ABSTRACT


This work aims to investigate the processes responsible for the morphodynamics of barred beach during storm events. The contribution compares the response of 2 nearshore bars during storm events at a microtidal double barred beach of the Gulf of Lions, NW Mediterranean Sea (France). Storm-specific experiments were undertaken to assess the morphological evolution of the shoreface. The initial and resulting morphologies are analysed together with wave parameters offshore and water level measurements. Current circulation on the bar system is simulated with MARS-SWAN numerical model. Both storm events presented almost similar hydrodynamic characteristics, and a pre-storm morphology characterised by crescentic bar patterns. However, the resulting morphological evolution was very contrasted. In first case, the bay of the well formed, small-size, crescentic bar was disrupted. In second case the longer crescentic pattern evolve to a more ample and skewed bar morphology. Model simulations indicate that the small size rhythmic crescentic bar patterns would be more able to generate rip circulation cells than the larger crescents patterns, even if a slight change in wave incidence is observed during one of the events. On this specific dataset, our analysis indicates that the nearshore hydrodynamics at the peak of the storm is driven mostly by the pre-storm morphology that is then responsible of the morphological response during the storm.

ADITIONAL INDEX WORDS: storm, nearshore bar, morphodynamic rip current.

INTRODUCTION

Coastlines and coastal plains, especially those suffering from long-term erosion, are particularly vulnerable to the impact of high energy events. Among the morphological responses to storm energy, impacts like huge beach erosion (sometimes producing dune and berm erosion cliff; see Castelle et al. 2007) are mostly prone to affect human activities in the beachface / backshore as well as lagoon systems. Another important impact is on the dynamics of nearshore sandbars. Rapid evolution of these morphologies has been widely described in the literature (Van Enckevort and Ruessink, 2003). According to the intensity and characteristics of the storm event, responses can encompass a temporary or definitive offshore migration (Winberg, 1995) as an important change in the tri-dimensionality of the bar systems (Almar et al., 2009). This process is particularly important as nearshore bars very often provide the shoreline with a natural protection dissipating storm wave energy, and thus contribute to the coastal sedimentary stock (Certain et al., 2005). An important literature was dedicated to nearshore bars systems (Van Enckevort and Ruessink, 2003), evidencing the role of offshore conditions, bar volume (Van Enckevort et al., 2004) and characteristics (wavelength, water depth above the crest, ...) on their morphodynamic (Calvet et al., 2007). However, most of the previous studies concerns meso- or macro-tidal beaches where processes are more complex given the exposition of the bar to shoaling, surf and swash processes during the tidal cycle (Masselink and Short, 1993). In microtidal or quasi non tidal environments (tide < 1 m) morphological evolution of nearshore bars is also highly variable: offshore migration, tridimensional to linear pattern, transition to transverse bars have already been observed (Goldsmith and al., 1982; Ferrer et al. 2009; Gervais et al., in press; Armaroli and Ciavola, 2010). The main factors involved in this evolution are the pre-storm morphology, the offshore hydrodynamic conditions, and the timescale of the event. Complex non-linear interactions occur in the surf zone (Stive and Reniers, 2003) and morphological responses are still difficult to predict. Self-organization models today explain most of the shoreface rhythmic pattern (Coco and Murray, 2007) as well as arising of crescentic bar morphology from non linear morphodynamical coupled models (Castelle et al. 2006).

The most dynamic bar system are usually the three-dimensional dynamic or transverse bars attached to the coast. Inner bar system in multi-barred beaches (Short and Aagard, 1993) is considered as the most dynamic system it is located in the shallowest shoreface, and also presents higher longshore variability. During storm events, offshore bed return flow is very often observed. However, planar circulation cells can develop (Aagard et al. 1998), whereby the mass flux of the waves is returned seawards through narrow longshore feeder and rip channels. According to pioneering study of Wright and Short
offshore significant wave heights (Gervais et al., 2010). Historical datasets in this area have evidenced the existence of storm side to expulse between the bar (MacMahan et al., 2005). The rip strongly affects the nearby bar morphodynamic.

Our contribution aims to investigate the main factors driving the 3D nearshore bar response during storm events, based on storm-specific field datasets, pre-storm bathymetry, forcing conditions (wave, current, and water level) and morphological responses (post-storm state) are analysed for two successive storms to evaluate their relative contribution to morphological responses. The study area is the Lido of Sète, on the French Mediterranean coast, where a storm-specific experiment was performed during two winter periods (2008-2009 and 2009-2010), within the European project MICORE (Morphological Impacts and Coastal Risks induced by extreme storm events).

STUDY AREA

The study area is a narrow microtidal sandy barrier: Le Lido de Sète à Marseillan isolating a large lagoon complex (Thau Lagoon) from the Mediterranean Sea (figure 1). The Lido of Sète is a double barred beach with a mean shoreline slope of ~0.9 % and grain size about 200 µm for the nearshore bars, including a quite important fraction of shells that can be observed in particular in the inner bar trough (Cortina et al., 2005). The inner bar is located between 80 and 170 m from the shoreline and its crest is around -2 m from the sea surface (see profile on figure 1). The outer bar distance is between 250 m and 400 m with a crest depth around 4 m. Mean tidal range is around 0.2 m and can reach 0.3 m during spring tides. Modal wave conditions are weak (Hs mean = 0.7 m; Tm mean ~ 4.5 s) but important wave episodes and storms in winter time are rather frequent. More than 3 events of Hs > 3 m per year occur in this region and annual return period for Hs is estimated at 4.3 m (Kergadallan, 2009). Storm conditions (around Hs > 3 m and Tm > 7.3 s) are often associated with onshore wind and low atmospheric pressure that generate a storm surge which may reach 0.8 m above mean sea level in most extreme case (water level measured outside breakers). Some rarer storm events are sometimes generated far away in the middle of the western Mediterranean basin, and in such conditions, the storm wave period, Ts, may reach 10 s without significant surge conditions on coast (Gervais et al., 2010, in press). The analysis performed on historical datasets in this area has evidenced the existence of storm threshold for morphological evolution that is mostly driven by onshore significant wave heights (Gervais et al., 2010, in press). When Hs reaches 2.7 m, morphologies are clearly modified: an offshore migration of internal nearshore bars begins, and overtopping of the berm occurs with large sand deposition on the backshore. However, the analysis of morphological response of successive events has also evidenced the probable influence of inherited morphologies on the magnitude of the observed evolution.

Previous field campaigns with current meters in Sète during oblique wave energetic events have shown that depth-average currents are dominated by longshore currents that increase shoreward with velocities up to 1 m/s in the inner trough with ~2.7 m of Hs measured offshore of the bar system (Cortina, 2002). Bed return currents dominate the cross-shore component over the beach profile with 0.25 m/s of maximum velocity in the inner bar trough. Cross-shore velocities are likely to increase with Hs that enhance the undertow (current reaches 0.35 m/s in inner trough for Hs around 3.5 m offshore).

Figure 1. Location of Sète beaches and Fieldsite (France). Nearshore bars are here visible with a DEM and a cross-section from the survey of November 2008 (before the storm of December 2008)

METHODOLOGY

In this study, analyses were focused on two major events of the winter 2008-2009 in order to investigate more specifically the processes involved in the complex evolution of 3 dimensional patterns of nearshore sandbars. Specific pre- and post-storm bathymetry (and topography) surveys were undertaken acquiring cross-shore profiles with a 50 m-spacing, using RTK DGPS coupled with an echosounder. Morphological evolution was analyzed using 11 profiles (~500 m alongshore distance) on the northern part of the Lido of Sète in a place where inner bar exhibited crescentic pattern while outer bar is relatively closer and in a shallower position compared to elsewhere, with a linear shape (figure 1). 3D patterns and volumetric evolution were studied from Digital Terrain Model (DTM) interpolation (using Golden Software Surfer 8, triangulation with linear interpolation method). The morphological parameters of the nearshore bars, i.e. elevation of the bar crest, obliquity, crescentic pattern (wave length amplitude), were used to determine the responses to storms. Hydrodynamics dataset (supplied by the DREAL-LR: Direction Régionale de l’Environnement, de l’Aménagement, et du Logement – Languedoc Roussillon) consists in wave measurements at Sète wave gauge (situated at 30 m water depth) and water-level series from a tidal gauge located in the harbour of Sète. Meteorological conditions are given by a weather station also located in Sète. In order to obtain hydrodynamics on the studied area, offshore wave conditions were propagated to the coast using SWAN model (Booij et al., 1999), and used to compute 2DH hydrodynamics over the bar systems using the MARS-SWAN model (Bruneau et al., 2007, 2009).

The MARS-SWAN model couples the spectral wave model SWAN (Booij et al., 1999) and the 2DH version of the flow model MARS (Lazure and Dumas, 2007). This model was successfully used to simulate evolving wave-driven circulations measured during an experiment conducted at Biscarrosse Beach on a strongly alongshore non-uniform bar and rip morphology (Bruneau et al., 2008, 2009). Default parameter settings were used throughout the present study. The model is not quantitatively
Table 1: Main hydrodynamic parameters of the two storm in Sète (Wave parameters at 30m water depth and water level above mean sea level in the harbour of Sète, and its surge component, averaged at storm peak).

<table>
<thead>
<tr>
<th>Wave parameters offshore and water level in the harbour</th>
<th>storm 1 (december 2008)</th>
<th>storm 2 (april 2009)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hs max (m)</td>
<td>4</td>
<td>3.4</td>
</tr>
<tr>
<td>Hmax (m)</td>
<td>6.3</td>
<td>6.4</td>
</tr>
<tr>
<td>Ts (s)</td>
<td>9.5</td>
<td>7.6</td>
</tr>
<tr>
<td>Incidence (°)</td>
<td>16.9</td>
<td>18.3</td>
</tr>
<tr>
<td>Water level (m)</td>
<td>0.24</td>
<td>0.27</td>
</tr>
<tr>
<td>Surge (m)</td>
<td>0.22</td>
<td>0.31</td>
</tr>
<tr>
<td>Maximum longshore wave energy flux (KW/m)</td>
<td>25.4</td>
<td>13.4</td>
</tr>
<tr>
<td>Duration for Hs &gt; 2.7 m (h)</td>
<td>16</td>
<td>11</td>
</tr>
<tr>
<td>Mean incidence for Hs &gt; 2.7 m (°)</td>
<td>16.6</td>
<td>20.2</td>
</tr>
</tbody>
</table>

RESULTS

Two storms have been selected in the storm dataset as they exhibited important similarity in term of wave incidence offshore and duration of the main storm peak above storm threshold Hs > 2.7 m, as well as relatively low storm surge (table 1 and figure 2).

The first storm of 26th December of 2008 was a long event (139 hours above 1m in Hs), with two separated peaks (Hs ~ 4 m for the first one, and Hs ~ 2.6 m for the second one 4 day after). Only the first really energetic peak is considered here since second one was below the storm threshold of Hs = 2.7 defined previously on a longer term dataset (Gervais et al. 2009, in press). Below this threshold, sediment dynamics still occurs but no significant change in the bar pattern is expected. The duration of this storm peak is 16 hours. Mean wave direction (at 30 m depth) of this peak was ESE (wave incidence = 16.6°) and reasonably unchanged for the whole peak duration (Hs> 2.7 m). Wave period at the peak was around 9 s. The wind was moderate and directed mostly seaward, and consequently storm surge was very limited (~ 0.22 m for the wave peak) as well as the resulting water level (0.24) since the tidal range was weak (figure 2). The main offshore wave parameters for the storm, considering either the maximum wave conditions or the whole peak is presented in table 1. Before the storm, the nearshore bar showed a very well-developed crescentic pattern with ~ 300 m of wavelength and cross-shore amplitude of ~ 40 m (see DTM in figure 3). The outer bar, almost parallel, was about 3.5 m depth and in oblique state and mean inner bar elevation was -1.5 m. After the storm, only inner bar exhibited a significant morphological evolution characterised by an onshore...
migration of the crescent horns (~ 50 m), with a slight SW (alongshore) migration in the direction of the wave propagation. These high points partially welded to the foreshore. Simultaneously, storm has forced the opening of the bay of the crescent with a retreat (~ 20 m) and disruption (flattening) of the bar crest in the bay. The computations with MARS-SWAN indicate that, during the December storm peak, a rip cell circulation was established over the rhythmic bar pattern with onshore mean currents on the horns, longshore current in the trough and offshore (stronger) rips in the bays (figure 3).

The second storm of the 26th April of 2009, was shorter (56 h above 1 m of Hs) with essentially a single peak of wave and less energetic maximum conditions (Hs~3.3 m, Ts ~ 7.6 s, incidence ~ 18°). However, storm peak duration (Hs > 2.7 m) is comparable to the December event, including two short-time wave pulses separated by 15 h, and having a total duration of 11 h. Wave direction was also ESE and very stable (mean incidence of 20.2°, slightly more than in December). The onshore wind was moderate but stronger at the wave peak. Thus, storm surge was slightly higher than in December, but remained moderate-low (0.31 m in the Sète harbour) and the resulting water level was low (0.27 m) due to the low tidal level. The initial morphology was also characterised by the presence of three-dimensional morphologies. However, this time, the wavelength of the crescentic pattern was more important (around 600 m, see figure 3). The resulting morphology, after the storm fall, was the development of more pronounced crescentic morphology and a strong asymmetry between the horns and the bays with a more oblique (or skewed) bar and rip system (figure 3). Once again, the bay of the crescent was affected and shifts offshore (~ 25 m) but with no total flattening of the crest relief. A small onshore migration (~ 10 m) of the horns was observed, but the entire rhythmic pattern was overall shifted south-westwards. Outer bar remain completely unchanged. At the storm peak, the MARS-SWAN model indicates that current velocities were more moderate over inner bar system and dominated by longshore current and bed return flows. However, the circulation pattern observed in December was partly reproduced in most stage of the events, but with more oblique rip currents at the output of the bay but still higher than elsewhere over the bar crest. This time no diverging flows form initially over the bar horn.

Both storms events have induced a large shift in inner bar location and shape while outer bar remain mostly unchanged. For both events, inner bar shape evolved from a relatively straight crescentic bar pattern to a more complex bar and transverse rip (channel) morphology. In December 2008 crescentic bar has been disrupted in the bay while in April 2009, crescentic shape is preserved but shift further with longshore transport. Elevation models give dominant erosion in the immersed domain, around 15 m³/m² for each event.

In order to qualitatively assess the magnitude of rip currents during the different phases of the storms, several nodes of the grid model have been extracted. It was checked first that during the two events a steady circulation pattern is observed all along the peak period. The magnitude of currents would appear to be modulated by the wave height for rising/falling conditions. Mean rip-current velocity was higher during the December storm (reaching twice the velocity of the rip-current during April 2009 event).

**DISCUSSION**

Morphodynamics of nearshore bars has been widely studied during the last decades, from the long-term evolution (Plant *et al.* 1999, Ruessink *et al.* 2009) to the short-term responses using video systems (Turner *et al.*, 2006; Armaroli and Ciavola, 2010). As pointed out by Stive and Reniers (2003) and Van Enckevort *et al.* (2004), crescentic bar morphodynamic and surf zone processes are highly non-linear, and create nontrivial responses to input forcings.

In this study, two specific storm events (December 2008 and April 2009) were chosen for their apparent similitude of the forcing conditions and same kind of initial nearshore morphologies (crescentic bars). The main differences between both events are:

- A slightly more energetic conditions during December event: Hs max at 4 m, while only 3.4 m for April, with respectively 9.5 s and 7.6 s for associated wave periods.
Difference in offshore wave incidence was very small (see table 1);
- Different previous morphologies with a very well-defined crescentic bar in December with a short wavelength, and a much larger crescentic bar in April (respectively 300 and 600 m).

During the December storm, MARS-SWAN model output indicates the development of a cell-circulation over the inner bar with strong shore-normal rip currents. The resulting morphology evolution was the disruption of bar crest in its bay as already observed by Ferret et al. 2009 in similar environment of the Gulf of Lion. Shoals attached to the shore and a rip channel was excavated. During the second event, a more longshore circulation was established with a low oblique rip current in the bay, resulting in the formation of very asymmetric crescentic bar with some rip channel resemblance with transverse bar.

Wave height normalized by wave period (Hb/T) is often considered as a key parameter in bar state change and evolution from crescentic-longshore bar to crescentic-transverse bar and rips as describe by previous work (Short and Aagaard, 1993). In this work storms conditions have not straightened the bar morphology but inversely favored a more pronounced 3D pattern. Onshore migration during the high-energy waves can be explained by different sediment transport processes such as flow velocity skewness or wave asymmetry (Bruneau et al. 2009). Previous works on rip current indicate that differences in the rip flow are mostly driven by the breaker wave height (from review of MacMahan et al., 2005). However, according to Certain (2002) in the same site, the significant wave height in outer trough seems to be limited from outer bar dissipation in storm conditions (Hs limited at 1.5 m seaward of the inner bar). Consequently, breaker height Hb over inner bar is not expected to be different for two studied events, even if wave period could have induced small difference in breaker type.

Offshore wave incidence was slightly more pronounced during the April event (20.2° while it was 16.6° in December), and could explain the longshore circulation that was established in the inner through. According to the numerical test work of Castelle et al. (2006) to model crescentic bar formation, wave incidence plays a significant role as well as wave period in order to enhance the surf-zone eddies that will in turn favor crescent development. Long period swell and frontal incidence are preferred. Even if the difference in wave incidence between the studied events was low, it could explain the higher longshore component in both currents and morphological evolution.

Since no significant difference (and small values) of surge and water level are observed, it is not expected to play any important role with more than 1.5 m of water depth under inner surf breakers. Wave set-up differences in inner surf zone, from the model at storm peaks, are about 15 % on crescent horns with ~0.2 m of amplitude between calm conditions and storm peaks. But set-up longshore difference between the bay and the horn is higher in December and could have induced the generation of rip-currents (Wright and Short, 1984).

The role of pre-storm morphology on the establishment on three-dimensional circulation and thus on the morphological evolution is also probable. Even if the debate between forced and self-organisation processes in the generation of rip-current and cell-circulation is still open, field observations have indicated the role of morphology (existence of rip channels or lower morphologies) on the location and spacing of rip-currents (Yos, 1976, Short and Bander, 1999). Other recent studies support that rip spacing, consequently nearshore bar rhythmicity, is not (only) controlled from the previous day wave conditions but more from a slowest evolution of nearshore topography (Turner et al., 2007; Smith et al., 2008).

The pre-storm morphology at the lido of Sète can have played an important role on the establishment of a cell-circulation in December. Moreover, with a slightly more incident wave and a wider crescentic shape, the longshore current in the internal trough is expected to be more canalised in the trough.

Figure 4. MARS-SWAN 2DH circulation in surf-zone simulates for the two storms peaks: December 2008 and April 2009 over a same immobile bathymetry. (Current speed is informed but is not validate with measurements)

In order to evaluate the respective role of incident wave/pre-storm morphology, a new hydrodynamics simulation has been performed with MARS-SWAN model (Figure 4). Hydrodynamics of the April 2009 event were used as boundary conditions on the pre-storm morphology of December 2008. The main objective was to determine the type of nearshore circulation that develops with lower and more oblique incident waves. Model outputs evidence that April storm would create same current template than during December storm for all the storm peak duration. Difference in velocity would be only of 10 % weaker in the rip neck at the storm peak of April than the one of December (for 3.4 m against 4 m of Hs max at 30 m depth). This result evidences the role of the pre-storm morphology in the current circulation that is generated in the surf zone. Even with lower waves, and more oblique wave approach, the current pattern is similar. Small difference in wave incidence to the normal direction would create less symmetric rip cells at each side of crescent horn, with diverging flows. This induced a more oblique rip current too.

The difference of two storms surf-zone model circulation is really low, and argues for the predominance of pre-storm morphology on the morphological evolution during the storm.

CONCLUSION

This work investigates the morphological evolution of crescentic bar patterns, in a microtidal site, during two storm events. MARS-SWAN model is use as a tool to represent the 2DH circulation cells patterns over the three-dimensional inner bar system during the storms. The present contribution does not aim to take a position on the theories for the generation of three-dimensional morphologies and rip-currents. The studied datasets of morphological responses during two storm events with almost similar forcings evidences the role of pre-storm morphologies on the current circulation pattern and the resulting morphological evolution. Further analyses and morphological modeling of these events would be useful to investigate more precisely the role of the wavelength of the crescentic bars on the morphodynamics during a storm event.

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LITERATURE CITED


