Understanding the coastal variability at Norte beach, Portugal

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ABSTRACT


Norte beach stands in a coastal stretch fully exposed to the high energetic North Atlantic wave regime. The beach is located updrift of the Nazaré submarine canyon head, a sedimentary sink that captures the southward directed longshore drift. Systematic monitoring of Norte beach has been conducted by a coastal video monitoring system since 2008. A total of 31 monthly coastlines were extracted and analyzed in the period between December 2008 and May 2012. Results show a rare high seasonal coastline variability which exceeds 160 m in the southward sector (adjacent to the headland) and 70 m at the central and north sectors. These coastline variations are related with modifications in the planform beach configuration: beach oscillates between a straight (generally from June to August) an arcuate configuration (during the remaining months of the year). Results suggest that Norte beach variability depends mainly on longshore drift gradients rather than with cross-shore sedimentary transfers. The intense wave refraction over the canyon head, associated with the westerly swell waves, generates a sedimentary convergence at the centre of the beach promoting the increase of the beach curvature, while, northern and/or short waves (more frequent in summer) tend to linearize the beach. This work contributed with valuable information about the sedimentary dynamics of the Norte beach and showed that this site is a suitable candidate to evaluate longshore drift from shoreline changes.

ADDITIONAL INDEX WORDS: Coastline variability, video monitoring, longshore drift, seasonality.

INTRODUCTION

Understanding beach morphological variability is essential to support coastal risk assessment and help in the decision making process, especially in what concerns the implementation of mitigation measures in response to erosive events reported worldwide.

It is now well established that shoreline erosion is closely related to longshore drift gradients, so the quantification of this process is essential to understand and predict coastline evolution.

The quantification of longshore sediment transport goes back to the middle of last century, and was accomplished by the evaluation of the sediment blocked in artificial structures, or by the inverse process i.e. by the quantification of the erosion rates downdrift of the blocking structure. This method was developed in the pioneering work of Watts (1953), and followed by numerous authors during the XXth century (see Komar, 1998 for a critical review of this theme). However, this method is prone to errors, such as the local effects of the structures on local wave and currents, sand bypassing in front of the structures, and the time needed to retain enough sediment that can induce shoreline changes that are unequivocally higher than the uncertainties of the measurement techniques.

Naturally, the quantification of sediment retention and associated longshore drift can also be performed in natural structures such as headlands, sand spits, inlets and estuaries. In the former the sand retention processes and coastline evolution are similar to the ones observed in artificial structures. However in headland settings it is not generally possible to define neither the conditions where the retention process began nor the transposing processes (time and magnitude). Yet, in some cases the coastline evolution related with the retention process can be identified; this generally occurs where the downdrift boundary of a littoral cell only allows one way sediment transposition (e.g. related to the existence of a submarine canyon). In these cases longshore drift inversions lead to a sedimentary depletion of the updrift beach adjacent to the headland; if the longshore drift inversion is persistent enough to retreat the coastline to a minimum the subsequent infill of the beach can be used to access longshore drift. This method is only suitable when the magnitude of coastline variations in relation to longshore processes clearly dominates the cross-shore component.

The use of video-monitoring techniques has already been established as an efficient tool for coastal monitoring providing high-resolution data both in the spatial and temporal domains (Holman and Stanley, 2007; Davidson et al., 2007 and Van Koningsveld et al., 2007). Since the works of Plant and Holman (1997) and Davidson et al. (1997) video monitoring has been widely used in coastline evolution studies (e.g. Aarninkhof et al. 2003; Alexander and Holman, 2004; Armaroli et al., 2007; Conley et al., 2007, Silva et al., 2009). Generally coastline detection is...
performed trough the location of the water/land interface in time average images (TIMEX) where the swash effects are eliminated.

The present study aims to understand the shoreline variability, using video monitoring techniques, at a headland restricted beach located updrift of the Nazaré submarine canyon head, ultimately targeting its relationship with the longshore drift processes.

Study area

The study site, Norte beach, is located at the Portuguese west coast, which is exposed to the high energetic NW North Atlantic swell and the locally generated sea that is characterized by a wide directional spreading (from N to SW octants). Offshore incident wave regime is characterized by significant wave height of about 2 m and average peak period of 11 s (Dodet et al. 2010). It is characterized by a mesotidal regime with an amplitude that ranges from 1.5 at neap tides and 3.5 at spring tide. The wave propagation over the complex canyon morphology is responsible for one of the largest wave height surf spots in the world (with waves that exceed 20 m).

Norte beach is located at the southern limit of the littoral cell that extends from Espinho to Nazaré canyon (Figure 1). The beach, composed of -2.6 φ to 1.79 φ (mean value 0.18 φ) quartzic sand (Cascalho et al., 2012), is characterized by a wide berm and a steep beach face.

METHODS

For 3.5 years, shoreline evolution at Norte beach was assessed through a combination of monitoring techniques (video monitoring and DGPS topographic surveys), data acquisition procedures (wave and tide measurements), modeling (tide and waves) and processing tools (image analysis and Principal Component Analysis – PCA), described below.

Video monitoring

Systematic monitoring of Norte beach has been conducted by COSMOS coastal video monitoring system (Taborda and Silva, 2012) since December 2008. The video camera is installed in the Nazaré headland, about 50 m above mean sea level and is looking obliquely to Norte beach (Figure 1). Image acquisition was performed at 1 image per second, during 20 minute intervals each daylight hour. TIMEX images were created for each 10 minutes image block to eliminate the swash effects.

Despite some time gaps, due to technical failures, a total of 31 monthly Timex images of the beach were carefully chosen in the period between December 2008 and May 2012. Images were chosen based on a predefined total water level (TWL); this value - 2 m above mean sea level (MSL) - was defined in order to restrain the maximum run-up level to the beach face (therefore minimizing the horizontal error) and assure comparable conditions.

Each of the 31 monthly images was rectified using the 2 m height as the level for the rectification, following the procedures described in Taborda and Silva (2012). Camera laboratory calibration and camera extrinsic parameters were estimated following the methodology described in Silva et al. (2009) and in Taborda and Silva (2012).

During the monitoring period a total of 20 topographic field campaigns were performed at Norte beach in order to orientate, calibrate and support the video monitoring. The campaigns involved DGPS surveys of ground control points for the external orientation of the camera (5 campaigns), of 14 cross-shore beach profiles (20 campaigns) and the survey of the run-up reach (8 campaigns).

Shoreline elevation

The quantification of the shoreline elevation includes three main components: 1) astronomical tide; 2) storm surge; and 3) run-up. The astronomical tide was estimated, at 10 min. interval, for Peniche harbor, located about 40 km southward of Norte beach. This tide model was estimated through harmonic analyses from the data of 2010, collected by the national hydrographic institution (IH – Instituto Hidrográfico), with 20 harmonic constituents and an estimated precision of 10 cm (Antunes, 2007). A short tide elevation record acquired by IH, at Peniche and Nazaré gauges, show small differences, in height and time, which are in the order of the model precision.

To compute the run-up component several empirical models available in the literature (e.g. Guza and Thornton, 1981; Holman, 1986; Nielsen, 1989; Aarninkhof et al. 2003; Stockdon et al., 2006 and Hughes et al. 2010) were tested against field measurements of maximum run-up levels (Rmax). Results showed the inadequacy of existent empirical models to predict run-up magnitude at Norte beach. This can be explained by the high wave deformation induced by the presence of the canyon, which inhibits the direct application of most empirical models that rely on the offshore wave. For this reason, an empirical site specific run-up formula was developed in the scope of the present work. The development of this expression was based upon the best linear fit between offshore wave and tide parameters with field data.

Wave data

The offshore wave data was provided by the MONICAN project from the Portuguese Hydrographic Institute (http://monican.hidrografico.pt/) particularly by the buoy MONICAN01, located in the oceanic domain c.a. 2000 m depth

<table>
<thead>
<tr>
<th>Wave parameter</th>
<th>Bias</th>
<th>rmse</th>
<th>correlation coefficient</th>
<th>N. Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hs (m)</td>
<td>-0.036</td>
<td>0.386</td>
<td>0.946</td>
<td>7478</td>
</tr>
<tr>
<td>Tp (s)</td>
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<td>1.821</td>
<td>0.745</td>
<td>7487</td>
</tr>
<tr>
<td>Dir W (°)</td>
<td>-9.885</td>
<td>23.814</td>
<td>0.722</td>
<td>7333</td>
</tr>
</tbody>
</table>
and about 50 km offshore the Norte beach (Figure 1). The gaps of the buoy data (about 8% of the record) were filled with NOAA (National Oceanic and Atmospheric Administration) hindcast wave data for the nearest point (3 h interval between each record). Error statistics from the data comparison between measured data and hindcast are presented in the table 1. From the above procedure, a continuous offshore wave time series from December 2008 to May 2012 with 1 h interval between records was obtained.

The wave offshore conditions associated for each of the analyzed month were estimated based on the average of the wave parameters (Hs – Significant height, Tp – Peak period and Dir - Direction) of the previous 30 days.

Coastline detection

Coastline detection was performed on 31 rectified TIMEX images using the maximum likelihood supervised image classification method within ArcMAP software. The spectral signature for both water and sand areas was defined on representative TIMEX images and were used to classify the other rectified TIMEX images. Due to variable lighting conditions and the irregular extent of the breaking zone, a total of 4 different spectral signatures were used. Image classification results were visually validated and about 6% of the initially images were discharged and replaced by similar ones.

The georeferenced interface between the water and the sand at 2 m above MSL, herein defined as coastline, was converted into vector format.

An estimation of the error related to the coastline detection was investigated through the comparison between the 2 m height points surveyed during the field campaigns and the coastline detected by the video monitoring system. The horizontally and vertically components of the displacements were investigated along the surveyed area whenever simultaneous video and topographic data existed.

Shoreline changes

The coastline variability at Norte beach was investigated through the analyses of the 31 coastlines using equally spaced, 100 m, transects. A total of 14 transects where considered along the 1400 m of the monitored beach.

The coastline changes were investigated through the use standard statistical parameters and principal components analysis (PCA) in order to extract the significant modes of the shoreline variability (Miller and Dean, 2007).

RESULTS

Shoreline elevation

The best fit between maximum run-up levels (Rmax) and a combination of offshore wave and tide forcing was found to be given by:

![Figure 2](image_url)

Figure 2. (A) Relation between measured water level at Norte beach and the water level estimated based on empirical formulae. (B) Timex (10 minute image) acquired during the water level survey with the coastline detected using maximum likelihood classification.

![Figure 3](image_url)

Figure 3. Vertical and horizontal uncertainties related to the video monitoring coastline detection.
where $H_s$ is the offshore significant wave height, $\text{Dir}$ is the offshore wave direction and $\text{AT}$ the astronomical tide. This relationship revealed a very high determination coefficient of 0.95 (Figure 2, A). The $270$ cosine argument is related to the average coastline orientation and the $\text{AT}$ component empirically accounts for the greater wave dissipation at low tide.

In order to estimate the shoreline elevation extracted from the TIMEX images it was necessary to deduce the run-up exceedence level ($R_{x\%}$) detected by the image classification algorithm and the corresponding elevation. These values were found in a specific field measurement where a systematic topographic survey of the level attained by each wave during a period of 10 minutes (the equivalent of the respective TIMEX image composition) was performed. Results shown that the coastline extracted from TIMEX image (Figure 2, B) corresponds to $R_{75\%}$ which is equivalent to 32% of the maximum run-up.

Using the aforementioned relationships, TWL was computed using the following expression:

$$TWL = 0.32 \times R_{\text{max}} + 0.69 \times \text{AT}$$

Representative monthly shorelines were extracted from timex images where TWL was within 2 ± 0.15 m, resulting in 31 georeferenced coastlines.

A total of 54 points where used to estimate the horizontal and vertical components of the displacement between the coastline detected by the video monitoring and the 2 m height contour level measured in the Norte beach during several field surveys. The results (Figure 3) revealed that the vertical uncertainties are in the order of a few tens of centimetres (mean -0.29; root mean square 0.72 m). In what concerns the horizontal displacement, the most relevant component for shoreline positioning, the displacements are of few meters (mean -2.41m; root mean square 5.30 m).

**Shoreline changes**

The coastline position during the monitoring period, which extends from December 2008 to May 2012, reveals that the Norte beach presents a huge coastline variability, with an amplitude that exceeds 160 m (Figure 4, A). The spatial distribution of these changes is clearly asymmetric, with a northern sector less variable than the southern one. The larger amplitudes are found at transects 2 and 3, progressively decreases up to the transect 7 (about 800 m northward of the headland), where the amplitude of shoreline variation attain a magnitude of about 70 m; northward of this transect it remains approximately constant (Figure 4, A and Figure 5). The apparent particular behaviour at transect number 1 is related to the smaller number of coastlines that extents to the vicinity of the Nazaré headland (only in 10 out the 31 coastlines there was a beach at transect location).

The variability of shoreline position at each transect was also investigated through the computation of the standard deviation of the coastline position (Figure 5). This parameter revealed a similar pattern, with the higher values in the southern sector of the beach, up to the 7th transect.

The beach behaviour also presents a high seasonality that in the summer periods is characterized by a very large beach, particularly in the southern sector up to the 7th transect, with a straight configuration (generally from June to August) while in the winter the beach presents an arcuate configuration (more typical of the remaining months of the year) (Figure 4, B).
Understanding the coastal variability at Norte beach, Portugal

The deviation of the beach relating to its mean position during monitoring period (Figure 6, A) also presents a very different pattern between the northern and southern sections of the beach. The transect located northward (14) do not show a clear evidence of seasonality effects, the higher beach accretion occurred during the March 2009, July 2009 and during December 2011 and January 2012.

At the southern section (represented by transect 3), the beach displays a strong seasonal signal (Figure 6, A) with a huge beach advance during the months between July and October that sometimes reach about 60 m (in relation to its mean position). On the opposite the maximum beach retreat occurred during February and March.

Despite the video monitoring gaps in the early 2009 (absence of data in April, May, July, August and September) the coastline position of June 2009 displays the beach advance in the summer of 2009.

DISCUSSION

The characteristic of shoreline variability at Norte beach were investigated using PCA analyses. Results showed that this variability can be explained by two major components which explain 90 % of the system variability. Although results should be considered a mathematical abstraction with no direct physical significance they provide a simple and objective description of the system behaviour.

The first PCA component, which by itself accounts for 68 % of the shoreline variability, is connected to the behaviour of the southernmost transects particularly transects 3 to 5 (Figure 6, B), representing therefore the beach width at the southern section of the Norte beach. The shoreline variability mode related with component 1 progressively fades out northward, while component 2 starts to increase its influence; at transect 9 the shoreline variability is essentially correlated with component 2, related to the beach width at the northern section particularly visible at transect 10.

Considering the time-series of the two main modes of shoreline variability at Norte beach (Figure 7) it can be seen that:

1) Component 1 have the highest positive values during the months of July, August and September, while negative values are observed in January, February and March (Figures 4 and 6). This evident seasonal behaviour is linked with seasonality of incident
wave regime, with beach accretion rotated northwards, inducing a southward longshore drift that progressively infill the southern section of the beach until the headland retention capacity is exceeded. During winter months the waves approaching more southerly than average invert the typical longshore drift direction resulting in the retreat of the shoreline near the headland. This process is responsible for the complete erosion of the beach at transect 1 and, sporadically, at transect 2.

2) Component 2 apparently does not have any seasonality with maxima at October/November 2010 and March 2009 minima at January/February 2011 and July/August 2011. This apparent lack of seasonality seems to be related with the time lag between the wave forcing and the shoreline response of the northern, less variable, sector of the beach.

CONCLUSIONS

This work describes the shoreline variability at Norte beach, Portugal. Results show a rare high seasonal coastline variability which exceeds 160 m in the southward sector (adjacent to the headland) and 70 m at the central sector and northern sectors (transect 7 to 14).

Coastline variability was related with modifications in the planform beach configuration: beach oscillates between a straight (generally from June to August) and an arcuate configuration (during the remaining of the year).

Results suggest that Norte beach variability depends mainly on longshore drift gradients rather than with cross-shore sedimentary transfers. The intense wave refraction over the canyon head, associated with the westerly swell waves, generates a sedimentary convergence at the centre of the beach promoting the increase of the beach curvature, while, northern and/or short waves (more frequent in summer) tend to linearize the beach.

This work, supported on video monitoring techniques, contributes with valuable information about the sedimentary dynamics of the Norte beach. Results show that the shoreline changes, in what concerns magnitude and time of response, make the Norte beach a suitable location to estimate the magnitude of the longshore drift and its relation with the oceanographic forcing.

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LITERATURE CITED


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