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MORPHOLOGICAL CHANGES IN THE ARTIFICIALLY EMBAYED BEACHES OF THE BARCELONA CITY (SPAIN)

Abstract - J. Guillén, G. Simarro, A. Coral, *Morphological changes in the artificially embayed beaches of the Barcelona City (Spain).*

The beaches of Barcelona acquired the present-day configuration on the occasion of the Olympic Games in 1992. Since then, they have become one of the hallmarks of the city, and one of its busiest places. These beaches are artificial and there is no natural sediment supply, so that there have been numerous actions for maintenance and regeneration during this period. Faced with stabilization actions aimed to reduce the dynamism of the beaches (trying to maintain a minimum width of the emerged beach), natural processes occur in the form of storms events, redistributing the sediment and producing a sedimentary deficit which is not compensated by the arrival of new sediments. Morphological changes of these beaches were investigated based on video monitoring and topographic and bathymetric surveys. The transformation suffered by beaches since 2001 has been considerable: several nourishments, new beaches "built" in the area near the Besòs River, several beaches protected through submerged detached groins and emerged detached breakwaters. In spite of these efforts oriented to maintain the emerged beach area, Barcelona beaches have a negative sediment balance due to the redistribution of the sediment along and across the coastal zone. Therefore, they constitute an excellent "laboratory-scale" zone offering a unique opportunity to evaluate man-made actions. The purpose of this paper is to assess the changes in the morphodynamic processes that have taken place in the beaches of Barcelona induced by different actions taken during the past 15 years.

Key words - shoreline, storm impacts, sediment budget, artificial nourishment, protection structures, Barcelona, Spain

Riassunto - J. Guillén, G. Simarro, A. Coral, *Variazioni morfologiche delle spiagge artificiali della città di Barcellona (Spagna).*

Le spiagge di Barcellona (Spagna) hanno acquisito l'attuale configurazione in occasione dei Giochi Olimpici del 1992. Da allora sono diventate uno degli elementi più caratteristici della città, oltre che uno dei luoghi più frequentati. Queste spiagge sono artificiali e non presentano alcun tipo di alimentazione naturale, tanto che si sono rese necessarie nel tempo numerose azioni volte al mantenimento e rigenerazione. Nonostante gli interventi di stabilizzazione finalizzati a ridurre l'alto dinamismo di queste spiagge (così da mantenere sempre un'ampiezza minima della porzione emersa), i processi naturali più significativi avvengono sotto forma di mareggiate, che ridistribuiscono il sedimento e producono un deficit sedimentario che non può essere compensato dall'arrivo naturale di nuovi sedimenti. Le variazioni morfologiche di queste spiagge sono state studiate per mezzo di video-monitoraggio e rilievi topografici subaerei e batimetrici. A partire dal 2001, le trasformazioni rilevate sulle spiagge sono state considerevoli: tanti ripascimenti, nuove spiagge "costruite" nell'area presso il Fiume Besòs, numerose spiagge protette grazie a pennelli sommersi e scogliere emerse. Nonostante tutti questi sforzi per mantenerne stabile la porzione subaerea, le spiagge di Barcellona hanno un bilancio sedimentario negativo a causa della ridistribuzione dei sedimenti lungo la linea di costa e verso il mare aperto. Esse rappresentano pertanto un laboratorio in scala 1:1, che offre un'opportunità unica per valutare le azioni dell'uomo. Lo scopo del presente manoscritto è di dare una valutazione delle variazioni dei processi morfodinamici indotte dai differenti interventi realizzati durante gli ultimi 15 anni sulle spiagge di Barcellona.

Parole chiave - linea di costa, impatto di mareggiate, budget sedimentario, ripascimenti artificiali, strutture di protezione, Barcellona, Spagna

1. Introduction

The transformation of coastal systems by human action over the past centuries has modified the sedimentary processes taking place on the coasts and has led to the emergence of new problems that were not perceived only fifty years ago. It has been observed, for example, that a significant part of the beaches along the Mediterranean coast is affected by erosion (Eurosion, 2004). Although the reasons of this erosion are multiple, lower continental sedimentary inputs that reach the beaches should be included among the most important causes. This reduction is mainly associated with both the regulation of watersheds as well as sediment transport interruption along the coast due to the proliferation of ports and protection structures. The massive urbanization of the coastline, the extraction of sand and gravel from rivers and beaches and the destruction of coastal dunes on the backshore are also important factors (Hanson *et al.*, 2002; Sanjaume & Pardo-Pascual, 2005; Brice *et al.*, 2008). It is interesting to note that to alleviate the problems of beach erosion, largely induced by human action, more actions are usually planned. The usual "solutions" implemented in order to increase the stability of the coastline can be divided between protection structures (breakwaters, jetties and offshore structures) and artificial regeneration of beaches. A common approach is to apply a combination of both actions.

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The beaches of Barcelona are a paradigmatic example of the interactions between anthropogenic activities and natural processes. On the one hand, the large deposit of sand on the coast is the result of the accumulation of sand supplied from the Besós River and the small streams of the "Maresme", which was transported to the SW by longshore drift from XV to XIX centuries. This sand was retained by the breakwaters raised during successive attempts to build the Port of Barcelona, in the late nineteenth century. Those beaches were urbanized and occupied during the first half of the twentieth century by industries and suburbs, although there were reserved sections to the recreational activities of citizens. Finally, the celebration of the 1992 Olympics Games was the great opportunity that took the city to retrieve its waterfront, setting the coast that we know today (Fig. 1).

Over the following 10 years (1992-2001), the beaches of Barcelona apparently worked properly (from the point of view of public administration) and only small interventions were performed. However, the great storm of November 2001 that affected the entire Catalan coast revealed a precarious situation of these beaches that triggered a series of interventions that still continue nowadays (Fig. 2). In addition to numerous artificial transfers of sand and small dredging activities at the entrance of the "Port Olimpic", there have been: artificial regenerations in the years 2002, 2006 and 2010; a new detached "T" breakwater in the Barceloneta beach, two submerged continuous detached breakwaters along the entire length of the beaches of Bogatell and Marbella, the prolongations of the breakwater of Selva de Mar, the expansion and strengthening of groins and the building of a new harbour (Port Forum) and the Llevant beach (Fig. 2).

The beaches of Barcelona are constrained between breakwaters and artificially fed. However, although profoundly altered by human intervention, sediment dynamics in response to waves and currents continue to force morphological changes. From a morphodynamic point of view (Wright & Short, 1984), Barcelona beaches are intermediate beaches, with a morphodynamic state ranging from "longshore bar and trough", "rhythmic bar and beach", "transverse bar and rip" and "low tide terrace". Interventions into the beaches have made the morphodynamic states to change over time.

2. Methodology

The Coastal Monitoring Station of Barcelona (ICM-CSIC) aims to collect physical, morphological and biological data with the highest possible resolution and, in a long term perspective, to determine the behavior and evolution of a coastal system where natural and human influences coexist, which is characteristic of many Mediterranean coastal ecosystems. Barcelona is located on the north-eastern coast of Spain (NW Mediterranean). In this region the tidal range can be considered negligible (about 0.2 m), and the waves are the main hydrodynamic force acting on the beaches. Statistical analysis of wave conditions in the region from 1984 to 2004 shows a mean significant wave height (Hs) of 0.70 m, with Hs maximum of 4.61 m, maximum wave heights of 7.80 m and an averaged mean period of 4.3 s. An Argus video system (Holman & Stanley, 2007) has been used to study the beaches and the submerged sandbars since October 2001. Five cameras located at a height of 142 m offer a 180° view

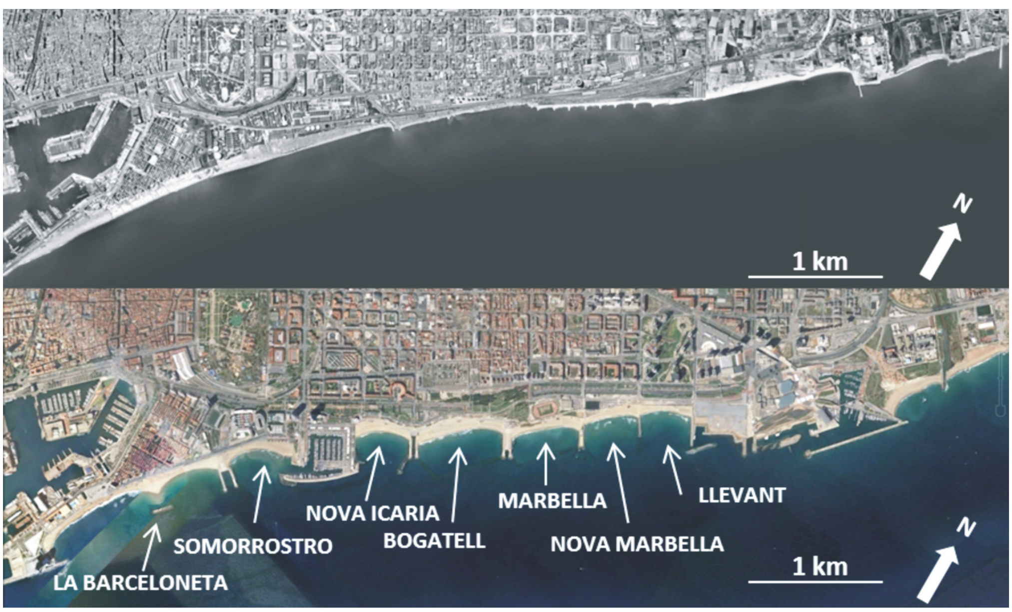

Fig. 1 - Comparison of the configuration of Barcelona city beaches in 1956 (above) and 2015 (below).

Fig. 2 - Main actions (in red) taken on the beaches between 2006 and 2016.

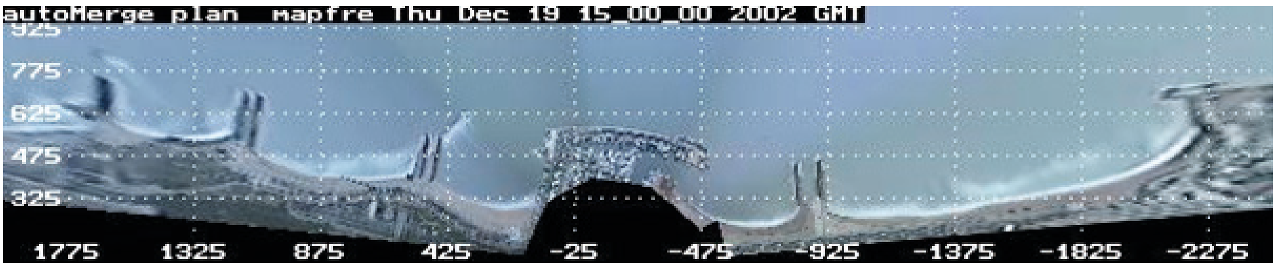

Fig. 3 - Plan view of the beaches of Barcelona obtained from five images (November 2001).

of the littoral zone (see Ojeda & Guillén (2008) for a more detailed description) (Fig 3). Since June 2015 the system uses six cameras, the SIRENA adquisition software (Nieto *et al.*, 2010) and the ULISES software for georeferentation and rectification (Simarro *et al.*, 2017). Pictures are taken every hour and the system provides an averaged image, an image of variance and a snapshot. After a geo-referentiation and rectification of the images, they provide relevant information such as shorelines (Simarro *et al.*, 2015). Images contained 760x580 and 2400x2000 pixels for the original and the new system respectively. After fifteen years of activity, it is possible to get a better understanding of the morphodynamics in a medium-term perspective. Variability of the shoreline (Ojeda & Guillen, 2008), morphodynamics of the bar systems (Ojeda *et al.*, 2007a,b), modeling of crescentic bars (Falqués *et al.*, 2007; Ribas *et al.*, 2007), vulnerability of the coastal zone with regard to storms (Sancho *et al.*, 2008) or the formation and persistence of rhythmic topography (Ortega *et al.*, 2008) were previously studied. In addition, the images allow the evaluation of the different activities that take place in this part of the coast such as new breakwaters and artificial regenerations (Ojeda & Guillén, 2006; Sancho *et al.*, 2013) and the development of techniques that allow improved management of the beach, such as quantifying the number of users (Guillén *et al.*, 2008). These observations are supplemented, since 2010, with bathymetric and topographic surveys that provide insights into the morphological changes of the beach (emerged and submerged) and to estimate the sedimentary budget of Barcelona beaches.

3. Results

The most severe storms impacting Barcelona beaches are Eastern/Northeastern episodes between October and November (Fig. 4). They produce a significant change in the morphology (shoreline erosion, nearshore bar dynamics) and, sometimes, the destruction of urban equipment. Ideally, the storms represent a redistribution of sediment in the emerged and submerged beach, which adopts a profile with a gentler slope.

3.1. Shoreline trends and beach nourishments

The observed morphologic response to storms of the shoreline of Barcelona beaches can be grouped into three categories: a) general erosion, b) rotation of the beach, c) differential erosion / accretion along the beach (Figg. 4, 5). The rotation and differential erosion / accretion are the most common situations caused by the oblique incidence of waves and the shoreline configuration previous to the storm. After storms, in low-energy conditions, there is a tendency of beaches to gradually recover their previous configuration. The shoreline evolution of Barcelona beaches from 2001 to the present day shows a general erosional trend, which

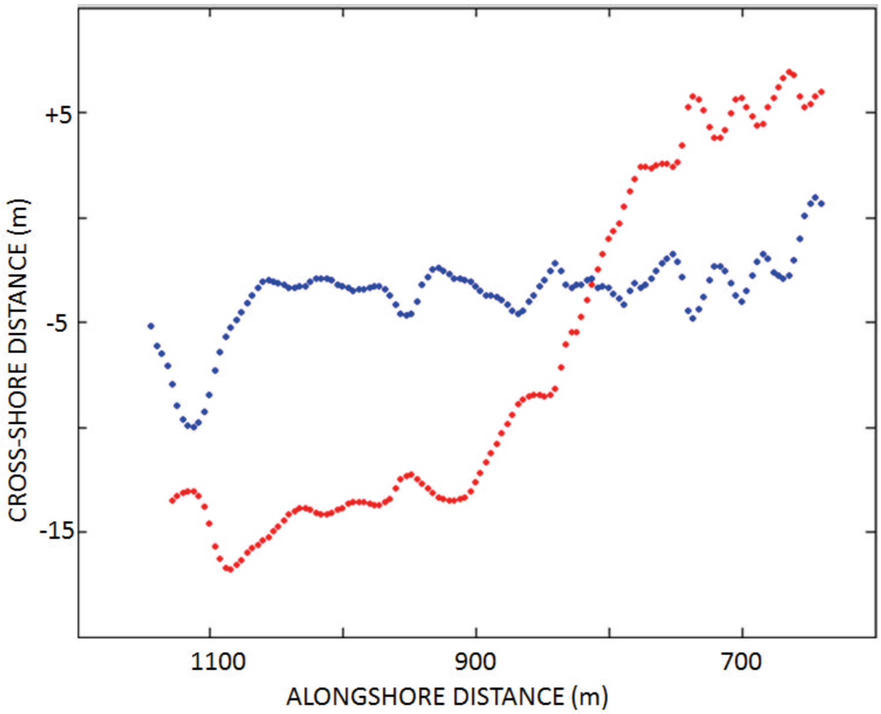

Fig. 4 - Changes of Bogatell beach shoreline caused by the November 2001 storm (dark blue before the storm and light red after the storm).

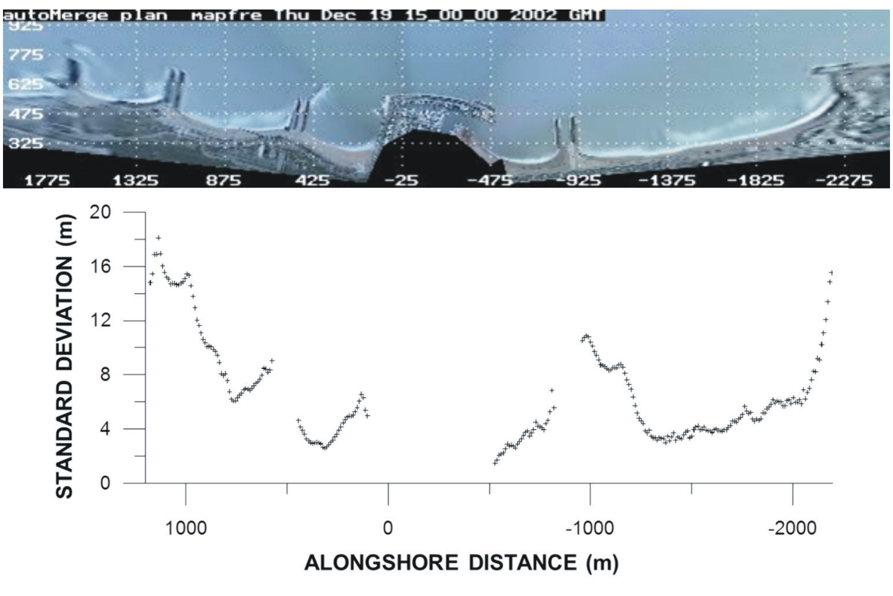

Fig. 5 - Variability of the shoreline expressed as the standard deviation of its position throughout the year (2002).

is partially offset by sand regenerations. For example, in June 2002, about 40,000 m^3 of sediments were dumped in the northern area of La Barceloneta beach, widening the beach over ten meters. After the nourishment, the coastline gradually retreated because the effect of storms and a configuration equivalent to the pre-nourishment was already achieved in February 2003.

The emerged area of La Barceloneta beach was approximately 60,000 m^2 in October 2001 and decreased to 50,000 m^2 in 2007, before the construction of a new detached breakwater (Fig. 6). These losses of surface in the emerged beach occurred in spite of the artificial nourishment conducted in summer 2002 and the relocation of sand from the south of the northern section in June 2004, which increased the total emerged area 6,000 m^2 and 2,000 m^2 respectively (see Ojeda & Guillen (2008) for additional information).

The latest significant sand nourishment was performed

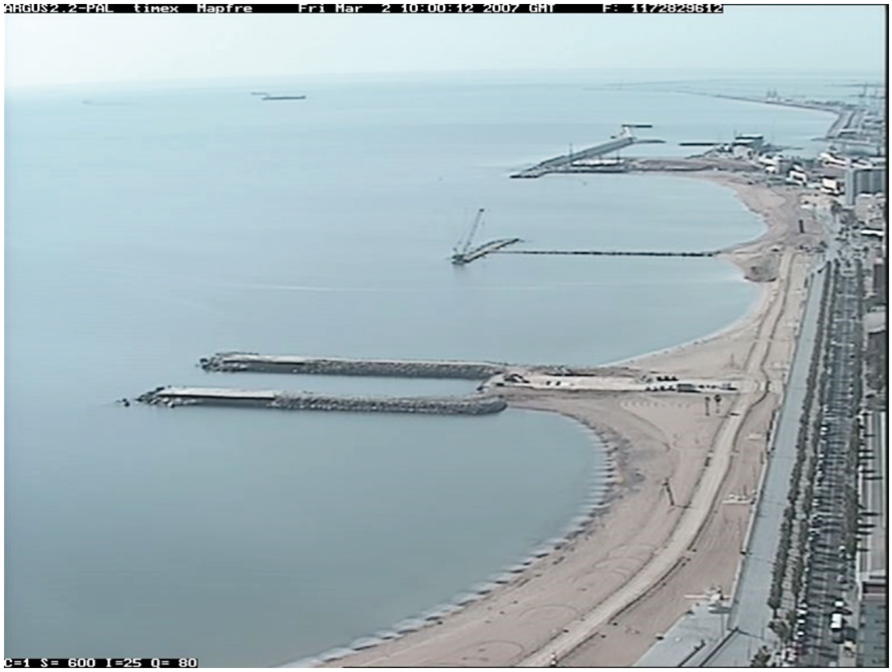

Fig. 6 - Beach nourishment and construction of a parallel detached breakwater in the La Barceloneta beach in 2007.

in July 2010, when about 537,000 m^3 of sand were dumped along Barcelona beaches. The comparison between topo-bathymetric campaigns (July 2010 and October 2014) indicates that 51% (273,000 m^3) of the dumped sediment was remobilized and transported offshore, and about 10-15% escaped of the coastal system. The emerged beach lost is around 17% of the surface during this period. It should be noted that storms were of low-medium intensity during this period.

In short, sediment transport associated with waves and currents causes a negative sediment balance on the beaches of Barcelona. In the absence of natural sedimentary inputs, the negative sediment balance should be compensated by artificial nourishments. The magnitude of the annual sediment deficit is variable and depends on the wave climate affecting beaches, although volumetric annual losses of about 5% after a nourishment (higher if only the emerged beach is considered) seem to be a reasonable value. Protection works have reduced the sediment deficit which could allow to distance artificial regenerations in time or, alternatively, decrease its volume.

3.2. Dynamics of submerged beach: sand bars

The sandbars are submerged longitudinal banks whose evolution is closely related to the evolution of the beach. These nearshore bars are oblique to the shoreline, with the northern end of the bar closer to the beach (Fig. 7). The most common planview configuration of the bars is characterized by a crescentic morphology. The formation of beach cusps is apparently related to the nearshore bars configuration, although they can stand for years. Waves break on the crest of bars and dissipate part of their energy before reaching the beach. The bars are very dynamic and migrate to sea and landward in response to certain storm or wave conditions. In general, if it is considered a significant wave height (Hs) increasing, the bar behavior evolves from a situation of non-migration, a migration landwards and eventually migration offshore during the most energetic storm period. Typical cross-shore migration rates (negative towards the beach) range between 7.2 and -3 m/day and 6.4 and -4.0 m / day in La Barceloneta and Bogatell beach respectively, with maximum total displacement of 70 m.

4. Concluding Remarks

Coastal urban Mediterranean environments are characterized by a huge number of users. The management of these beaches is mainly oriented to the maintenance of the emerged beach surface to allow recreational uses and the protection of the urban equipment. This would ideally imply some kind of stabilization of the emerged beach to reduce their mobility. Most of actuations in Barcelona beaches followed this goal, reducing the mobility of the beach by segmenting the coast and decreasing the wave energy that reaches the beach through different kinds of breakwaters. Additionally, several beach nourishments were carried out. The main morphodynamic changes in Barcelona beaches during the 2001-2016 period have been caused by

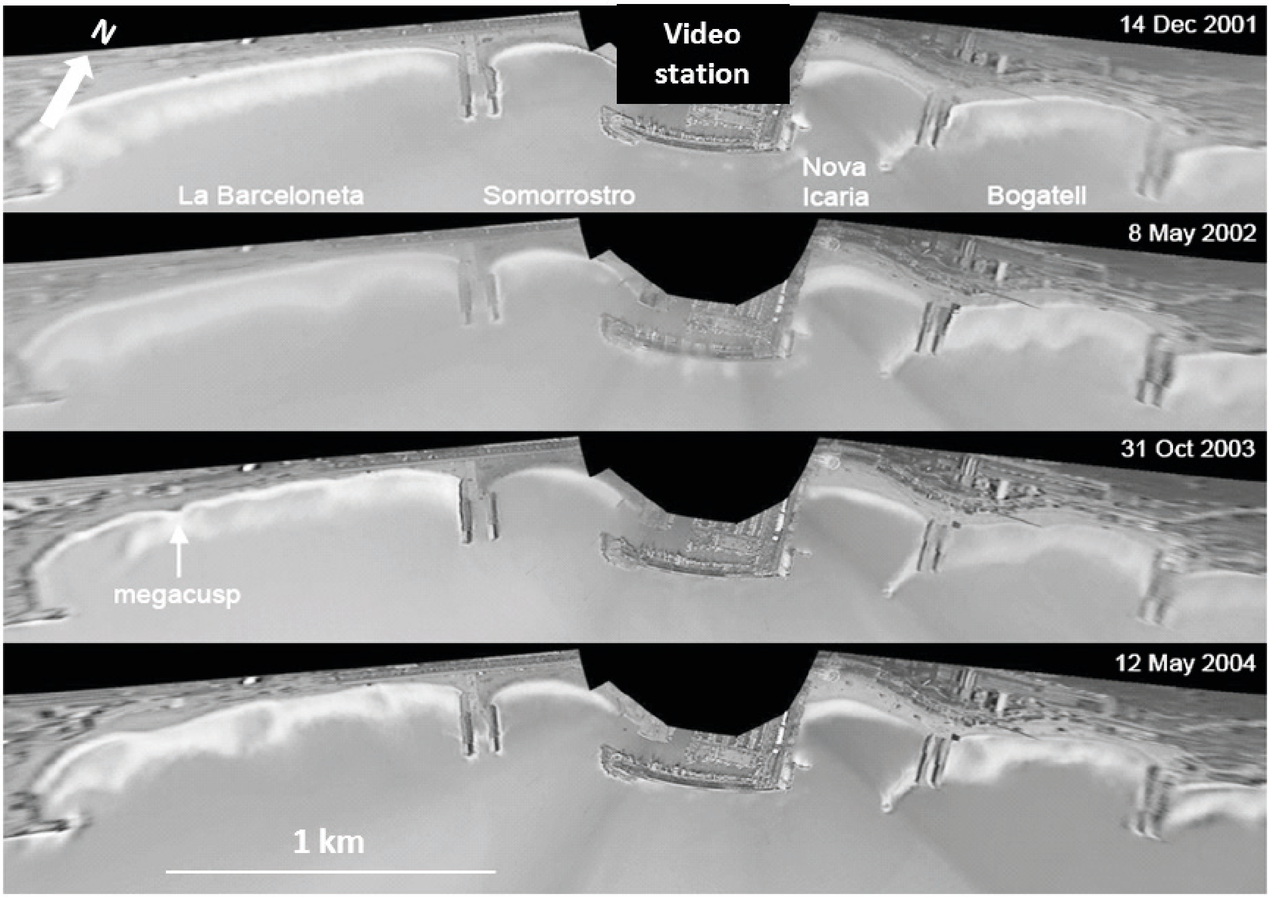

Fig. 7 - Evolution of nearshore bars and location of megacusps before the construction of detached breakwaters.

the construction of detached breakwaters that transformed the system from morphodynamic states characterized by nearshore bars to a system where the bar is replaced by fixed detached offshore breakwaters. Potential induced changes in the slope of the beach have not been detected.

Therefore, the anthropic actions have substantially changed the dynamics of the different sedimentary processes on the beaches. In spite of that, and although with less intensity, the shoreline continues to be very dynamic and significant cross-shore sediment transport occurs. The interventions oriented to beach stabilization made during the last decade have helped to reduce the mobility of the beaches and the impact (erosion) of the storms. However, in the future, new actions will be required (artificial nourishment, maintenance of breakwaters, sand by-pass, etc.) hopefully with a lower frequency or lower intensity than in the last recent years.

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