beach area. Secondly we compare the temporal evolution of the beach area with the temporal evolution of the beach orientation to establish which changes in beach orientation are related to episodes of beach rotation. Finally, we examine the response of the beaches to storm events and try to find a relationship between the alongshore component of the radiation stress and changes in the beach orientation.

2. The study area: Barcelona City beaches

The Catalan coast is a micro-tidal zone (range <20 cm) in which waves are the main stirring mechanism controlling coastal evolution. The most energetic storms approach from the east, have a typical duration of a few days, and are often associated with the cyclonic activity in the western Mediterranean. Statistical analysis of wave conditions in the region from 1984 to 2004 shows mean significant wave height values (Hs) of 0.70 m, with Hs maxima of 4.61 and maximum wave heights of 7.80 m (Gómez et al., 2005).

Significant wave height during the study period displayed a cyclic behaviour, with storm periods (October–April) separated by periods of low storm activity (May–October) (Fig. 2). The most energetic period affecting Barcelona City beaches was from October 2001 to May 2002, with a major storm from the NE direction in November 2001 involving two consecutive intensity peaks separated by a short time lapse.

The city of Barcelona is located in the north-western Mediterranean, flanked by two rivers, the Besos in the north and the Llobregat in the south (Fig. 3). It has approximately 13 km of coastline containing the city harbour in the southernmost part of the city, three marinas and more than 3 km of beaches. These beaches are one of the city attractions and are occupied during most of the year by local inhabitants and tourists (Guillén et al., in press). The northern area of the city beach had almost disappeared by the 1980s due to the invasion of urban and industrial areas and the decrease in the input of sediment to the coastal zone. Only a section of approximately 1.5 km remained in the southern part, supported by the Barcelona Harbour dike. The beaches were created as part of the renewal plan that took place in the zone for the 1992 Olympic Games, when small industries, garages and industrial warehouses were eliminated to create the Olympic Village (now transformed into a residential district), and new beaches were built on both sides of the Olympic Marina. The beaches have now become a symbol of the city's revitalized waterfront.

This study focuses on three beaches (Fig. 3): a) La Barceloneta, a barred beach bounded by Barcelona Harbour in the south and the Somorrostro dike in the north; b) Nova Icaria, a non-barred beach located on the north side of the Olympic Marina, separated from Bogatell beach by a double dike and also protected by two submerged breakwaters, the longest of which extends from the tip of the dike; and c) Bogatell, a barred beach at the northern limit of the study area, enclosed by two double dikes.

Barcelona's beaches are continuously affected by human activity such as sand cleaning before the summer season and small-scale sand redistribution along the beaches after storms. Two major beach interventions were carried out during the study period, a nourishment of Bogatell and La Barceloneta in summer 2002 (Ojeda and Guillén, 2006), and a sand relocation at La Barceloneta in summer 2004.

The nourishment was a rapid solution to the erosion caused by the highly energetic period from October 2001 to May 2002. The works commenced at Bogatell beach, which received around 70 000 m^3 of sand in 22 days (between 13th June and 5th July), and continued at La Barceloneta beach, which received around 40 000 m^3 of sand between 5th and 17th July 2002. The sand borrow areas were located approximately 20 km up-drift of the study region. The median grain size of the sand

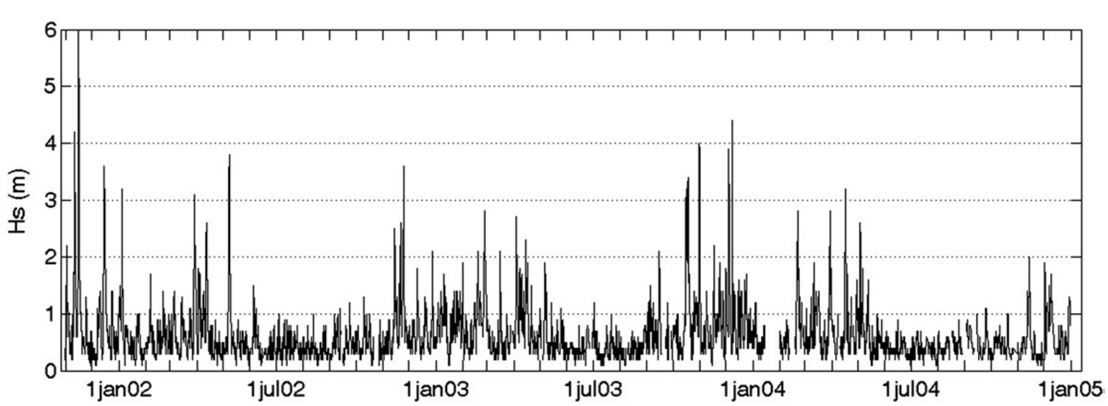

Fig. 2. Significant wave heights off Barcelona during the study period.