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# Storm Induced Morphological Changes in Carcavelos Beach, Portugal: Contribution for Coastal Management

## *Variações Morfológicas Induzidas por uma Tempestade na Praia de Carcavelos, Portugal: Contribuição para a Gestão Costeira*

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ABSTRACT: Field data based information on the coastal sediment dynamics becomes even more relevant for coastal managers in the present context of climate changes. Due to the sea level rise and the increase of frequency and intensity of coastal storms, coastal managers need to implement effective and efficient solutions for increasing coastal resilience, namely through reprofiling the beach for restoring the sediment balance and providing space for the beach natural dynamics. The study characterises and quantifies the morphological changes in an Atlantic urban sandy beach under extreme wave energy and sea level conditions. The erosion of the foreshore and backshore of this particular beach was characterised as function of the intensity and duration of the hydrodynamic forcing parameters (waves and sea level). This 24-hour duration storm event, which delivered to the beach a total energy of $1.7x10^9$ J, caused the seaward displacement by the undertow current of approximately $3x10^3$ $m^3$ of median well sorted sand from the beach foreshore and backshore.

Keywords: coastal erosion, short-term, beach response, maritime storm, beach elevation monitoring, coastal management.

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*RESUMO: Informação sobre a dinâmica sedimentar costeira baseada em dados de campo torna-se ainda mais relevante para gestores costeiros no presente contexto de alterações climáticas. Devido à subida do nível do mar e ao aumento da frequência e intensidade de tempestades marítimas, os gestores costeiros necessitam de implementar soluções eficazes e eficientes para melhorar a resiliência costeira, nomeadamente através do reperfilamento da praia para restabelecer o balanço sedimentar e conceder espaço para a dinâmica natural da praia. O estudo caracteriza e quantifica as variações morfológicas numa praia arenosa, urbana e Atlântica sob ação de condições extremas de energia das ondas e nível do mar. A erosão da face e do topo da praia foi caracterizada em função da intensidade e duração dos parâmetros forçadores hidrodinâmicos (ondas e nível do mar). Este evento de tempestade com duração de 24 horas, que transmitiu à praia uma energia total de $1.7x10^9$ J, causou a extração de aproximadamente $3x10^3$ $m^3$ de areia média da face e do topo da praia e o seu transporte pela corrente de retorno para maiores profundidades.*

*Palavras-chave: erosão costeira, curto-prazo, resposta da praia, tempestade marítima, monitorização da elevação da praia, gestão costeira.*

## 1. INTRODUCTION

Natural factors, namely the sea level rise, the long-term variation of mean hydrodynamic conditions, and the increase of frequency and intensity of maritime storms due to climate changes, and human-induced factors, such as the reduction of the littoral drift due to sediment trapping by jetties, port sand trapping and dredging, river damming and sand mining, and advanced occupation/urbanization of maritime fronts, are recognised for being the most frequent causes of longterm erosion in coastal regions (European Commission, 2004). However, on the short-term, extreme hydrodynamic conditions, such as storms or hurricanes, might lead to irreversible erosion, when the mean conditions are such that there is a net longshore transport pattern and the beach-dune system does not recover its previous dynamic equilibrium (Steezel, 1993).

Several studies point out the trends of erosion aggravation along the Portuguese coast (Salman *et al.*, 2004; Dias, 2007; Gomes, 2007). The sea level rise as a cause of erosion is unanimously accepted among the scientific community (Cazenave and Cozannet, 2013). However, other possible causes, associated to uncertainty and controversy, pointed out by some authors (Andrade *et al.*, 2006 and 2007; Meehl *et al.*, 2007) should also be considered. These are the future increase of frequency and intensity of storm events and the 5-15 % increase of the net littoral drift that can occur, in response to the future clockwise rotational shift of the offshore wave regime, until the shoreline reaches its new equilibrium shape, reoriented normally to the wave regime.

In urbanised coastal areas as the present case study, the beach is a place of recreational, social and economic activities and natural heritage embedded in the local people's culture. But the beach is also an essential coastal protection element once it has a crucial defence role against wave action over the existing urban infrastructures, in many cases excessively advanced towards the sea. For this reason, understanding how the beach responds to storms is critical to safe and responsible coastal planning and management (Stockdon *et al.*, 2007). The quantification and characterization of the maritime storm events and their impact in the beach morphology based on data, which is difficult to acquire, eventually under conditions of high risk, and might be expensive, is, therefore, highly valuable information. Due to the importance of the theme, the focus of this study is the characterization of a short-term erosion phenomenon occurred in Carcavelos beach near Lisboa, Portugal, when the wave height and the water level were higher than usual due to the simultaneous occurrence of strong wind, low atmospheric pressure, spring astronomic tide and high wave setup. The erosion event which caused immediate lowering of the beach is here characterized based on the incident wave and the sea level data measured during the storm and on the pre and post-event foreshore and backshore topographic survey. Such knowledge, on the forcing hydrodynamics and the rapid beach morphological response, is essential for the local authorities' management and planning in a context of increase of frequency and intensity of storm events due to climate changes: it feeds models that predict the hydro-morphological behaviour of the beach under storm conditions and it provides information for planning cost-effective beach protection solutions, such as the required sediment volumes for reprofiling the beach providing space for coastal processes.

The study site is the Carcavelos beach, with about 1400 m of alongshore extension and 100 m of width (in its central part, the widest), located near Lisboa, in the west central coast of Portugal (Figure 1). Its narrow backshore is limited by a vertical seawall of concrete and several infrastructures. It faces the North Atlantic Ocean, therefore, is exposed to an average wave regime highly energetic, with strong seasonality which characterises the

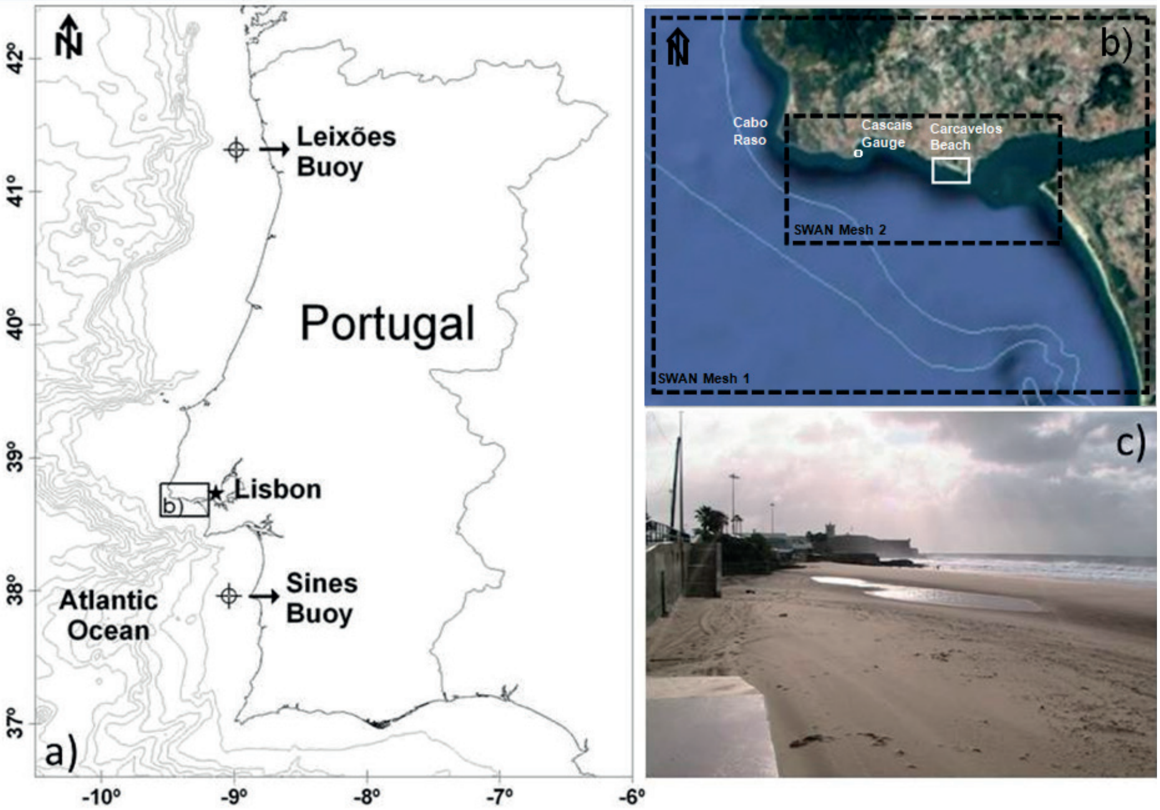


Figure 1 - Location of the study area: a) Leixões and Sines buoys; b) SWAN model meshes and Cascais gauge; and c) beach view towards SE (oblique photograph).

*Figura 1 - Localização da área de estudo: a) bóias de Leixões e Sines; b) malhas do modelo SWAN e marégrafo de Cascais; e c) vista da praia para SE (fotografia oblíqua).*

west coast of the country (Oliveira *et al.*, 2016). Despite the existence of headlands in both extremes, it is not a pocket beach as the closure depth, that is, the submerged limit of the active beach, is located further offshore than the headlands. The wave regime to which it is exposed and the proximity to a densely populated urban area make the beach a sea-land interface of high coastal risk. A relevant fact of this maritime storm event, which occurred in October 2011 during spring astronomic tide conditions and triggered a coastal event warning by the Portuguese Institute for Sea and Atmosphere (Jornal de Notícias, 2011), is that it was the first of that maritime winter season (October-March, inclusively).

## 2. DATA AND METHODS

The data monitored and the methodologies applied are described in the following subsections.

### 2.1 Hydrodynamics

The characterisation of the 24-hour hydrodynamic storm event (wave parameters and sea level), offshore and in five positions at the closure depth along the beach, considered as the offshore limit of the active zone regarding the longshore sediment transport (Oliveira *et al.*, 2002; Larangeiro *et al.*, 2009; Oliveira and Freire, 2011), was achieved by integrating buoy data and numerical modelling of wave propagation.

The offshore wave climate in front of the study area was calculated based on wave data from the two nearest offshore buoys: one located in Leixões, 280 km north of the study site, and the other located in Sines, 80 km south of the study site (Figure 1a). A weighted average, in which the weights were the relative distance (in the North-South direction) from each buoy to the offshore position in front of the study area, was applied to the time series (of sampling time equal to 10 minutes) of the parameters significant wave height, Hs (m), zero up crossing period, Tz (s), and mean direction relative to the geographic North (positive clockwise), Dir (°) (Figure 2a, b and c). The geographic proximity of the study area determined the best approach to the wave climate offshore of Sines. This fact agrees with the findings of a previous study that compared the average wave climate between the buoys deployed at offshore of Sines and at offshore of Figueira da Foz, also located north of the study site but closer than Leixões (Costa *et al.*, 2001). The study period was the time interval between the 11:00 (hh:mm) of the 27

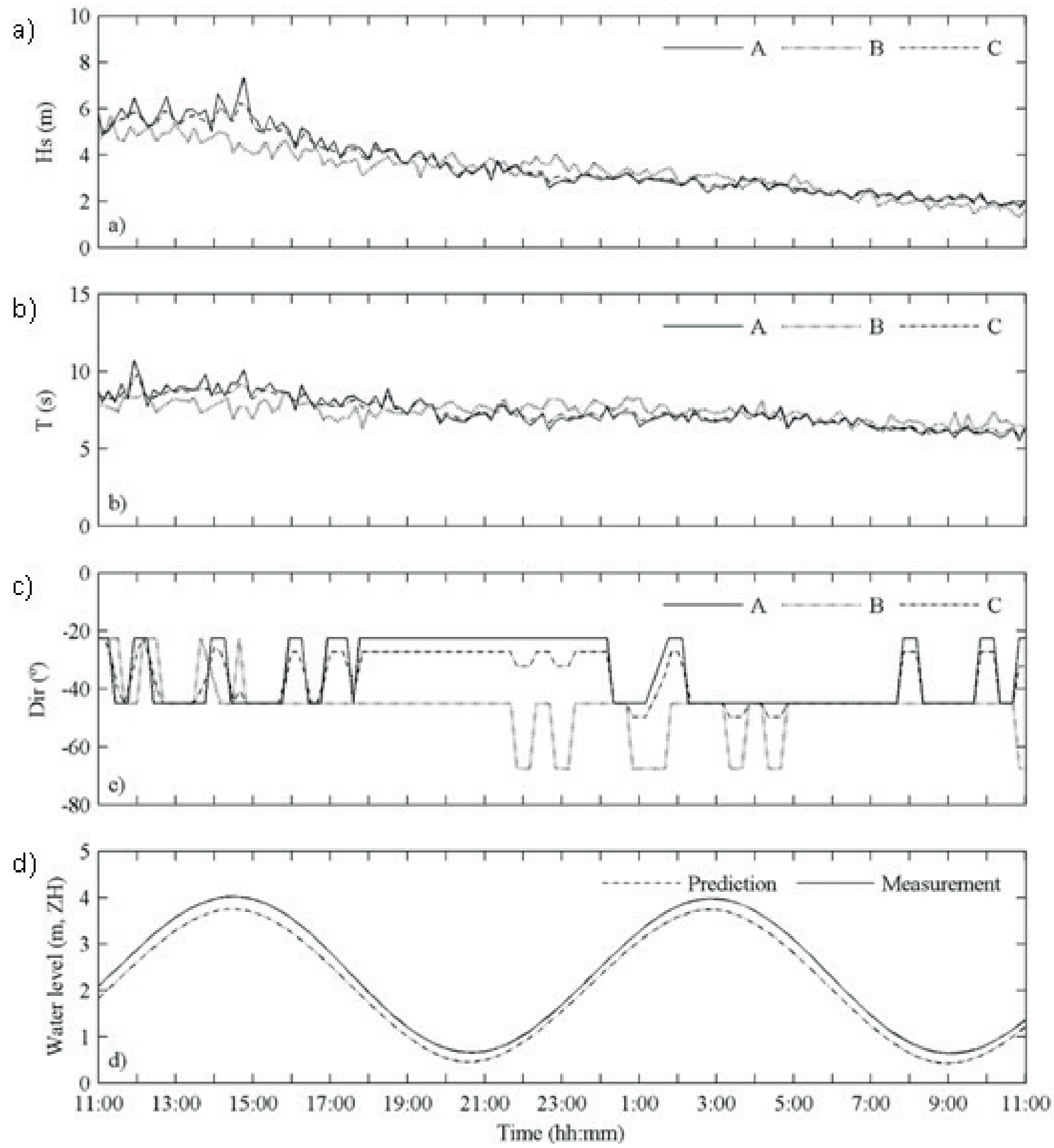


Figure 2 - Offshore wave parameters a) Hs, b) Tz and c) Dir relative to the geographic North (positive clockwise) in Sines (A), Leixões (B) and in front of the study area (C); and d) sea level at Cascais gauge during the study period.

*Figura 2 - Parâmetros de onda ao largo a) Hs, b) Tz e c) Dir relativa ao Norte geográfico (positiva no sentido horário) em Sines (A), Leixões (B) e em frente à área de estudo (C); e d) nível do mar no marégrafo de Cascais durante o período de estudo.*

of October of 2011 and the 11:00 (hh:mm) of the 28 of October of 2011.

The sea level data series was obtained from a nearby gauge, located in Cascais (Figure 1b). It includes the two components, tide and surge. The average (during the study period) of the surge, estimated based on the difference between the measured sea level and the predicted astronomic tidal level, was 0.36 m (Figure 2d). The sea level is referred to the national Hydrographic Datum reference level, named *Zero Hidrográfico* (ZH), which level is 2.21 m below the present mean sea level (MSL) in the study zone.

The wave climate at the closure depth, 10 m ZH (Oliveira *et al.*, 2002; Larangeiro *et al.*, 2009; Oliveira and Freire, 2011), in five positions located in front of the beach in the alignment of the cross-shore profiles surveyed at the beginning and end of the storm event, was calculated using the SWAN model (Booij *et al.*, 1999). The model was applied using a system of two mesh fitting (Figure 1b). For the coarser mesh, a uniform square grid spacing of 250 m was applied over a total area of 910 km$^2$. For the refined mesh, a uniform square grid spacing of 50 m was applied over a total area of 180 km$^2$.

## 2.2 Pre and Post-storm Morphology

Five cross-shore profiles, located strategically in order to provide a good coverage of the total alongshore extension of the beach foreshore and backshore, where surveyed at low spring tide on the 27 and on the 28 of October, between 9:00 and 11:00 (hh:mm). The profiles were named from A to E from SE to NW, respectively (Figure 3). The angle of the beach shoreline main alignment with respect to the geographic North was approximately N120°. The survey was performed through a RTK-DGPS (with vertical precision of ±20 mm + 1.0 ppm). The horizontal coordinate system was the ETRS89 - European Terrestrial Reference System 1989. The vertical coordinate system was converted to the ZH. Due to the sea-state conditions it was not possible to perform hydrographic surveys in the surf zone and the surveyed cross-shore extension (on the horizontal plan) of the beach foreshore and backshore was slightly shorter on the 27 of October (pre-storm) than on the 28 of October (post-storm): it varied (minimum-maximum profile length) between 107-146 m and 150-179 m, respectively. The profiles were interpolated along a uniform grid in the horizontal plan of spacing $\Delta x$=1.00 m.

The assessment of the morphologic impact of the event was achieved through the comparison of the pre and post-storm cross-shore profiles and the evaluation of the beach foreshore and backshore erosion volume.

## 2.3 Beach Sediments

Surface sediment samples were collected from georeferenced locations in the upper part of the beach face in each of the five pre-storm profiles (one sample in each profile) and analysed in the laboratory. For each sample a sediment grain size analysis was performed. The grain size distribution parameters, as the median diameter, $D_{50}$, the 90$^{th}$ percentile, $D_{90}$, the 84$^{th}$ percentile, $D_{84}$, and the 16$^{th}$ percentile, $D_{16}$, were calculated. Together with the geometrical spreading, $\sigma=(D_{84}/D_{16})^{(1/2)}$, these parameters, frequently used in models that predict the hydro-morphological behaviour of the beach under storm conditions, were used to characterise the grain size distribution of the beach sediments (Table 1).

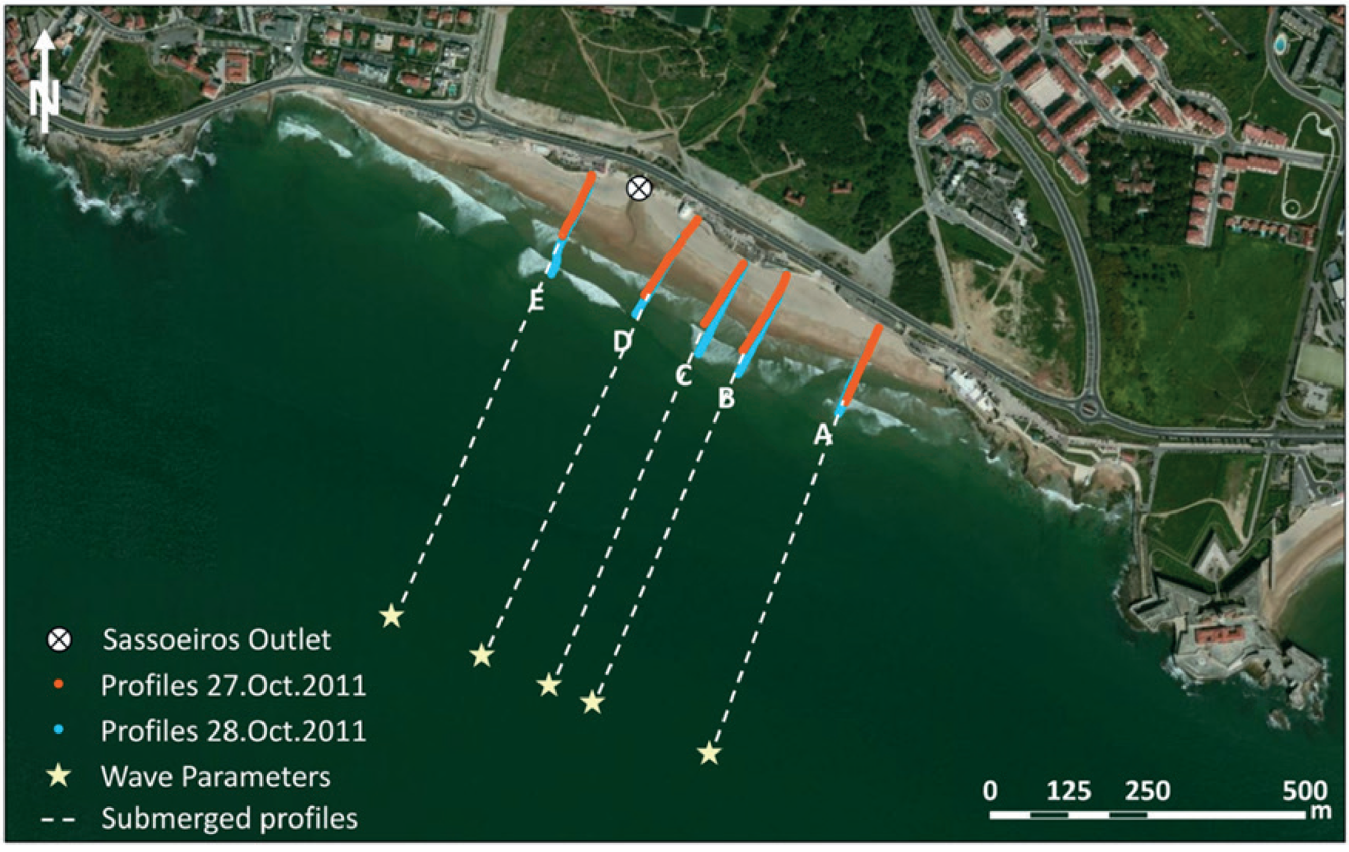


Figure 3. Location of the cross-shore profiles A, B, C, D and E surveyed on the 27 and 28 of October; position corresponding to the closure depth (10 m ZH) and to the wave parameters of each cross-shore profile; and location of the Sassoeiros stream outlet.

*Figura 3. Localização dos perfis transversais A, B, C, D e E medidos em 27 e 28 de Outubro; posição correspondente à profundidade de fecho (10 m ZH) e aos parâmetros de onda em cada perfil transversal; e localização da foz da ribeira de Sassoeiros.*

Table 1. Sediment grain size distribution parameters for profiles A, B, C, D and E.

*Tabela 1. Parâmetros de distribuição granulométrica nos perfis A, B, C, D e E.*

| Profile | $D_{16}$ (mm) | $D_{50}$ (mm) | $D_{84}$ (mm) | $D_{90}$ (mm) | σ (-) |
|---|---|---|---|---|---|
| A | 0.26 | 0.34 | 0.45 | 0.49 | 1.315 |
| B | 0.23 | 0.32 | 0.48 | 0.55 | 1.444 |
| C | 0.27 | 0.35 | 0.47 | 0.54 | 1.319 |
| D | 0.28 | 0.34 | 0.45 | 0.49 | 1.267 |
| E | 0.23 | 0.28 | 0.34 | 0.35 | 1.215 |

## 3. RESULTS AND DISCUSSION

The findings and their interpretation are described in the following subsections.

### 3.1 Hydrodynamics: spatial and time variation

The results of wave propagation from offshore until the five positions at the closure depth of the cross-shore beach profiles revealed the time and spatial (alongshore) variation of the wave climate in front of the beach, at the entrance of the surf zone, during the study period (Figure 4).

a. Regarding the time variation of the wave climate, it was found that:
   - The wave height decreased from nearly 2 to 0.5 m. Values above 1.5 m were observed until 14:30 (hh:mm), that is, approximately during the first 3.5 hours, and values above 1.0 m were observed until 02:00 (hh:mm), that is, approximately during the first 15 hours of the event;
   - The wave period decreased from 9 to 6 s, being the highest rate in the first 9 hours (from 11:00 until 20:00 (hh:mm) on the 27 of October);
   - There was a significant change in the incident wave direction from the first to the second day. The incident waves, which showed a nearly normal incident direction to the shoreline during the first day (the direction normal to the main shoreline alignment is N210°), became slightly oblique, that is, rotated towards NW on the second day (after 00:00 (hh:mm) on the 28 of October).

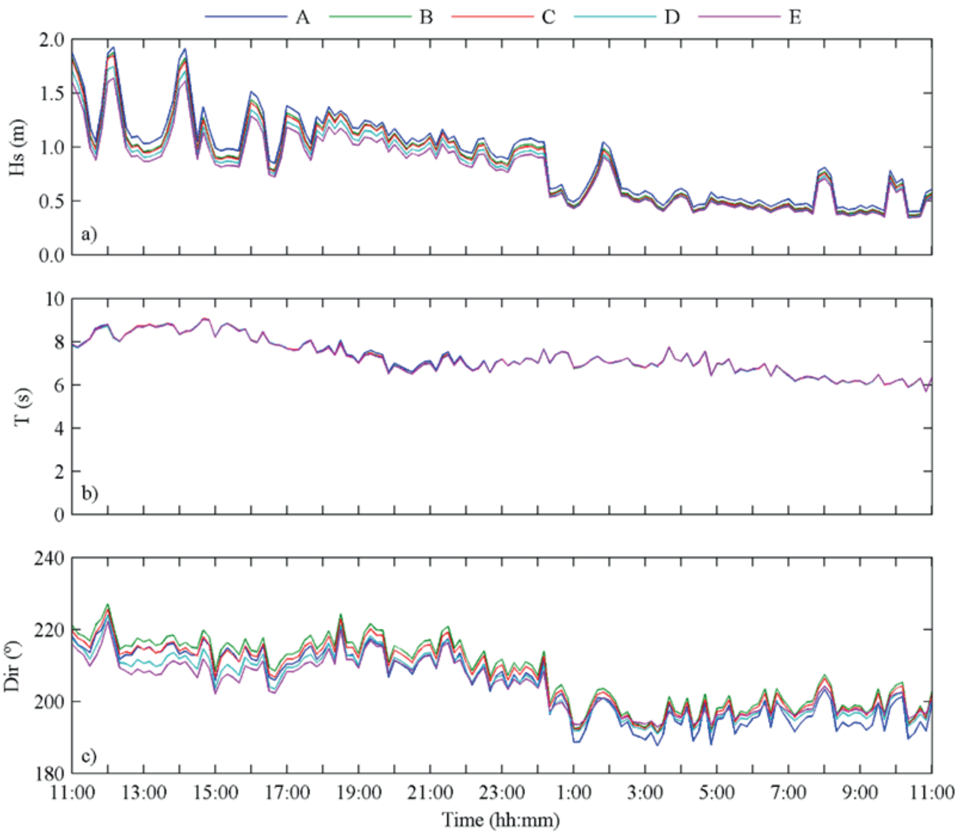


Figure 4 - Wave parameters Hs, Tz and Dir relative to the geographic North (positive clockwise) at the closure depth (10 m ZH) of profiles A, B, C, D and E during the study period.

*Figura 4 - Parâmetros de onda Hs, Tz e Dir relativa ao Norte geográfico (positiva no sentido horário) à profundidade de fecho (10 m ZH) para os perfis A, B, C, D e E durante o período de estudo.*

The simultaneous analysis of the wave parameters and the sea level evolution during the event allows to conclude that the most severe hydrodynamic condition occurred on the 27 of October at 14:00 (hh:mm), when the waves reached the greatest height and simultaneously the sea level was higher than 4 m ZH.

b. Regarding the spatial variation of the wave climate, it was found that:
   - The wave period was practically constant in space;
   - The wave height revealed a slight increase of incident energy alongshore, from NW to SE (from profiles E to A, respectively). This was mostly due to the protection effect against offshore incoming waves offered by Cabo Raso (Figure 1b), the large scale headland north of Carcavelos, which induces a change of direction in the main alignment of the shoreline in the region and causes wave diffraction (energy transmission laterally along the wave crest in the sheltered zone) when the direction of the offshore incoming waves (in Figure 2) is intercepted, as it is the case;
   - For the incident wave direction, the spatial variation is more evident for the highest waves, during the first day. The highest waves tended to be more oblique relatively to the cross-shore direction from the NW to the SE profiles.

It can be concluded that the spatial variation of the wave parameters height and direction is relevant because the alongshore extension of the beach is only about 1400 m.

c. Regarding the total amount of energy delivered to the total alongshore extension of the beach during the 24-hour study period, the results point out to the value of $1.7 \times 10^9$ J.

## 3.2 Geomorphology: spatial and time variation

The analysis of the profiles measured on the 27 of October showed that the upper part of the beach face, above MSL, was slightly steeper in profiles A and B (SE part of the beach) than in profiles C, D and E (Figure 5). It also showed that the crest-trough feature observed on the beach berm was almost absent in the case of profiles C and D and that for these profiles the beach elevation was distinctively lower. This fact is likely to be due to the temporary discharge of a stream named Sassoeiros, which outlet is located on the top of the beach backshore (Figure 3). This stream is diverted during the summer (bathing season), but during episodes of storm, with intense rainfall, the discharge increases and the stream flows directly to the beach. The 100-year return period watershed flood causes a maximum discharge of about 45 $m^3.s^{-1}$ (Câmara Municipal de Cascais, 2013). During occasions of intense rainfall and absence of interaction with waves, the stream presents a varying meander pattern in the sector of the beach near the outlet, causing local erosion, by pushing the surface sediments seaward and lowering the beach foreshore. Such features were observed in the pre-storm profiles (Figure 5).

Regarding the evolution of the stream trajectory during the study period, it was noticed that on the 27 of October the watercourse was aligned with the cross-shore direction near profile D, whereas on the day after the watercourse revealed a meander pattern along the top of the beach berm and its mouth was displaced towards the cross-shore profile C. At the peak of the storm, the waves reached the top of the berm in the beach central sector, that is, the interaction between the stream and the waves occurred along the total beach foreshore and backshore. The association of this fact to the time variation of the incident wave direction during the event (section 3.1) leads to the conclusion that the stream was pushed towards SE by the wave action during the event.

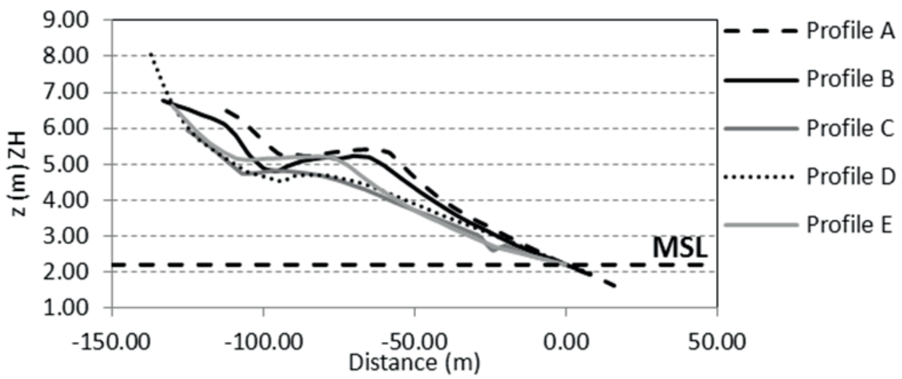


Figure 5. Cross-shore beach profiles A, B, C, D and E measured on the 27 of October.

*Figura 5. Perfis transversais de praia A, B, C, D e E medidos em 27 de Outubro.*

The results of the sediment grain size analysis revealed that the beach sediment was mainly median grain size sand and that the well sorted (low variance) sediment was uniform alongshore (Table 1). Thus, it can be concluded that the higher steepness of the beach face of profiles A and B was not correlated with coarser sediment in those profiles. Such fact leads to another conclusion: that the alongshore variation of the profiles morphology was mostly due to the impact of the Sassoeiros stream and to the alongshore variation of the incident wave action.

The five cross-shore beach profiles measured on the 27 of October and on the 28 of October (pre and post-storm, respectively) are plotted in the left column of Figure 6. The parameter "change in z" along the profile (calculated as the final minus the initial vertical elevation, for each grid point), which allows a better interpretation of the morphological evolution, is plotted in the right column of Figure 6. Negative values of "change in z" correspond to erosion and positive values correspond to accretion.

The volume mobilised in each beach foreshore and backshore profile during the study period can be seen in Figure 7. Two indicators were used for a better analysis, the volume of the total emerged (foreshore and backshore) profile and the volume of the emerged profile below 5 m ZH.

The morphological evolution had the following characteristics (Figures 6 and 7):

a. There was a distinct response from each of the five monitored profiles regarding the total foreshore and backshore sediment balance;
b. In the two SE profiles, A and B, occurred intense erosion;
c. In profile C the sediment balance in the foreshore and backshore zone was accretion. When observing the morphological evolution in detail, it can be seen that this phenomenon of accretion was mostly localized in the upper part of the beach profile, above 4 m ZH. This is likely a consequence of the interaction effect between the stream discharge and the waves;
d. In the five profiles, most of the erosion occurred above the MSL, more precisely in the beach face between the levels 3 and 4 m ZH;
e. In the two NW profiles, D and E, the global cross-shore sediment balance of the emerged profile was nearly null. However, like in profiles A and B, occurred erosion below 5 m ZH, despite much less than in these last two (about 20%);
f. The average sediment balance in the five profiles was -2.16 $m^3.m^{-1}$ and -2.23 $m^3.m^{-1}$, for the total and the below 5 m ZH emerged parts, respectively.

The decrease of the incident energy, from SE to NW, acknowledged from the results of the hydrodynamic analysis (section 3.1) explains partially the alongshore erosion gradient observed in the beach. However, it is likely that the differences observed in the evolution of the profiles, besides being due to the interaction between the stream discharge and the waves are also due to the highest steepness of the pre-storm beach face of profiles A and B.

## 4. CONCLUSIONS AND RECOMMENDATIONS

This paper addresses the fast morphological response of a narrow urban beach to an erosive maritime event. Both phenomena, the forcing hydrodynamics and the beach response, were quantified. Such information has always been important for coastal planners and managers taking decisions for reprofiling the beach and thus increase coastal resilience. However, since the future risk of coastal storm impacts is likely to increase, the subject gained extreme importance.

Immediately pre and post-storm surveyed cross-shore profiles were used to characterise the beach foreshore and backshore. The bathymetry of the surf zone could not be inspected due to the lack of safety conditions (for humans and instrumentation). However, since it was the first storm of the maritime winter season it is likely that the submerged bottom slope was relatively uniform (observations did not detect wave breaking positioned in a particular place that could indicate the presence of a submerged alongshore bar for energy dissipation). A surveillance of the beach sand grain size distribution was also performed during the first beach inspection in order to evaluate the alongshore and cross-shore variability of the sand characteristics. The hydrodynamic forcing conditions at the entrance of the surf zone were calculated based on a methodology which uses data from the two nearest offshore buoys and from a local gauge.

The results of the sediment grain size surveillance revealed that the beach sediment, mainly median well sorted sand, was uniform alongshore. The differences of the significant wave height at the closure depth between the five cross-shore profiles revealed an alongshore gradient of energy, that is, an alongshore variability of the beach exposure to wave action. A stream outlet, which discharge is larger during intense rainfall events, also proved to influence locally the morphology of the beach. The interaction of the stream with the waves caused less erosion in the foreshore and backshore of the beach than the one observed in the foreshore and backshore of the beach sectors submitted only to wave action. This 24-hour duration storm event delivered to the total alongshore

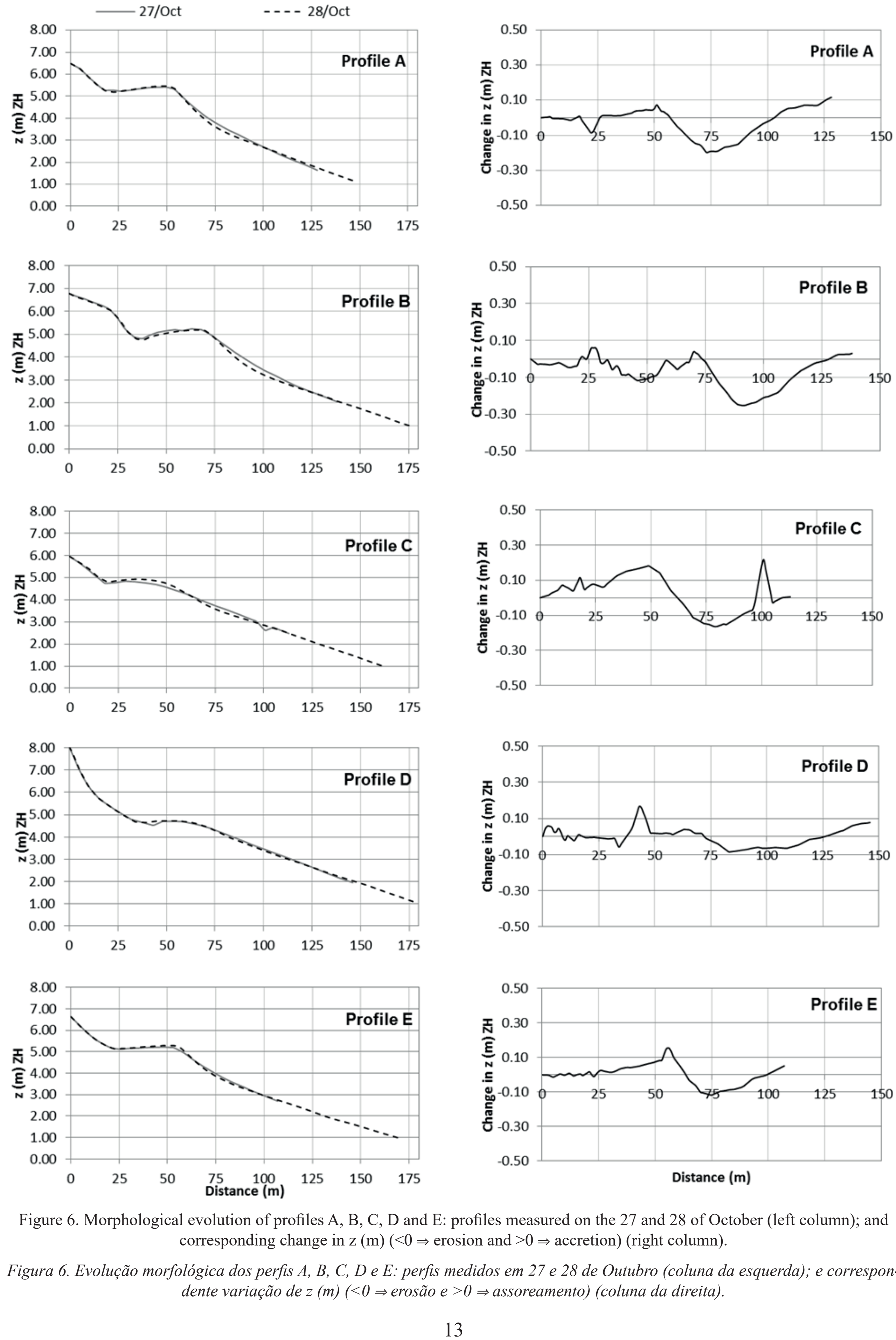


Figure 6. Morphological evolution of profiles A, B, C, D and E: profiles measured on the 27 and 28 of October (left column); and corresponding change in z (m) (<0 ⇒ erosion and >0 ⇒ accretion) (right column).

*Figura 6. Evolução morfológica dos perfis A, B, C, D e E: perfis medidos em 27 e 28 de Outubro (coluna da esquerda); e correspondente variação de z (m) (<0 ⇒ erosão e >0 ⇒ assoreamento) (coluna da direita).*

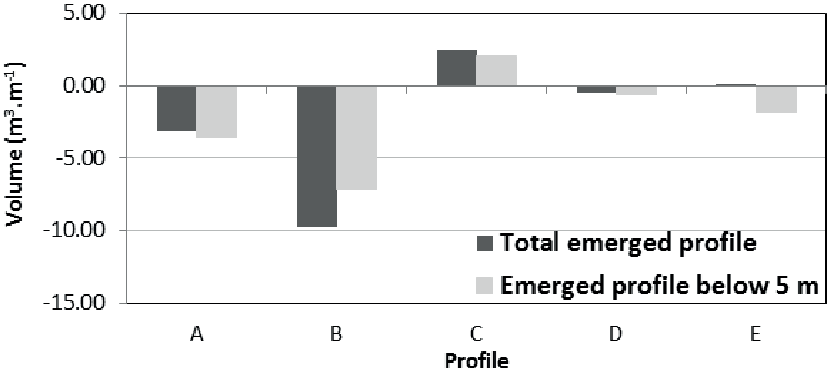


Figure 7. Change in volume in profiles A to E (<0 ⇒ erosion and >0 ⇒ accretion), for the total and the below 5 m ZH part of the emerged profiles.

*Figura 7. Variação de volume nos perfis A a E (<0 ⇒ erosão e >0 ⇒ assoreamento), para a totalidade emersa e a parte emersa abaixo dos 5 m ZH dos perfis.*

extension of the beach a total energy of $1.7 \times 10^9$ J which caused the extraction of approximately $3 \times 10^3$ $m^3$ of sand from the beach foreshore and backshore and its transport seaward by the undertow current.

Evidence-based information such as the findings of this study is essential for coastal planning and management, particularly in the context of climate changes. Therefore, it is recommended the deployment and validation of monitoring approaches for automated and systematic field data acquisition, ideally based on reliable non-intrusive techniques to capture relevant parameters (like the topo-hydrography of the total active zone, the vertical profile kinematics and the vertical sediment concentration) in such adverse environment, that would bring additional data-sets to cover a wider range of sea-states and beach morphology conditions. Despite having an initial cost, monitoring approaches for automated and systematic field data acquisition might be reimbursed at medium to long-term by the cost-effectiveness optimization of the beach protection solutions.

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