Relation between beachface morphology and wave climate at Trafalgar beach (Cádiz, Spain)

Miguel Ortega-Sáncheza,⁎, Sandra Fachinb, Francisco Sanchob, Miguel A. Losadaa

a Grupo de Puertos y Costas, Centro Andaluz de Medio Ambiente, Universidad de Granada, Avda. del Mediterráneo, s/n. 18006 Granada, Spain
b Núcleo de Estuários e Zonas Costeiras, Laboratório Nacional de Engenharia Civil, Av. do Brasil, 101, 1700-066 Lisboa, Portugal

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Abstract

Two years of offshore wave data and daily time exposure images from Trafalgar beach, a 2-km-long sandy beach located on the southwest coast of Spain that frequently exhibits rhythmic features, were used to (1) explore the variability of the beachface morphology and (2) determine environmental conditions associated with the different morphological states. The beachface morphology at three distinct alongshore sectors was analyzed and classified and five different morphological states were found that are related with the presence or absence of beach cusps and a berm: (1) large beach cusps, (2) small beach cusps, (3) low-tide terrace; (4) plane beach berm and (5) plane beach. The predominant beachface morphology is characterized by the presence of large beach cusps, and the main wave climate consisted of offshore significant wave heights ranging from 0.5–1 m and wave periods between 4 and 12 s. An alongshore variation of the morphology is found which might be related to the nearshore wave variability (SWAN wave model results). The morphologies are, in some cases, well-correlated with the daily offshore incident wave climate (described by the daily maximum significant wave height and the corresponding period), particularly for the moderate to high energy wave conditions. Small beach cusps appear under short period waves, whereas when the wave periods are longer the morphology tends to change to large beach cusps. This transition only occurs if the forcing is maintained as constant for a certain duration, which depends itself on the wave energy. It is concluded that correlations over 90% are only found for the highest wave energy conditions or under long wave periods. For the remainder, it is not possible to generally correlate the beachface morphology based only on the wave forcing because the previous morphological state cannot be ignored.

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1. Introduction

Many authors have worked on the identification, classification and temporal evolution of general beach morphologies. Wright and Short (1984) derived the most commonly used beach-type classification. They identified 3 main beach states: dissipative, intermediate and reflective, and defined the parameter Ω (ratio between the water particle velocity and the sediment fall velocity) to characterize the different beach states. Masselink and Short (1993) included the effects of the breaking wave height and period, upper beachface sediment characteristics and mean spring tidal range. Ranasinghe et al. (2004) devised a conceptual model to predict variations in general beach morphology in terms of surf zone properties, and related them to the environmental conditions (offshore wave height, steepness and wave power). Besides these studies, attention to intertidal beach morphology has been scarce, as pointed out by Masselink et al. (2006) who reviewed the presence of intertidal bars under wave-dominated environments.

It is common to find rhythmic topographic features such as beach cusps on the beachface. These features have been studied by several authors, i.e. Guza and Inman (1975), Sallenger (1979), Inman and Guza (1982), Holland and Holman (1996), Masselink et al. (1997), Masselink and Pattiaratchi (1998), Holland (1998), Masselink (1999) and Coco et al. (2001, 2003). Nowadays, two theories appear to provide an adequate explanation of the formation of regularly spaced beach cusps on natural beaches: (1) standing sub-harmonic edge waves (Guza...
and Inman, 1975); and (2) self-organized swash motion (Werner and Fink, 1993). The standing edge wave hypothesis suggests that swash from incident waves is superimposed upon the motion of standing edge waves to produce a systematic longshore variation in swash height which results in a regular erosional perturbation (Guza and Inman, 1975). The self-emergence model, proposed by Werner and Fink (1993), suggests that beach cusps develop through a combination of: (1) positive feedback between beach morphology and swash flow that can operate to enhance existing topographic irregularities; and (2) negative feedback that inhibits accretion or erosion on well-developed cusps. Dean and Maurmeyer (1980) also propose that cusp spacing strongly depends on the swash excursion length.

In general, it is well-established that the beach cusp geometrical characteristics are dependent on the background wave forcing (Coco et al., 1999), i.e. their alongshore spacing and protruding distances depend on the wave height and period. Attempts have also been made to relate their formation with the wave climate. Holland (1998) concluded that cusps are formed mainly under normal wave incidence and during the 2–4 days after the peak of a storm. Masselink et al. (2004) also focused on the relation between the offshore wave forcing and the formation of the rhythmic topography concluding that cusps are formed under calm conditions and destroyed by the larger energetic conditions. Sunamura (2004) discussed the importance of the longitudinal distribution of the wave height in the initial cusp formation. Nevertheless, although beach cusp formation and evolution have been intensively studied, there are no clear relationships between their presence (or absence) and the wave forcing. This is, thus, further addressed in the present paper.

In order to properly study the beachface morphology it is necessary to obtain high quality data (temporal and spatial resolution) under different forcing conditions. Video-imaging techniques have been an important tool for morphological studies (Holman and Stanley, 2007), particularly for studying the bathymetry and sand bars (Aarninkhof and Holman, 1999; Plant et al., 1999; Van Enckevort and Ruessink, 2001; Ruessink et al., 2003; Aarninkhof et al., 2003), but they have seldom been applied to beachface morphological studies. One of the main investigations was carried out by Holland (1998) through the analysis of a temporal series of 9 years of data to study the formation of cuspate morphology; and Coco et al. (2003) and Masselink et al. (2004) used video-images to measure protruding swash flow distances in combination with detailed field measurements.

From the above, it remains to be explored whether the beachface morphological state, related to the presence and form or the absence of beach cusps, can be strongly correlated with the incident wave climate. Thus, the main objectives of the present work are (1) to study the variability of the beachface morphology in a swell-dominated, low energy coastal environment, based on video-imaging data, and (2) to correlate those morphologies with the offshore wave forcing. It may also be established from the literature (e.g. Benavente et al., 2000) that the beachface morphology does not respond instantaneously to the external wave forcing. Thus, dependencies of the beachface morphological state are explored further in terms of the previous morphology and evolution time.

2. Field site description

Trafalgar beach is located in a mesotidal and swell-dominated coastal environment along the southwest Spanish coast, at the Gulf of Cádiz (Fig. 1). It is an approximately 2-km-long sandy beach with a mean alignment NNW–SSE. Trafalgar beach is limited to the south by Cape Trafalgar, where the coastline alignment changes abruptly to the east. Strong wave-driven currents and rhythmic features are frequently found along the beach, with cuspatate features being the most common beachface morphology.

The continental shelf width is approximately 30–40 km with the shelf break located at a depth of 120 m. The shelf has a
relatively mild beach slope of 1.5°. A sand bank, which is a source for the majority of the sand extractions for beach nourishment in the Gulf of Cádiz, is located in front of Trafalgar beach at the 30 m isobath. East of Trafalgar, a flat sand planform limited by a steep profile where the depths go from 50 m to 500 m in 20 km distance, can be found (Losada et al., 2004). The isobaths are almost perpendicular to the coast in front of the Cape (Fig. 1).

Beach topography and nearshore bathymetry were surveyed in May and June 2006 using a real time kinematic differential global positioning system (RTK-DGPS) and a portable digital echosounder in conjunction with the “Hypack” hydrographic survey software. Results indicate that Trafalgar beach has a backshore width ranging from 40 to 70 m, increasing towards Trafalgar Cape.

A plane beach morphology dominates the nearshore zone and no shoreface sand bars were found (Fig. 2). However, some rocky formations of flysch (Crespo-Blanc and Campos, 2001) are present in the nearshore environment mainly at the northern border of the study area, extending close to the beachface. Sediment samples were collected in the beachface and backshore (Fig. 2) and sedimentological analysis (according to Folk and Ward, 1957) shows the presence of a sandy beach composed of a high percentage of sediments with grain sizes ranging between medium (0.25–0.5 mm) and coarse sand (0.5–1 mm) (Fig. 2b).

The astronomical tide is semi-diurnal with average amplitude 1 m and a tidal range between 0.2 m and 3.8 m. Waves are predominantly coming from the west and break on the beach within a narrow breaking zone mainly due to their relatively low energy (significant wave height less than 1 m).

For the modal wave height (see “Wave and tidal data” section), $H_s = 0.8$ m. The mean spring tidal range is 3.2 m (Anfuso et al., 2003) and the relative tidal range, $RTR = TR / H_s$, is 4. Estimating the settling velocity for a medium grain size ($D_{50} \approx 0.5$ mm) (Soulsby, 1997), $W_s = 6.6$ cm/s, and for the most frequent wave periods corresponding to the modal wave height ($8 < T < 12$ s), the beach-type parameter $\Omega = H_s / (W_s T)$

Fig. 2. a) Beach topography and bathymetry, where the black solid line is the shoreline contour, and location of sediment samples; b) median grain size and standard deviation of the sediment granulometric distributions for all samples marked in (a).
(Wright and Short, 1984), is between 1.0 and 1.5. These values are representative of a low-tide terrace beach, dominated by low energy and long period (swell) waves (Masselink and Short, 1993). It should be noted, however, that a shorter-period wind sea ($4 < T < 6$ s) also occurs frequently, yielding $\Omega \approx 3$, which produces a low-tide transverse bar and rip morphology, according to the same authors.

3. Methodology

Below, we present the data analysis methods used herein in order to characterize the wave hydrodynamics and beachface morphology. The data analysis consisted mainly of (1) daily classification of the beachface morphology and offshore wave forcing, and (2) searching for the dominant correlations between them. In addition, the alongshore variability of the beachface morphology was studied.

It should be pointed out that early attempts were completed in order to include the varying tidal range into the present analysis, but no correlations were found, and thus this effect was excluded in this paper.

3.1. Hydrodynamics

3.1.1. Wave data

Data provided by Puertos del Estado (Spain) were used to analyze the wave climate. Two points are located near Trafalgar beach, “wana45” in the northern part at 30 m depth and “wana44” in the southern part at approximately 150 m depth (Fig. 3). These data are daily wave forecast output from the WAM wave model (Günther et al., 1992). The wave records analyzed cover a two-year period from 2003 to 2005 and consist of significant spectral wave height ($H_s$), spectral peak period ($T_p$) (henceforth referred to as wave period) and mean wave direction ($\theta$), reported every 3 h. Due to the location and the water depth, “wana45” was selected to be more representative of the offshore wave conditions at Trafalgar. The WANA data analysis was used to address the following:

(1) Characterize the general sea state in the study area during the period of analysis. The wave data are represented by monthly dispersion plots and frequency histograms for the 2-year period. These plots were used for classification of the wave data, to provide comparisons between the wave climate present during different months and years and to identify significant events.

<table>
<thead>
<tr>
<th>Table 1: Offshore waves classification</th>
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<tr>
<td><strong>Significant wave height</strong></td>
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<tr>
<td>Low energy conditions</td>
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<tr>
<td>LEC_1: $0 &lt; H_s \leq 0.5$ m</td>
</tr>
<tr>
<td>LEC_2: $0.5 &lt; H_s \leq 1$ m</td>
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<tr>
<td>LEC_3: $1 &lt; H_s \leq 1.5$ m</td>
</tr>
<tr>
<td>Moderate energy conditions</td>
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<tr>
<td>MEC: $1.5 &lt; H_s \leq 2.5$ m</td>
</tr>
<tr>
<td>High energy conditions</td>
</tr>
<tr>
<td>HEC: $2.5 &lt; H_s \leq 4$ m</td>
</tr>
<tr>
<td>Storm conditions</td>
</tr>
<tr>
<td>SC: $H_s &gt; 4$ m</td>
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</table>
(2) Classify daily offshore wave conditions. Average wave height and wave period were calculated for each day. Additionally, the daily maximum significant wave height and the corresponding period were identified and a table was created to compare the results with the morphology for statistical analysis. The underlying question was what value should be used to properly represent the wave forcing as it pertains to morphological evolution. Thus, considering that the morphology responds more rapidly to the more energetic events, the daily maximum significant wave height and the corresponding wave period were chosen. These values were then grouped into the energy intervals shown in Table 1.

3.1.2. Nearshore wave propagation

Nearshore wave conditions were simulated using the SWAN model (Booij et al., 1999). It is a phase-averaged third generation model based on the wave action balance equation with sources and sinks accounting for the following phenomena: diffraction, refraction, shoaling, dissipation by whitecapping, bottom friction and depth-induced wave breaking. The model domain consists of two quadrangular grids: one covering the entire Trafalgar region (25 km × 30 km) with a resolution of 200 m, and a nested grid (6 km × 7 km) with a resolution of 25 m, covering the area closer to the beach (Fig. 3). Simulations were performed assuming a constant tidal level equal to the mean value of 2 m.

The input wave data are the result of a parameterisation of the WANA data. Thus, for each set of significant wave height, wave period and direction, a directional wave spectrum using a JONSWAP parameterisation was defined at the boundary of the coarse grid. The frequency discretization used 21 frequencies ranging from 0.04 to 0.4 Hz, with a logarithmic distribution. The directional discretization covered a range of 360° with a resolution of 5°. All the computations were carried out in a stationary mode, with no tidal currents or wind stress acting over the study region. The coarse grid model produced the wave spectra used as input conditions along the boundary of the finer nested grid. SWAN results on every node of the domain consisted of significant wave height, mean wave period and wave direction, directional spreading, wavelength and water depth. To analyze the alongshore variability of the wave climate, wave data were extracted at 2 m and 5 m (corresponding to average mild and storm wave breaking depths), and 10 m isobaths (offshore the breaking zone). Such analysis will allow, identifying and understanding of the alongshore variations of the beachface morphology.

3.2. Beachface morphology

3.2.1. Video-images

In October 2003 a video-monitoring station based on the ARGUS technique (Aarninkhof and Holman, 1999) was installed at the Trafalgar lighthouse, 50 m above mean sea level. The station includes 3 video cameras that collect images during the first 10 min of each daylight hour at a frequency of 2 Hz (Fig. 4). Video-images consist of an instantaneous image (snapshot), a 10-minute time-averaged image (timex) and a variance image over the same period. Timex images average the waves impinging on the beach and can frequently show the underwater morphological features (Fig. 4). Hourly images from each day were themselves averaged to create a “daytimex”, a composite image that reveals the daily mean morphology.

After installation, the location of the cameras and a number of clearly visible ground control points (GCPs) were surveyed relative to a known benchmark. When no fixed GCPs were available, virtual GCPs were used (i.e. camera 2). From
comparison of the image and world location of the GCPs, the photogrammetric transformation from image to world space was computed using the technique presented by Holland et al. (1997) to allow georeferenced digitization of morphological features. Accuracy of this process is typically one pixel. At midbeach, one pixel corresponds to a ground accuracy of 0.25 and 1.4 m in the cross-shore and alongshore directions, respectively, worsening to 0.49 and 5.59 m at the far end of the beach.

3.2.2. Beachface morphology classification

The main different morphologies that can appear on the beachface were defined to provide a basis for the classification scheme. Both timex (corresponding to the maximum and minimum daily water level) and daytimex images were used. After a preliminary analysis of the video-images it was found that, in general, the beachface morphology varies frequently from a plane beach, occurring for few days, to a cuspidal beach with cusps of different characteristics. According to that transition, the definition and classification of the beachface morphology was based on: (1) the presence or absence of any morphological features; (2) the presence of cuspatate features; (3) the protruding distances of the cuspatate features; (4) the presence of “mini-rip currents”; (5) the presence of drainage channels and (6) the presence of a berm. The protruding distance, also known as the cuspidal horn, is defined as the distance between the average position of the cusp embayment and the first bathymetric contour showing no cuspatate features. The classification was made individually by the first three authors of this work to establish consistency.

3.2.3. Longshore variability

After preliminary analysis an alongshore variation in the beachface morphology was frequently observed (Fig. 5). The alongshore variability of the morphology was analyzed by dividing the beach into three alongshore regions: a) zone C1, which corresponds to the part of the beach closest to the Cape (0–[50–100 m]), and nearly coincides with the field of view of camera 1; b) zone C2, which corresponds to the central part of the beach, approximately from C1 and extending north 600–800 m, and closely matching the field of view of camera 2); and c) zone C3, which corresponds to the farthest part of the beach (Fig. 6). Subsequently, the entire 2-year dataset, separated into these alongshore zones, was classified under one of the beachface morphological types for each day.

4. Results

4.1. Hydrodynamic characterization

4.1.1. Wave data classification

Wave conditions for the period 2003–2005 were analyzed using the 7753 available data points corresponding to the “wana45” point. Results shown in Fig. 7 indicate that the most likely waves come from the W quadrant, with 85% of the incident...
angle of the incoming waves in the range of 255°–300°. The most frequent wave directions are between 270° and 285°. The most frequent significant wave height is between 0.5 m and 1 m, and 83.4% of the time the wave height is below 1.5 m. The most likely wave periods are within 8 to 10 s and between 4 and 14 s 84.4% of the time. These results are similar to those obtained from larger time series of wave data (Losada et al., 2004).

Using the classification proposed on Table 1, the results obtained for the period of analysis (Table 2) show that 79.1% of the time the daily maximum significant wave height is below 1 m, corresponding to LEC 1 and 2, and the most likely interval is between 0.5 and 1 m. Wave periods associated with the maximum significant wave height are typically (74.4% of the time) lower than or equal to 12 s, with the most likely less than 8 s (SPP condition).

4.1.2. Nearshore wave propagation

The bottom morphology of the continental shelf, shoreface and nearshore plays an important role in the hydrodynamics of Trafalgar beach, particularly in dictating the alongshore variability of the wave field. Results suggest that the rocky submerged morphology extending 3 km offshore in front of Cape Trafalgar acts as an underwater groyne, creating focusing and defocusing zones of wave energy depending on the incoming wave direction. Thus, close to the cape, there is an increase of wave height for all incoming wave directions (Fig. 8). This influence is more important in the case of waves coming from the S–SW quadrant. For waves coming from the W this influence also occurs, however it is less pronounced. Waves coming from the NNW propagate almost parallel to the beach, creating a shadow zone at the northern end of the beach. Other important bottom features are two sand banks parallel to the northwestern section of coast, one at 30 m depth and the other at 20 m depth. These banks also focus wave energy for waves approaching from the SW and W.

For the predominant offshore waves, SWAN was used to characterize the alongshore variability of the wave field at the 5 m depth contours (Fig. 9). In general, wave height tends to decrease from the southern (left part of the figure) to the northern part of the beach in zones C1 and C2, but a slight increase in the wave height and a change in the wave direction occur about 1200 m from the Cape (Fig. 9).

<table>
<thead>
<tr>
<th>Significant wave height</th>
<th>Wave period</th>
<th>Occurrence (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low energy conditions</td>
<td>Short wave period</td>
<td>39</td>
</tr>
<tr>
<td>LEC_1 0&lt;H_s&lt;0.5 m</td>
<td>SPP T_p&lt;8 s</td>
<td>82.2</td>
</tr>
<tr>
<td>LEC_2 0.5&lt;H_s&lt;1 m</td>
<td>Mean wave period</td>
<td>40.1</td>
</tr>
<tr>
<td>LEC_3 1&lt;H_s&lt;1.5 m</td>
<td>MPP 8&lt;T_p&lt;12 s</td>
<td>12.3</td>
</tr>
<tr>
<td>Moderate energy conditions</td>
<td>Long wave period</td>
<td>7.3</td>
</tr>
<tr>
<td>MEC 1.5&lt;H_s&lt;2.5 m</td>
<td>LPP T_p&gt;12 s</td>
<td>42.2</td>
</tr>
<tr>
<td>High energy conditions</td>
<td></td>
<td>18.1</td>
</tr>
<tr>
<td>HEC 2.5&lt;H_s&lt;4 m</td>
<td></td>
<td>7.3</td>
</tr>
<tr>
<td>Storm conditions</td>
<td></td>
<td>1.2</td>
</tr>
<tr>
<td>SC H_s&gt;4 m</td>
<td></td>
<td>0.1</td>
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</table>

Larger nearshore wave heights occur when waves coincide closer to the shore-normal direction (225° and 270°). Smaller wave heights are observed when waves travel parallel to the coast (315° and 180°). Thus, results show that the nearshore wave height varies significantly alongshore, and with the incoming wave direction. According to the main hypothesis of the present work, a non-negligible longitudinal variation of the beach morphology at Trafalgar could be expected if this is strongly dependent on the wave height.

4.2. Morphology classification

During the 731-day period only 695 days had available images due to failures in the acquisition system. The morphology classification performed by the authors only differed on 19 days (average), which is less than 3% of the total record length. These differences were greater for zone C1 (26 days) than for zones C2 (18 days) and C3 (12 days) due to the smaller field of view and the orientation of C1.

During the two years of video data five main morphologies, discussed below in more detail, were identified on the beachface (Fig. 10). Spacings between cuspsate features were measured during the field survey carried out during May and June 2006 and also using the rectified video-images. Slopes were measured during the field survey and also from the rectified images using a video-based technique for mapping intertidal beach bathymetry (Aarninkhof et al., 2003). The beachface and nearshore slopes generally decrease towards the Cape. The average beachface slope within the cuspsate features ranges between 0.06 and 0.10 for the cusp embayments and between 0.10 and 0.18 for the cusp horns. The nearshore beach slope away from the cuspsate features ranges between 0.016 near the Cape and 0.026 close to the northern end of the study area.

4.2.1. Large beach cusps (LBC)

The beachface morphology is characterized by the existence of large beach cusps with mean spacing of 30 m (Fig. 10a). This spacing can vary alongshore, being larger closer to the Cape (around 35 m) than farther away (20 m). Some days, the spacing reached 60 m. Their main “characteristic” morphological feature is the protruding distance which is always larger than 5 m with some measurements showing values up to 50 m.

4.2.2. Small beach cusps (SBC)

This morphology is characterized by small beach cusps in the upper beachface near the position of the maximum daily water level (Fig. 10b). Cusp vertical amplitudes (Nolan et al., 1999) can be up to 1.5 m. Average cusp spacing is 20 m, sometimes showing an alongshore variability with greater spacing closer to the Cape. Protruding distances are always less than 5 m. Thus, the protruding distance was the principal parameter to distinguish between LBC and SBC morphologies.

4.2.3. Low-tide terrace–ridge runnel (LTT)

This morphology is characterized by the presence of ridges that are interrupted by shore-normal drainage channels. The
Fig. 8. Map of the modeled significant wave height contours and direction (vector) for the predominant offshore waves ($H_s = 0.75 \text{ m}$, $T_p = 10\text{ s}$) for two different incoming directions: a) $247^\circ$ and b) $180^\circ$. 
lower part of the profile tends to be horizontal, showing the lowest slopes (<0.01), although the upper beachface can show a berm or cuspatc morphology. The spacing of the drainage rip-channels is of the order of 60 m, and their location is not related with the presence of cusps (Fig. 10c).

4.2.4. Plane beach berm (PBB)

The plane beach berm is characterized by a plane profile that ends with a berm in the upper part, near the position of the maximum daily water level (Fig. 10d). This morphology differs from the following one by the presence of a distinct berm.

4.2.5. Plane beach (PB)

The plane beach is found after very high energetic conditions. The profile is planar with an average slope of 0.01, and there are no significant morphologic features (Fig. 10e).

4.2.6. General results of the daily classification

A synthesis of the frequency of occurrence of the daily morphological classification is shown in Fig. 11. We find that large beach cusps (LBC) are the predominant beachface morphology, followed by small beach cusps (SBC) for zones C1 and C2, and the presence of a berm (PBB) occurring more frequently in zone C3. The alongshore distribution shows that zones C1 and C3 have the highest variability. It is hypothesized that this can be related to the nearshore wave forcing, which is slightly different from zone to zone (Fig. 9) due to the local bathymetry and the shoreline alignment.

4.3. Relationships between beachface morphology and wave climate

4.3.1. Offshore wave period

For each alongshore zone, it appears that the beachface morphological state and the wave period interval are related (Fig. 12). The predominant beachface morphology (LBC) is present under any incoming wave period, but SBC is usually present only under mean or short wave periods. Similar behaviour is found for PBB. Results indicate that shortening of the wave period is associated with a slight smoothing of the beachface morphology, with more frequent occurrences of
PBB, LTT and PB. This is in agreement with most of the previous beach cusp theories (Coco et al., 1999) that relate beach cusp dimensions to the incident wave period.

4.3.2. Wave height

For the lowest energy interval (LEC_1), the beach is dominated by LBC for long wave periods (LPP), with up to a 90% probability (Fig. 13). The same behaviour is found for mean wave periods for zones C1 and C2, but not for zone C3, where PBB is present 33% of the time. If short wave periods (SPP) are considered, the morphology is dominated by LBC and SBC in similar proportions for zone C1 and C2, and by LBC, SBC and PBB for zone C3. Therefore, results show that the northern end of the beach (zone C3) can exhibit a different beachface morphology than the remainder of the study area for mean and short wave periods.

If we increase the wave energy (LEC_2), LBC still predominates for long and mean wave periods. For long wave periods the probability of LBC morphology is approximately 64% for C1 and C3, and 75% for C2. For mean wave periods, the probability is close to 80% for C1 and C2 and about 75% for C3. An additional increase in wave energy (LEC_3) produces similar results for long wave periods, but for mean and short wave periods the morphology variability increases. This variability is at a maximum for mean wave periods, where almost all the morphologies can occur in similar proportions, mainly in zones C1 and C3.

Under moderate energy conditions (MEC_1 [$H_s = 1.5$–$2$ m] and MEC_2 [$H_s = 2$–$2.5$ m]) large beach cusps dominate for long wave periods and small beach cusps for short wave periods. The maximum variability is found under medium wave periods. For high energy conditions, only LBC are found, whereas for storm events ($H_s > 4$ m) the beach evolves to along-shore non-variable states of PB and LTT.

According to these results, long wave periods show a very stable trend, having a predominance of large beach cusps for all

Fig. 10. Beachface morphology classification at Trafalgar beach. Left panels: daytimex rectified images of the beach; right panels: corresponding oblique images from camera 2.
the wave energy conditions; medium wave periods show also a stable trend for MEC_1 and MEC_2 (also mainly consisting of large beach cusps), whereas short wave period only exhibited stable trends for moderate conditions (small beach cusps).

4.4. Transition between beachface morphologies

According to the results presented in the previous section, Trafalgar beach morphology shows large variability under some wave energy and wave period conditions. The main goal of this section is to first discuss what changes in wave forcing can produce a change in morphology, and second to investigate the relationships between the beachface morphology and offshore wave climate, and the natural (or background) morphological state.

Changes in the wave forcing parameters produce changes in the beach morphological type. A search for simultaneous transitions between wave forcing and beach morphologies indicated that a significant number (> 10) of these occurred only for changes from LBC to SBC and vice versa. The effect of this influence was analyzed using the daily maximum significant wave height and the corresponding period as the relevant hydrodynamic parameters.

The results show that when the wave period decreases, a change from LBC to SBC often follows (Fig. 14a). The time over which these changes occur is related to the wave height, where for low energy conditions (LEC_2) about 2 days are required for the changes to be completed. Analysis of the transitions from SBC to LBC shows, on the contrary, an associated increase in the wave period (Fig. 14b).

Fig. 15 shows for each region and beach type, the averaged wave height and period, and the corresponding 75 and 25% quartiles (shadowed areas), and upper and lower limits, to allow immediate association between offshore wave forcing and beach type. The indicated shadowed areas and limits are thus a measure of the standard deviations. Observed wave periods from LBC morphology are highly variable with a mean value around 10 s; in contrast, observed wave periods from SBC morphology are less variable with a mean value around 6 s. A similar behaviour to SBC is found for PBB, whereas for LTT and PB the periods are highly variable. Regarding the wave height, there is no clear relationship between the forcing and the morphologies, except for LTT, PB and PBB, which are produced by the highest energy events, but differently in the three zones.
Although the beach system has a natural tendency to adapt itself to the new forcing conditions, it was observed that some changes were produced without any variation in the wave forcing. This occurred when the forcing that produced SBC remained constant and the beach morphology still tended to LBC. In fact, the LBC morphology can be considered as the baseline or typical beachface morphology for this beach. From our analysis, the evolution time is of the order of few days, although it depends on the energy content of the wave forcing.

In those cases the wave height seems to determine how fast the transition between morphological states will occur. Therefore, the new forcing conditions need to be maintained for a certain period of time. According to our dataset, this duration depends on the magnitude of the incoming wave energy: (1) for high energy waves, the changes can be produced in 3–6 h; (2) for moderate energy waves, the changes can be produced in 9–12 h; (3) for low energy waves, 2–3 days seem to be required.

Due to this fact, occasionally, the wave period changes but the morphology does not, and this seems to be the reason why SBC are, sometimes present under long wave periods.

5. Summary and conclusions

A 2-year dataset of daily time exposure images has been analyzed to characterize the variability of the beachface morphology at Trafalgar Beach, a 2-km-long sandy beach located in a swell-dominated coastal environment. Five main morphologies were identified, two of them having cuspidate features (large beach cusps — LBC, and small beach cusps — SBC), one a berm feature (plane beach and berm — PBB), with the other two corresponding to a low-tide terrace with small ridges and runnels (LTT) and a simple plane beach (PB).

Based on the 2 years of data, it was found that the predominant beachface morphology is characterized by the presence of large beach cusps (LBC). The predominant wave
Fig. 14. Time sequences of significant wave height, wave period and morphology for two transitional events: (a) transition from LBC to SBC (upper graph); (b) transition from SBC to LBC (lower graph).

Fig. 15. Wave heights (upper graphs) and wave periods (lower graphs) for each morphology (LBC, SBC, LTT, PB and PBB) and alongshore zone (C1: left graphs; C2: middle graphs; C3: right graphs). For each subset, the upper and lower limits represent the maximum and minimum values of that subset, respectively; the upper, middle and lower box lines represent the 75%, 50% (median) and 25% quartiles, respectively.
climate consists of wave heights of 0.5–1 m and wave periods between 4 and 12 s. According to our results, the occurrence of the individual beachface morphologies depends on the wave height and wave period. The latter is found to play an important role in the development of small beach cusps. A beach berm is mostly found under mean or short wave periods, whereas large beach cusps can appear under all wave periods. Shortening the wave period is associated with a smoothing effect of the beachface morphology.

Regarding the combined analysis of wave energy and wave period, the morphology under long wave periods shows a clear predominance of the large beach cusp morphology for any wave height. By contrast, morphology under shorter wave periods shows the greatest variability associated with changing wave energy. When the incoming wave periods are shorter, the morphology will change to small beach cusps, whereas when the incoming wave periods are larger the morphology will change to large beach cusps. Nevertheless, the new forcing conditions need to be maintained for a certain time for the change to be produced and the necessary persistence time depends on the amount of wave energy present. Thus, anticipating the morphology using only one daily value to represent the offshore wave conditions may be possible only under some wave energy and wave period classes, and within a certain statistical confidence.

For low energy conditions and long wave periods the results indicated that we can establish a 90% probability of having LBC beachface morphology. The probability of occurrence of LBC reduces to around 40% if short wave periods are considered, and thus no simple correlation can be established under those conditions. For those cases it is necessary to know the previous morphology and the previous wave conditions. Regarding the presence of SBC morphologies, there is a high percentage of occurrence of this beach type (and capability to predict it) for waves with short and mean wave periods. Except for zone C3, PBB morphologies mainly appear only for moderate energy conditions, with short and mean wave periods, but predictions lack some reliability. Changes between LBC and SBC can also be anticipated, but insufficient data were available to analyze properly other typical transitions that may occur.

Considering the limitations and simplifications of our methodology, over 90% confidence correlations between the beachface morphology and the offshore wave climate may be possible only for the high wave energy conditions or for long wave periods. For low to moderate wave energy situations it is necessary to know: (1) the previous beachface morphology and (2) the previous wave climate. Results of this work indicate that a longer time series of data would be necessary both to explain transitions between other morphologies and to study the high energy wave events properly.

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