

The morphodynamic responses of artificial embayed beaches to storm events

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Abstract. The morphological changes caused by storm events in two Barcelona beaches were recorded using video monitoring techniques during the period 2001–2006. Changes in shoreline position and configuration and submerged bar position and shape were analyzed during the 25 major storm events that occurred during the study period. Beach responses to storms were grouped into three categories: shoreline advance or retreat (including rotation), sandbar migration and/or configuration change (linear or crescentic shape) and formation of megacusps. This work provides examples of the differential adaptation of both beaches to the same storm and of some unexpected morphological responses of both beaches. The response of the beach to storm events is not straightforward because wave conditions are not the only relevant parameter to be considered. In particular, in such embayed beaches it is crucial to take into account their specific morphodynamic configuration prior to the storm.

though artificial groins limit alongshore sediment transport and protect sections of the beach from waves approaching from a range of directions (Short and Masselink, 1999). The morphodynamic responses of a beach to the storm are (apparently) simple: beach face is eroded, bar moves offshore (due to undertow currents), 3-D features are wiped out and, for oblique incidence of waves in embayed beaches, beach rotation occurs. After the storm, the bar moves onshore (due to wave skewness and asymmetry) and 3-D features (e.g., rips) develop and grow while the eroded beach face slowly recovers and the orientation of the emerged beach re-adjusts to the main wave direction approach.

This contribution focuses on the morphological changes of the shoreline and the submerged sandbars of artificial embayed (sandy) beaches due to the effect of high-wave conditions associated to storms. We characterize the morphological response of the emerged and submerged beach profile of two of the artificial embayed beaches of the Barcelona city coast, and we subsequently couple it to the corresponding storm characteristics.

1 Introduction

The plan-view and the profile shape of sandy beaches largely depend on the incoming wave-energy (Wright and Short, 1984). In this sense, storm events are responsible for major changes in the configuration of sandy beaches and the cumulative effect of storms and fair-weather conditions determines the morphodynamic state of a certain beach. With increasing wave energy, the beach changes from the *Reflective* state to the *Low Tide Terrace, Transverse Bar and Rip, Rhythmic Bar and Beach, Longshore Bar and Trough* and finally to the *Dissipative* beach state. These morphodynamic states are also observed at artificial embayed beaches, al-

2 Field site and methods

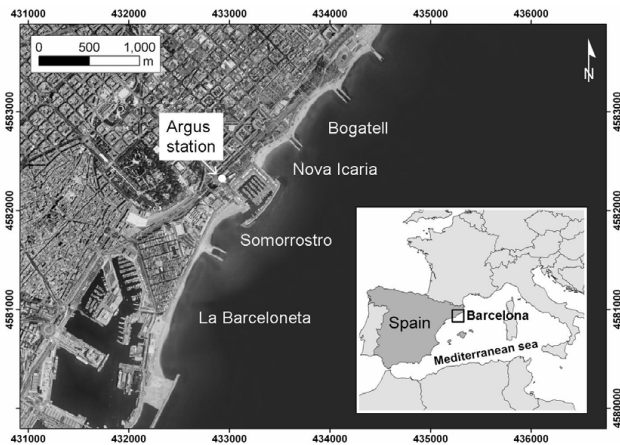
La Barceloneta and Bogatell are two of the artificial embayed beaches of Barcelona, Spain (NW Mediterranean, see Fig. 1). They are single-barred beaches subject to the same climatic conditions but with different morphological characteristics. La Barceloneta is 1100 m long and it is oriented 20° N. Bogatell beach has a length of 600 m and its orientation is 38° N. The study comprises more than 4 years of data, from November 2001 to March 2006, obtained through an Argus video system (Holman and Stanley, 2007). The extraction of the shoreline and barline locations is accomplished using 10-min time-exposure video images. Shorelines were extracted directly from oblique images (see Ojeda and Guillén, 2008, for a complete description) and rectified



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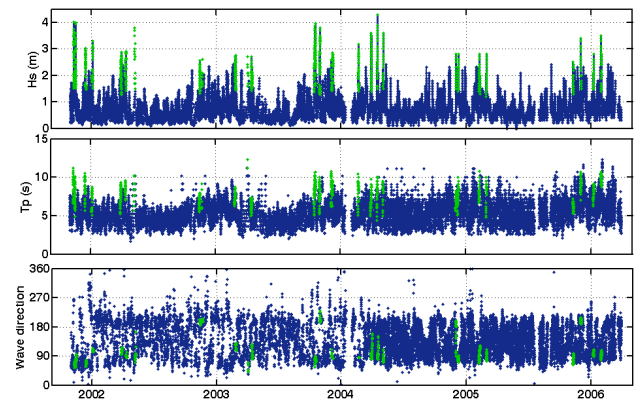
Table 1. Shoreline and bar response (%) with respect the total number of analyzed storms.

	Parallel displacement	Beach rotation	Differential displacement	Increase of bar sinuosity
La Barceloneta	25%	30%	45%	42%
Bogatell	13%	50%	37%	80%

**Fig. 1.** Study area and location of the Argus station at Barcelona city, Bogatell and La Barceloneta being the studied beaches. The coordinates are given in UTM (m).

afterwards. Sandbars were inferred from the rectified time-exposure video images based on the preferential wave breaking over shallow areas, so they required a minimum significant wave height (H_s) which allowed the occurrence of a clear wave-breaking pattern. The barline extraction was accomplished through an automated alongshore tracking of the intensity maxima across each beach section (Van Enckevort and Ruessink, 2001). The suitability of the video monitoring for the study of the dynamics of sand bars in the Barcelona beaches had previously been shown by Ribas et al. (2010).

The mean H_s during the study period was 0.71 m and the averaged peak period was 5.7 s. The wave height time series shows a cyclic behaviour, with storm periods (October–April) separated by periods of low storm activity (May–October). The two most energetic periods affecting the beaches were from October 2001 to May 2002 and from October 2003 to April 2004 (wave data were obtained from a WANA node [virtual buoy] and direct measurements of the Barcelona-Coastal buoy) (Fig. 2). Following Ojeda and Guillén (2008), significant storms were defined as those with H_s higher than 2.5 m during the peak of the storm and a minimum duration of 12 h with H_s greater than 1.5 m. Based on this criterion, 25 storm events have been identified during the study period. The wave approach to the coast was oblique during most of the storms. Waves were coming from the eastern direction (E-NE or E-SE) for most of events (20 storms) and, in a few cases (5 storms), waves were coming from the south (Fig. 2).

**Fig. 2.** Deep-water wave conditions off Barcelona from November 2001 to March 2006 (from top to bottom, significant wave height, peak period, and approaching wave direction). Green dots indicate the major 25 storms analyzed. Storm conditions are predominantly from the East.

3 Results

The responses of the beach to storm events were grouped into three categories: shoreline advance or retreat (including rotation), sandbar migration and/or configuration change (linear or crescentic shape) and formation of megacusps.

3.1 Shoreline advance or retreat

Ojeda and Guillén (2008) analyzed the evolution of the shoreline of the Barcelona city area from November 2001 to December 2004. At La Barceloneta and Bogatell they found a retreating trend temporally alleviated by the artificial nourishment of the emerged beach on summer 2002 and by a sand relocation in La Barceloneta on summer 2004. At a shorter time-scale, Ojeda and Guillén (2008) highlighted the importance of the beach response to storm events (producing beach rotation or local erosion or accretion) in the beach evolution and they also suggested the existence of a certain coupling between the bar and the shoreline, i.e., an interrelation between the bar and the shoreline behaviours. In general, La Barceloneta and Bogatell shorelines displayed similar responses to storm events. Shoreline displacements associated with storms varied between -18 and $+34$ m at La Barceloneta and -20 m and $+15$ m at Bogatell. The observed shoreline responses were grouped as a) almost parallel displacement of the shoreline (beach orientation remains the

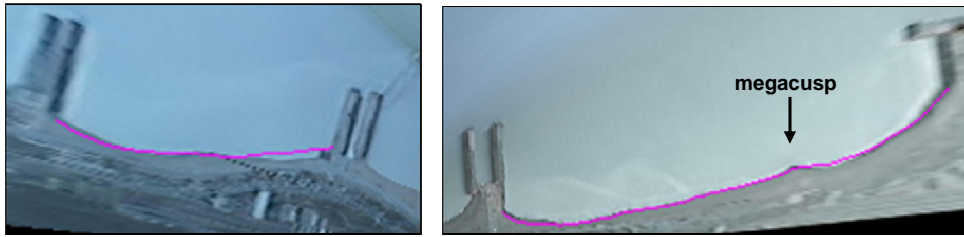


Fig. 3. Bogatell (left) and La Barceloneta (right) planviews on 3 November 2003. The coloured line indicates the shoreline location before the southern storm event, on 30 October 2003, showing beach rotation at the Bogatell beach and the formation of megacusp and shoreline retreat at La Barceloneta beach.

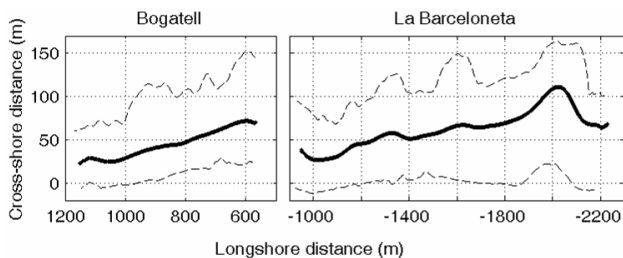


Fig. 4. Time-averaged barlines during the study period (dark line) and the most remote locations reached by the bars during the study period (lighter lines). Cross-shore distances are relative to a reference shoreline. Longshore distances relative to the location of the ARGUS station.

same); b) beach rotation and c) differential erosion/accretion along the beach not related to beach rotation (Table 1). The parallel displacement of the shoreline (unchanged beach orientation) occurred at 13% and 25% of events at Bogatell and La Barceloneta beaches respectively. This response is caused by a generalized erosion/accretion along the beach. The change of beach orientation was caused by beach rotation or differential displacement of the shoreline along the beach. Beach rotation is the usual expected behaviour for oblique wave approach, but it was only observed half of the analyzed storms. At the Bogatell beach, most of the analyzed storm events (87%) produced significant changes in the beach orientation and, of these events, 57% were associated with beach rotation (e.g., Fig. 3). However, at La Barceloneta, 75% of the analyzed events produced changes in the beach orientation, of which 42% were associated with beach rotation (Table 1).

3.2 Sandbar morphological changes

The time-averaged barline during the study period was approximately rectilinear, oblique with respect to the reference shoreline (averaged position from all available shorelines fitted to a polynomial curve) (Fig. 4). This obliquity was more evident at Bogatell beach, where the angle was approximately 5.3° , whilst at La Barceloneta beach it was

2.6° . Both of them were closer to the beach on their northern sides. Compared to La Barceloneta, the Bogatell beach showed a more dynamic bar with more frequent changes in the bar morphology from linear to crescentic (Table 1). At Bogatell beach, every documented eastern storm produced an increase of bar sinuosity (3-D increases). La Barceloneta showed a smaller amount of changes in the sinuosity and only 42% of the storms produced significant increases in sinuosity. Regarding the changes in the morphodynamic state of the beaches, the bar at Bogatell switched more frequently among the four intermediate morphodynamic states during the study period than the bar at La Barceloneta. The bar at La Barceloneta only underwent the complete “reset” of the nearshore morphology (i.e., abrupt change of the plan-view shape of the beach towards a *Longshore Bar and Trough* state) once, associated with the high-energy wave event occurring on November 2001. At this beach, the remainder storm events produced the offshore migration of the bar and a certain decrease in the bar sinuosity, but did not generate an alongshore parallel bar (e.g., Figs. 5 and 6).

3.3 Formation of megacusps

Megacusps of approximately 10 m of horizontal amplitude or larger were observed during the study period at La Barceloneta and Bogatell beaches (Fig. 5). They were formed after storms that transformed the submerged bars into crescentic bars and caused them to become attached to the beach during periods of high sediment availability, a clear example of coupling between the bar and the shoreline morphologies (Ojeda et al., 2006). La Barceloneta showed the largest and longest-lasting megacusps and crescentic bars observed during the study period. The most evident of such configurations started at La Barceloneta beach in mid-October 2003, right after an ESE storm with $H_s > 4$ m. On the beach, two stable megacusps were formed with eroded regions on their flanks, coupled with the closest sections of the submerged bar (Transverse bar and Rip state) (Fig. 5). This configuration lasted for more than a year.



Fig. 5. Plan view image obtained on 8 November 2003 showing the Transverse Bar and Rip state at La Barceloneta with two stable megacusps coupled with the closest sections of the submerged bar. One megacusp is also visible at Bogatell beach.

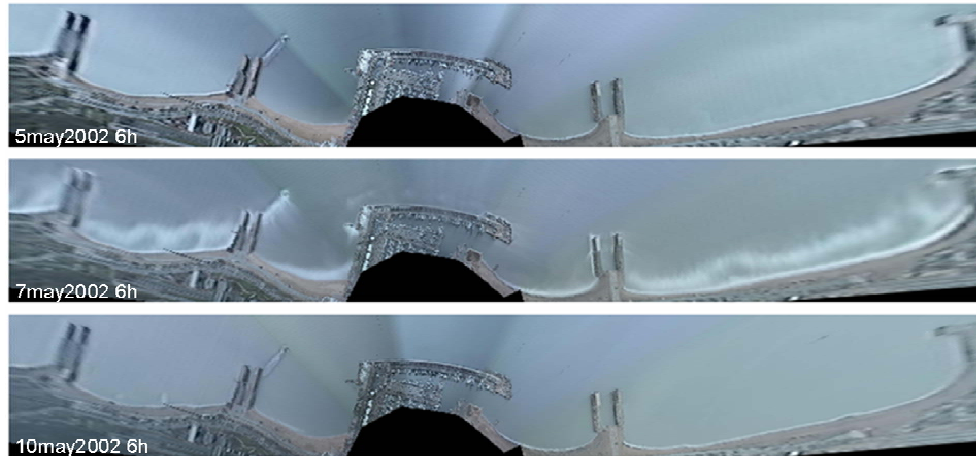


Fig. 6. Planviews showing the effect of the eastern storm event occurring on early May 2002. Two megacusps were developed at La Barceloneta beach and crescentic bar features at the Bogatell beach.

4 Discussion and summary

Storms are responsible for major morphological changes in the Barcelona beaches. The greatest modifications are due to beach rotation caused by waves approaching obliquely to the coast. However, the relation between beach rotation and wave conditions is sometimes unclear. For instance, we would expect that the eastern storm in May 2002 and the southern storm of October 2003, caused beach rotation in both beaches due to the oblique approach of waves to the shoreline. However, after May 2002 we observed the formation of a megacusp at La Barceloneta and a shoreline retreat at both extremes of Bogatell beach (Fig. 6). In October 2003, general accretion and the formation of a megacusp were detected at La Barceloneta and shoreline rotation and formation of megacusps were visible at Bogatell (Figs. 3 and 5). Therefore, the same storm caused different effects on the two adjacent beaches and, furthermore, the effect of storms of similar characteristics (obliquely incident waves of similar height and period) on the same beach was also different.

Observations of the Barcelona beaches show that the response of the beach to the storms is not straightforward and different parameters should be considered in addition to wave conditions for understanding morphological changes during storms. During the 4.5 years covered in this study, the beaches behaved in accordance with the expected theoretic-

cal response (as presented in the introduction of this paper) at roughly 40% of the storm events. Thereby, the wave conditions are not sufficient to describe the emerged and submerged beach dynamics during storms. In order to explain the remainder 60% of cases, other factors affecting beach dynamics should be included. In the artificial beaches of Barcelona, the main factors to be taken into account are the morphodynamic configuration of the beach before the storm event (sediment availability, sandbar morphology and shoreline orientation), the storm sequence and the proximity (in time) of human interventions (beach nourishments). These factors (and their interaction) should be considered in addition to the hydrodynamic conditions to achieve an adequate prediction of the morphological change induced by storms on artificial embayed beaches.

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