Dynamics of the rhythmic morphology on the low-energy Trabucador beach (Ebro delta)

Dinámica de la morfología rítmica en la playa de baja energía del Trabucador (Delta del Ebro).

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Abstract: Observations of rhythmic morphology along the Trabucador beach are contrasted with two numerical models to unravel the mechanisms of their formation. The Trabucador is a long narrow barrier at the SW side of the Ebro delta (Catalonia). Its inner side is a microtidal low energy beach with a sandy shallow terrace featuring an intricate rhythmic morphology. Sixteen aerial orthophotos from 1946 to 2014 have been analyzed and complemented with field observations from 1986 to present. The morphology is dynamic and it is usually characterized by: a) long transverse finger bars (LTFB) and b) large scale shoreline undulations (LSSU). The LTFB are thin and elongated, commonly opening an anticlockwise angle of 10°–40° with the shore normal. Their alongshore spacing is in the range 15 − 25 m, with a secondary wavelength in the range 30 − 65 m. The LSSU typically have wavelengths in the range 150 − 250 m. Numerical modelling shows that both features could emerge out of feedbacks between hydrodynamics and morphology during the SW wind events involving a) deflection of the longshore current by the bars combined with the refractive wave focusing and b) gradients in total alongshore sediment transport rate triggering the high-angle wave instability.

Key words: transverse finger bars, shoreline undulations, protected beaches, Ebro delta, morphodynamic instabilities

Resumen: *En esta comunicación se contrastan dos modelos numéricos con observaciones de la morfología rítmica de la playa interna en la barra del Trabucador. El Trabucador es una barra larga y estrecha situada en el flanco Sur-Oeste del Delta del Ebro. La parte interna de la barra es una playa micromareal de baja energía con una terraza de arena que contiene una compleja morfología rítmica a lo largo de la línea de costa. Se ha utilizado ortofotogrametría de la zona desde 1946 hasta 2014 y medidas de campo realizadas desde 1986 hasta la actualidad. La morfología es dinámica y se caracteriza por: a) barras transversales alargadas (LFTB) i b) ondulaciones de la línea de costa a gran escala (LSSU). Las LFTB tienen una forma delgada y larga, y una orientación anti horaria de 10°–40° con respecto a la dirección normal a la costa. El espaciado longitudinal entre estas barras es entre 15 y 25 m con una segunda longitud de onda entre 30 y 65 m. Las LSSU tienen una longitud de onda entre 150 y 250 m. El modelo numérico muestra que ambas morfologías pueden formarse de la retroalimentación entre la hidrodinámica y la morfología durante los eventos de viento de Sur-Oeste a través de a) deflexión de la corriente longitudinal en las barras combinada con la concentración de olas refractadas y b) gradientes en el flujo de sedimento en dirección longitudinal desencadenando la inestabilidad de ola de ángulo grande.*

Palabras clave: *barras transversales alargadas; ondulaciones de la línea de costa; playas protegidas; Delta del Ebro; inestabilidades morfodinámicas*

INTRODUCTION

The nearshore bathymetry and the shoreline in plain view may display complex and intriguing spatial patterns. These patterns can be alongshore rhythmic, that is, they consist of morphological features which are approximately recurrent along the coast with a typical alongshore length L. Several of such patterns have been identified (Guillén et al. 2017) but we here focus on: i) *transverse bar systems* (TB) and ii) large scale shoreline undulations (LSSU). The TB occur in the surf/shoaling zone and are sand bars extending perpendicularly to the coast (or with a relatively small angle with the shore-normal). They use to attach to the shoreline at the apexes of shoreline undulations which are known as *megacusps.* Several types of TB have been described and we here refer to the *long finger transverse bars* (LFTB)(Pellón, Garnier, and Medina 2014). LFTB are persistent in time and appear in low to medium wave energy beaches with a very flat terrace (Falqués 1989).

They are oriented with a small angle from the shore normal and they are characterized by long crests, with their length being larger than the alongshore spacing (which is typically between 10 and 500 m). The LSSU are shoreline undulations with an alongshore wavelength larger (one order of magnitude or more) than the megacusps. They are linked to similar undulations in the bathymetric lines extending both in the surf and shoaling zones (Guillén et al., 2017).

The formation and driving mechanisms of nearshore rhythmic patterns is one of the important unknowns that coastal scientists have tried to unravel during the last decades. This remarkable spatial regularity in such complex systems involving both hydrodynamics and morphodynamics suggests that these patterns are the visible imprint of dominant physical processes occurring at their particular length scale, L. It has been shown that many of these patterns can emerge out of the corresponding featureless morphology through instabilities caused by a positive feedback between water motion and morphology via the sediment transport. This is known as the self-organization theory for their formation. But checking the self-organization theory is not easy since a very frequent monitoring is needed (bathymetries, currents and wave measurements). The Trabucador beach, located at the southwestern flank of the Ebro delta is a long spit/barrier beach that separates the Alfacs Bay from the open Mediterranean Sea. Its inner side often displays transverse bars with megacusps as shown both by the aerial photos available since 1946 and the in-situ observations. At the same time, large scale shoreline undulations sometimes appear. Because of the clear signature of LFTB and LSSU, their persistence and their dynamic nature, the Trabucador beach is an ideal site to test the self-organization hypothesis and to investigate the specific mechanisms driving their formation and dynamics.

This paper presents a study of the shoreline of the inner Trabucador beach at different times, including the transverse bars, the megacusps and the large scale shoreline undulations, by using the spectral analysis of the aerial orthophotos to describe their spatial characteristics. Furthermore, we use numerical modelling based on the self-organization hypothesis, to give some light on the driving mechanisms triggering the formation and the dynamics of these rhythmic morphologies.

STUDY AREA AND MORPHOLOGY

The Ebro delta is located at the western Mediterranean sea, NE of the Iberian peninsula, in Catalonia. The Trabucador barrier is long (6 km) and narrow (125 m) and forms the southern spit of the delta tending to the SW, ending at La Banya and enclosing the Alfacs Bay. This bay can be hydrodynamically classified as an enclosed lagoon with a micro-tidal regime and water circulation dominated by the local wind and the occasional seiche activity (Cerralbo et al. 2014). The wind regime is mostly from NW in winter (80% of the time) and it is often from SW in summer (sea breeze). Fig. 1 shows the wave fields created by these two wind conditions. The study area is a sandy and shallow shelf (125 m width and 0.7 maximum depth) composed of fine sand (Mujal-Colilles, Grifoll, and Falqués 2019) located at the inner side of the Trabucador, facing the Alfacs Bay.

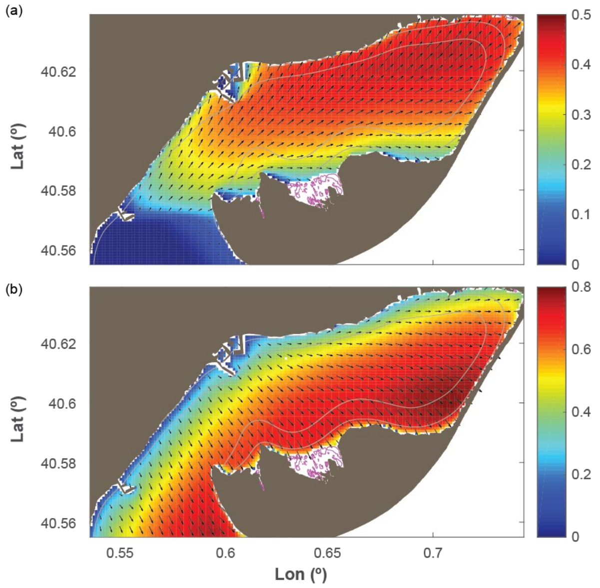

FIGURE *1. Spatial distribution of the significant wave height and wave direction of propagation obtained with SWAN model. (a) SW events with 9 m/s of wind speed (b) NW events with 15 m/s of wind speed.*

The LFTB are intertidal, elongated and orientated with a slight angle with respect to the shore normal varying from 10º to 40º (to the left, viewing them from the beach). The spacing between bars can range from 5 to 100 m with a typical distance of 20 m, the largest ones having smaller bars in between. Most bars are attached to the shoreline and their attachments form the apexes of the megacusps. (Evans 1938) described similar LFTB on low energy beaches with abundant sediment supply forming a shallow terrace. Moreover, the LFTB have a cross-section asymmetry that suggests the presence of an alongshore current directed to the NE. (Fig. 1). Our working hypothesis is that SW wind events may trigger the growth of the bars through a morphodynamic instability.

On the other hand, large scale shoreline undulations, Fig. 2b, have been detected after the visual inspections of the aerial photos, with a wavelength on the order of 100-250 m. The apexes of these undulations sometimes coincide with the attachment of one of the largest LFTB but not always.

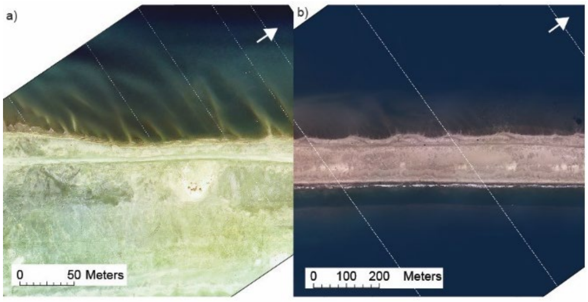

FIGURE 2. *(a) Transverse bar system in 2012; (b) large scale undulations in 2013. Source: ICGC*

METHODS AND RESULTS

The methodology used to investigate the formation and driving mechanisms of the patterns in at the Trabucador inner shoreline combines the study of the aerial photos and the use of numerical models.

A total of 16 orthophotos taken from 1946 to 2014 were analyzed to better describe the physical characteristics of the shoreline undulations. First, the apparent shoreline/bar signal (ASB) is obtained from a manual profiling of the orthophotos, followed by a rotation along the x-axis using the permanent road that crosses the barrier beach. Afterwards, an interpolation is needed to have a digital signal with equi-spaced points (Fig. 3). Fig. 4 shows the ASB signal obtained from all the orthophotos available.

Subsequently a Fourier analysis of the ASB signal is performed. Bartlett's Fourier analysis is used to obtain the low wavelengths whereas FFT yields better results when looking at the high wavelengths present in each signal. It is important to highlight that the methodology described previously does not allow to capture wavelengths lower that 10 meters mainly due to the interpolation. Also, since the studied ASB signal length is 2 km, no wavelengths larger than 1 km can be resolved.

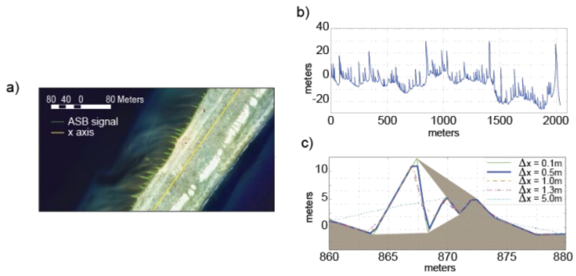

FIGURE 3. *Methodology used to analyze the evolution of the shoreline. (a) In yellow: signal obtained from the manual profiling; (b) Signal obtained after rotating the original data; (c) Interpolation of equi-spaced points using different Δx.*

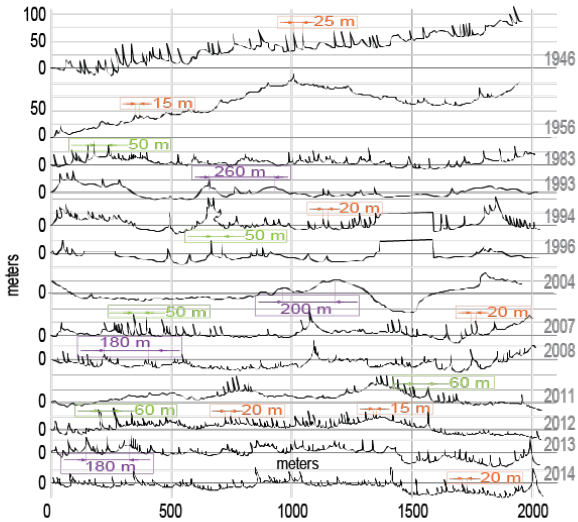

FIGURE 4. *Time evolution of the apparent shoreline/bar signal .*

Wavelength, λ (m)	# of analyzed years where each range is present
$\lambda < 20$	15
$30 < \lambda < 65$	16
$100 < \lambda < 200$	12
$\lambda \sim 400$	4
$\lambda \sim 600$	7

Table 1. Statistics of the main wavelength results obtained from the Fourier analysis of the aerial orthophotos.

The results of the Fourier analysis are shown in Table 1 and confirm the existence of two main groups in the low wavelength range: i) 15-25 m and a ii) 30-65 m. Likewise large wavelengths can be grouped into three main bands: (a) 150-250 m, (b) 400 m and (c) large undulations with 500-700 m of wavelength.

Three numerical models were used for different purposes. Firstly, SWAN provides the maximum wave height and incidence angle close to the shoreline for given wind conditions (see Fig. 1). The results obtained from the SW events indicate that at a water depth D=1.6 m waves can have a significant height of H_s = 0.25 m and an incidence angle with respect to North of 260º, that is, 46º with respect to the shore normal.

The results yielded by SWAN are used as reference input variables for the morfo55 model, a 2DH morphodynamic model. The computational domain is 100 m alongshore and 50 m crosshore with a grid size of 0.5 m. The forcing wave parameters are considered constant and set to H_s = 0.28 m, T_p = 2.5 s and θ = 30º. After 14 hours a weak rhythmic pattern of up-current oriented bars with a wavelength of 10 m is noticeable. Subsequently, this pattern grows and evolves undergoing nonlinear processes that bring a final wavelength of 33 m. After 37 hours a transverse bar system which is qualitatively very similar to the observed one is already fully developed (Fig. 5).

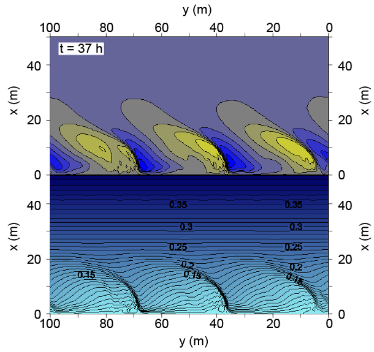

FIGURE 5. *Final morphology of the bars obtained with the morfo55 model.*

The morfo55 model cannot deal with the dynamics of the large scale undulations, not only due to computational constraints but also because the fast evolving surf zone bars would spoil down the longer term dynamics. Therefore, a one-line type shoreline model (1D-morfo) has been used to study the possible LSSU triggered by high-angle wave instability in case of SW winds (Ashton, Murray, and Arnault 2001). Fig. 6a shows the cross-shore profile used as model input, which is based in a bathymetric survey. Fig. 6b shows the dominant wavelength as a function of the wave angle for different parameter values. The modelled large scale shoreline undulations have a wavelength in the range of 100 to 500 m, which is consistent with the observed range from the orthophoto analysis (Table 1). The characteristic formation time is about 1 month, much larger than that of LFTB.

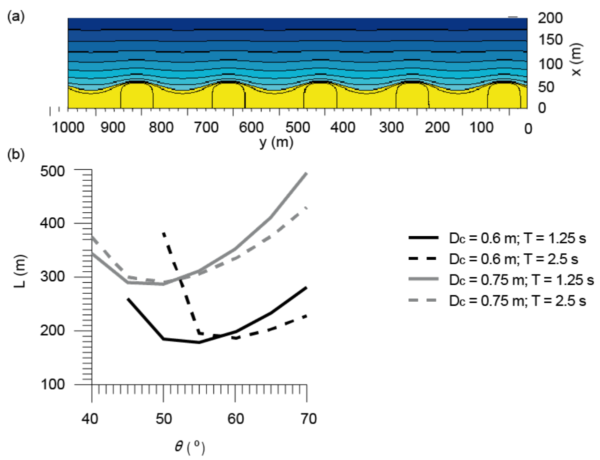

FIGURE 6. *Results obtained from 1D morfo model. (a) plain view of large-scale undulations of 200 m wavelength with bathymetric lines every 0.1m (amplitude value in the model = 10m), (b) dominant wavelength (black: Dc = 0.6, gray: Dc = 0.75; continuous: T = 1.25; dashed T = 2.5)*

CONCLUSIONS

The analysis of the orthophotos and the field observations has shown that the complex morphology of the inner side of the Trabucador barrier is nowadays active. There are three main ranges of wavelengths linked to two different morphologies: LFTB/megacusps, with wavelengths between 15 to 65 m (commonly, 20 m) and larger scale shoreline undulations, with two principal wavelengths, that is, i) 140-400 m (commonly 150-250) and ii) larger than 500 m.

The hypothesis of the self-organized origin of such features, mainly driven by SW wind events, seems plausible according to the preliminary results of the numerical models. However, further research is needed to gain confidence and to unravel the specific dominant driving mechanisms. This would require: i) detailed and continuous field observations to elucidate the effect of the different meteorological conditions and ii) model runs for such conditions.

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