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Dynamics of a nearshore bar system in the northern Adriatic: A video-based morphological classification

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ABSTRACT

The aim of this paper is to define a simplified morphodynamic classification suitable for low energy beaches exposed to microtidal conditions. The study site is located in the northern Adriatic (in Italy), it is an almost 2 km-long rectilinear beach bordered at the northern edge by coastal structures and at the southern end by a small river inlet. The mechanisms related to the evolution of the submerged part of the beach were derived from video-monitoring using Argus technology. The morphodynamic evolution of the system was studied using an automatic procedure on images for the characterisation of nearshore bars that showed good correspondence with hand-based (visual) interpretation. To apply this automatic procedure, the bar's plan crest shape was mapped using cross-shore pixel luminosity transects traced on time-averaged video images. A careful sensitivity analysis was undertaken to determine the best spacing between transects for the correct tracing of the shape of the bar crest. The error associated to a transect spacing every 25 m resulted in being comparable with the pixel resolution in the area and with the error found comparing the video interpretation with bathymetric surveys.

From the study of a four and a half year dataset (February 2003–May 2007), the submerged beach was found to be characterised by the presence of a single bar in the area next to coastal protection structures. However, moving southwards of these, inner and outer bars were present. The morphodynamics of the outer bar and its plan shape modifications were dominated by rhythmic forms. Occasionally, after high energy events, the bar became rectilinear but during the following lower energy periods rhythmicity was re-established, supporting the hypothesis of self-organization mechanisms. The cross-shore position of the bar's crests only showed limited cross-shore mobility through time.

1. Introduction

One of the main questions that have fascinated geologists and oceanographers specialising in coastal studies is stated at the beginning of one of the first quantitative studies on the subject (Huntley and Bowen, 1975): "Why are some beaches steep and other shallow?" Obviously the morphology results as a combination of factors such as the grain size of beach material and beach slope, which in turn is dependent on exposure to wave action. This explains why changes in wave climate can modify beach slope at time intervals of the order of hours to days and often produce cyclic changes of beach profile over longer time scales. At the time of the study of Huntley and Bowen (1975), laboratory modelling was largely empirical and the relevance of 2-D laboratory experiments to field conditions was doubtful. Therefore the authors focused their attention mainly on hydrodynamic processes such as wave breaking, energy dissipation, swash oscillations and presence of edge waves, which were believed to be a driving factor for the formation of rhythmic features (Bowen and Inman, 1971).

About 10 years later, with the publication of the seminal work of Wright and Short (1984) on beach morphodynamics, coastal research adopted a new approach to the study of beaches, wherefore physical measurements and monitoring of morphological changes became closely linked, providing input to energy descriptors (e.g. surf scaling and surf similarity parameters) that account for the relationship between beach slope and the type of breakers. The paper cited above was in reality a comprehensive review of a large field database collected by the authors in the period 1976–1982 (see also Short, 1979; Wright et al., 1979, 1982a, 1982b; Wright and Short, 1983), with study sites spanning from micro- to macro-tidal conditions, whereby wave energy (modal breaking wave height) varied from low (0.3 m) to high (5 m). Recently Short (2006) reviewed over 10,000 beach systems all-around the coast of Australia and basically showed that such a wide scale generalization is still of utmost importance for beach classifications. The applicability of the classification has been widely validated by studies carried out in various parts of the world, including the Mediterranean (e.g. Gómez-Pujol et al., 2007). However, in such a context dominated by an average low wave energy, the

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calculation of morphodynamic indexes based on modal wave energy alone may be misleading, as the duration of high energy events may play an important role in controlling dominant beach states (Armaroli et al., 2007; Jiménez et al., 2008).

Field studies of bar morphodynamics in the Mediterranean are scarce and particularly limited regarding rhythmic systems. Noticeable contributions are those of Barusseau and Saint-Guily (1981), Goldsmith et al. (1982), Bowman and Goldsmith (1983), Guillén and Palanques (1993), Certain (2002) and Certain and Barusseau (2005). The studies of beaches in the Mediterranean using Argus technology are so far rare and only focussed on the shoreline variability of beaches protected by structures (e.g. Armaroli et al., 2006b; Ojeda and Guillén, 2006, 2008; Ojeda et al., 2006; Archetti, 2009). To the knowledge of the authors, most previous studies of bar morphodynamics along open coastlines in the Mediterranean have not used high frequency monitoring methods based on video monitoring, as the studies cited above reach their conclusions on the basis of traditional echo-sounding surveys. The only published work on nearshore bar variability using Argus video methods (Holman and Stanley, 2007) is that of Ribas et al. (2010) who proved the suitability of the technique for studying tideless beaches adjacent to coastal structures along the urban coast of Barcelona.

As traditional surveys (e.g. bathymetric surveys and aerial photography) cannot resolve short-term (from hours to days) large-scale bed changes, the response of such systems to varying wave energy changes during and immediately after storms is not known. In addition to financial restrictions to be able to carry out frequent bathymetric surveys, logistical limitations exist (e.g. rough seas for soundings by boat, water turbidity for LIDAR flights) and normally fair-weather conditions are preferred.

As Turner et al. (2006) observed, the use of video systems in the last 20 years has allowed the monitoring of coastal changes at a frequency (from minutes to hours) which is unthinkable for direct bathymetric surveys (from days to months). Recent applications of video monitoring have enhanced the understanding of the evolution of large-scale morphologies on open coasts (e.g. Ortega-Sánchez et al., 2008), coastal spits (e.g. Medellín et al., 2008) and inlets (e.g. Siegle et al., 2007). Morphological numerical modelling of nearshore bar evolution has been enhanced by the coupling with video systems (e.g. Coco et al., 2004; Ranasinghe et al., 2004). However, as remarked by Stive and Reniers (2003), the non-linearity of surf zone processes is testified by the complexity associated with bar morphodynamics and with beach-cusps, which at present cannot be fully explained without citing the debate between self-organization and forced response.

The general scope of the current paper was to analyze the morphodynamic behaviour of an intermediate beach in the Mediterranean, focusing on changes in the plan shape of the nearshore bar and developing a morphodynamic classification able to account for spatial variability of the bar crest at scales of hundreds of meters alongshore. Since according to the reference work cited above these changes may be ephemeral and only seen during or immediately after high energy events, traditional surveying methods (e.g. bathymetries) may not be the appropriate mode of study because of the difficulty of accessing the surf-zone in these conditions. On the other hand, remote-sensing techniques based on video-monitoring allow a continuous observation of the breaking wave patterns which are related to the submerged morphologies. Thus, the study was focused on the development of a semi-quantitative morphodynamic classification, based on the observation of breaking wave patterns.

1.1. Field site

Lido di Dante is a small village in the Emilia–Romagna Region (northern Italy), 10 km from the city of Ravenna (Fig. 1). The beach is a 3 km-long stretch of coast, almost aligned in a N–S direction, divided in two parts: the one in front of the Lido di Dante village (almost 1 km) is protected by a breakwater and three groynes. The other one (almost 2 km) is completely natural with dunes backed by a pine forest (Fig. 1). The present study deals with the unprotected part of the beach that extends from the southernmost groyne of the protected beach to the Bevano River mouth (Fig. 1).

According to Ciavola et al. (2003), the shoreline started to retreat in the late 1970 s, initially because of a regional decrease in river sediment supply and subsidence generated by gas extraction (Teatini et al., 2005). The comparison between several HWLs (High Water Lines, *cf.* Dolan and Hayden, 1983) mapped on aerial photos, using GIS techniques, reveals that the area still suffers from erosion even though many coastal protection schemes were undertaken to avoid the loss of sediment and the narrowing of the beach. The coastal structures in front of the village were built starting from the 1980s (Casadei et al., 1998). Three rock groynes and a breakwater were constructed and sandbags were placed on the beach. Moreover, several replenishments were undertaken with either sands extracted from inland quarries or dredging relict marine sediments accumulated in front of the Emilia–Romagna coast. In April–May 2007 a beach replenishment was undertaken, placing 107,000 m^3 of sand (M. Ceroni, personal communication) both inside the protected area and on the northern part of the natural beach, up to 800 m southwards from the groyne. Despite all these interventions the erosion is still undergoing and the beach is narrowing, mainly in the natural area next to structures. The southern boundary of the study area is delimited by a river mouth (Bevano River). Between 2003 and 2006 the river outlet was very active and moved northward by several hundreds of meters, eroding the dunes laterally (Balouin et al., 2006a). To prevent the erosion, the Regional Authorities moved the mouth 500 m southwards opening a new outlet and reconstructing the dunes (Gardelli et al., 2007).

The tidal regime is strongly asymmetric, showing both diurnal and semi-diurnal components. The maximum tidal range is about 0.9–1 m during spring tides. The wave climate is usually of low energy, with $0.5 \leq H_s < 1$ m, mainly from the east (65% of occurrences) (Gambolati et al., 1998). The 11% of data is defined as calm conditions ($H_s < 0.5$ m), therefore the total occurrence of low energy conditions is 76% (Idroser, 1996). Two different storm directions prevail in the northern Adriatic Sea: the Scirocco, from SE, and the Bora from E-NE. A high energy event ($H_s > 3$ m) occurred at the beginning of 2003 but unfortunately the Argus station was not operative yet. For further details on the characteristics of the events during the monitored period see Armaroli et al. (2007). The studied period was characterised by variable wave conditions (Fig. 2) and included a very strong storm which occurred in September 2004 with a wave height of more than 5 m, equivalent to a 25-year return period event (Ciavola et al., 2007). Energetic events occurred at the end of 2004, and at the beginning of 2005 and 2006. These last two periods were characterised by the clustering of several storms. From Spring 2006 to the end of 2007, the wave height did not exceed 3 m and was most of the time below 2 m (Fig. 2).

The sub-aerial beach sediment mean size is between fine to medium sand (2.3–1.1 φ); the submerged beach is composed of fine sand (2.22 φ; Gardelli et al., 2007). The submerged beach, with depths below Low Water Springs (−0.5 below MSL), in the area is characterised by the presence of offshore bars (Armaroli et al., 2007). The bathymetry close to the groyne shows a single bar next to the shoreline. Moving to the south, the bathymetry changes and the system is composed of two bars: the outer one is the termination of the single bar located near the groyne and its cross-shore distance from the shore increases along the study zone; the inner one is alternately attached and detached from the shore and shows rhythmic forms (Fig. 3). The morphodynamics of the submerged features are characterised by different states that change frequently according to variability in wave energy levels, but once they reach an equilibrium configuration they are stable over long periods (Armaroli et al., 2007).

As described by Armaroli et al. (2005) and Balouin et al. (2006b), the study area can be divided in three main parts. The northern one is characterised by shoreline and dune foot retreat, one bar attached/