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Beach and Cliff Retreat Induced by Storm Groups at Forte Novo, Algarve (Portugal)

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ABSTRACT

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Littoral cell dynamics may change through time as a reaction to modifications of the coastal system. Along the Vilamoura-Quarteira coastline, the construction of a groin field limited the sediment supply to the already narrow Forte Novo beach, located downdrift, enhanced wave action on the cliff base and lead to long-term persistent cliff retreat. This research uses a set of surveys from November 2009 to March 2010 to determine short-term soft cliff erosion associated to storm groups at this sediment starved area. Following the initial LiDAR survey, three subsequent surveys were performed using a reflectorless total station for monitoring the cliff face, and RTK-DGPS to monitor the position of the cliff top, the cliff foot and the topography of the adjacent beach. Results indicate an important reduction in beach levels during successive storms (without significant beach recovery in between), allowing waves to further attack the cliff base and contributing to further enhance the structural and permanent cliff retreat. This work demonstrates how a combination of magnitude and frequency of extreme events coupled with development of the coastline, has led to increased cliff-beach recession and to the permanent dislocation of the cliff face.

ADDITIONAL INDEX WORDS: *Coastal Erosion, Beach Levels, Storm Impacts*

INTRODUCTION

The interrelationship between the cliff and foreshore is an essential element in explaining the episodic and uncertain nature of the cliff recession process (Lee and Clark, 2002). Sites which have experienced cliff erosion have been correlated to areas of decreased beach width and elevation, suggesting that areas with high beach erosion rates may correspond to higher rates of cliff recession (Sallenger *et al.*, 2002). Mathematical models corroborate that the loss of the beach at the cliff base, will lead to the acceleration of cliff retreat (Walkden and Hall, 2005). Similar linkages have recently been established between beach levels and cliff recession rates (Lee, 2008), highlighting the importance of beach elevation over beach width in controlling the wave attack at the cliff base (Dornbusch *et al.*, 2008).

This paper presents the results of recent analysis of geomorphological change at Forte Novo cliffs following erosion of the beach which had been protecting the cliff base. The main goal is to analyse the relationships between beach and cliff erosion during successive storms.

STUDY AREA

The Forte Novo cliffs (Figure 1), are located along the south coast of Portugal, immediately to the south east of Quarteira in the Algarve region. The cliffed area of Forte Novo is approximately 400 metres long and the cliffs are highly fractured, and composed of poorly to non-consolidated Plio-Pleistocene red sands and sandstones (Dias and Neal, 1992).

Coastal erosion at Forte Novo has been previously studied in the medium to long-term by several authors including Correia, Dias and Boski (1995), and Marques (1997). The latter found that the cliffs retreated at rates between 0.2 and 0.8 m/year in the 1970's, before the construction of the Vilamoura marina jetties and Quarteira groin field, located updrift of the cliffs. Recent measurements (Oliveira *et al.*, 2008) highlight a significant increase in cliff retreat rates (up to 2.27 m/year between 1991 and 2001). The construction of the hard engineering structures, on the westward location, resulted in the complete disruption of the littoral drift. The high shoreline retreat rates in the study area are therefore attributed not only to the geological composition of the soft rocks of the cliffs, but also to the influence of the engineering structures and consequent disruption of sediment supply. It is further suggested as contributing factors the vibration induced by vehicles near the cliff edge, the narrow protective beach and the energetic storm waves experienced in the area (Oliveira *et al.*, 2008).

The wave climate in the study area is dominated by W-SW swell (71%), with SE waves accounting for 23% of the total wave incidence. Mean annual significant wave height (H_s) is 0.92 m and mean annual peak period (T_p) is 8.2 s (Costa, Silva and Vitorino, 2001). Wave conditions associated with storms ($H_s > 3$ m) do not exceed 2% of the recorded data (Costa, Silva and Vitorino, 2001). The area is exposed to a semi-diurnal mesotidal regime with a mean tidal range of about 2 m, although a maximum of 3.5 m can be reached.

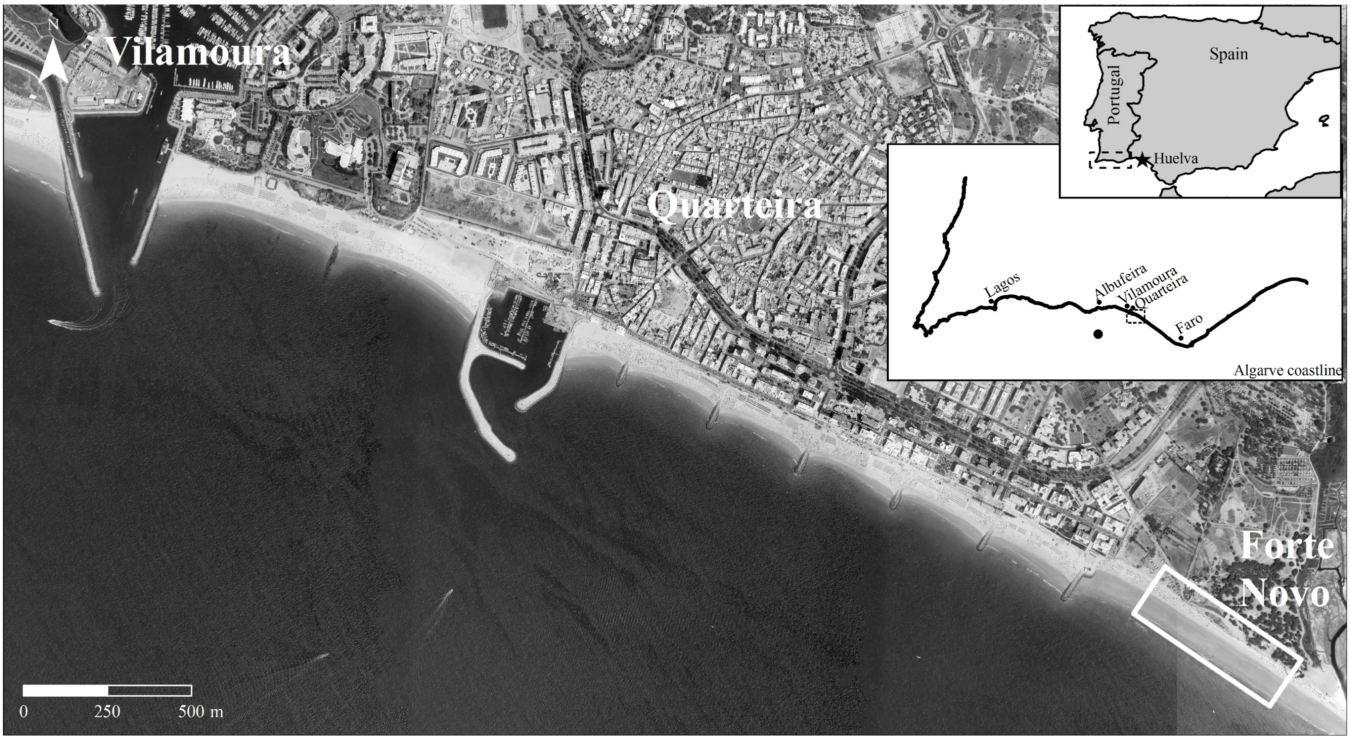

Figure 1. Location of the study area with the position of the modeled wave point from WANA network (circle) and Huelva tide gauge (star). Forte Novo cliff and beach are located within the white square.

METHODS

The data used in this research covers a survey timeline from November 2009 to March 2010. A topographic LiDAR survey covering the study area was carried out on November 6, 2009. The system of data collection used for this survey was the LiDAR Top Eye MK II B, acquiring 5 to 9 points per m^2 with an estimated vertical accuracy better than 10 cm. The subsequent three surveys on February 5th, 19th and 1st of March were performed using a reflectorless total station and RTK-DGPS with centimetric accuracy. A Leica TCR 705 reflectorless total station was used to measure the cliff face and a Trimble RTK-DGPS to monitor cliff top, cliff foot and the topography of the adjacent beach.

Wave and tide data were obtained to characterize the hydrodynamic conditions during the monitoring period. Due to the existence of gaps in Faro directional wave buoy records, modelled wave data from a WANA network deepwater grid point (Lahoz and Albiach, 2005) was used. Albufeira is the closest grid point to the study area (16 km away, 40 m water depth) and presents high correlation with Faro buoy (24 km away, 93 m water depth) for both wave height ($\rho \leq 0.001$, $n = 6695$, $R = 0.84$) and direction ($\rho \leq 0.001$, $n = 6695$, $R = 0.68$). Due to the unavailability of observed tide levels in southern Portugal, tide data from the Huelva tide gauge, located 110 km eastward of the study area (Figure 1), was used. Daily maximum tide levels were obtained from the analysis of the hourly records.

The cliff top line, the mean sea level contour (MSL), and the 2m contour above MSL were extracted from the first (November 6th) and last (March 1st) surveys to assess the study area net retreat for both the cliff and beach. Three profiles were extracted from the survey data (PW - west, PC – centre, and PE - east) in sites with distinct cliff top retreat. In order to better assess the cliff-beach system retreat several parameters were calculated: (i) cliff top retreat by the receding of this line measured from the cliff top to the profile origin point; (ii) beach height measured at the cliff foot, at the contact between the cliff and the beach; (iii) shoreline retreat measured from the 2 m contour above MSL to the cliff foot, and (iv) volume (m^3/m) calculated above MSL.

In order to facilitate data analyses and interpretation, the periods between surveys will be referred henceforth as terms I (first), II (second) and III (third). Term I corresponds to the period between the first and the second survey; II corresponds to the period between the second and the third survey; and III corresponds to the period between the third and the forth survey.

RESULTS

During the monitoring period the study area was exposed to two storm groups (Figure 2), one with four storms at term I and another composed by three storms at terms II and III. The group of four storms from the south-west occurred in a short period of time during the first term, with maximum significant wave heights (H_s) of 5.2 m, 4.2 m, 4.0 m and 3.6 m. These storms occurred during spring-tides, reaching maximums of 1.4 m, 1.5 m, 1.9 m, and 0.9 m above MSL, respectively. In the second term, one storm from the south-west was registered, with H_s of 3.5 m coincident with the peak of spring-tides record at 1.8 m. Although H_s during the third term was generally high, only two storms occurred. The first storm, from the south-west, had H_s of 3.8 m and maximum sea level of 1.3 m. The last episode occurred from a southward direction with H_s of 3.7 m coincident with spring-tides and a maximum sea level of 1.9 m.

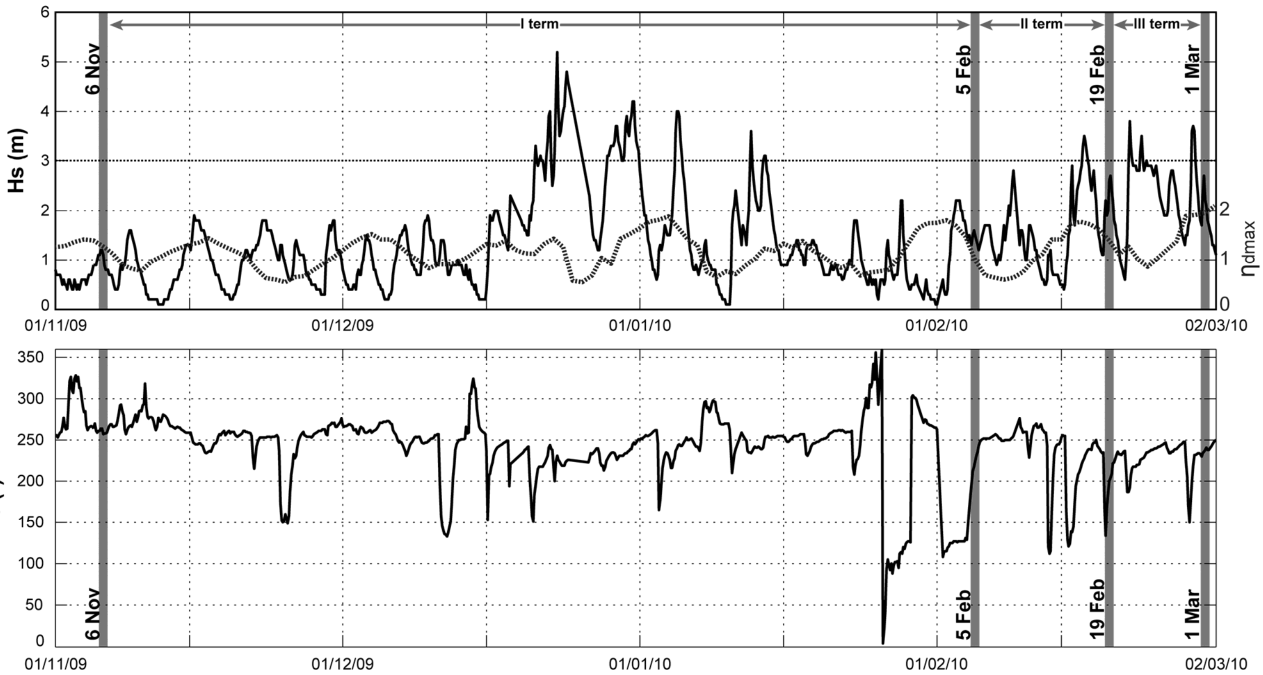

Figure 2. Offshore significant wave height (H_s, black line) along with the maximum daily sea level above MSL (η_{dmax}, grey line), and direction (θ, bottom graph). The grey vertical lines correspond to the surveys. The upper graph shows the storm threshold for the area ($H_s = 3$ m).

The impact of the registered storms and storm groups is translated into the erosion of the cliff-beach system (Figure 3). Across the whole study area, the average cliff top retreat recorded was 2 m with a maximum retreat of 7.2 m. Measurements of the beach topography revealed a beach width reduction, with an average retreat of the MSL contour of 7.8 m and a maximum retreat of 12.4 m (Figure 3).

The heterogeneous pattern of cliff top retreat contrasts with the almost linear pattern of MSL retreat (Figure 3). The area which protruded the most along the cliff top in the first survey (western and central part; roughly from PW to PC) is also the area that registered the greatest cliff retreat. This recession rate was only surpassed in the westward section of the study area, where the cliff is low and the proximity to the groin induced even higher retreat.

The three profiles illustrate the evolution of the cliff-beach system in the different sectors of the area during the monitoring

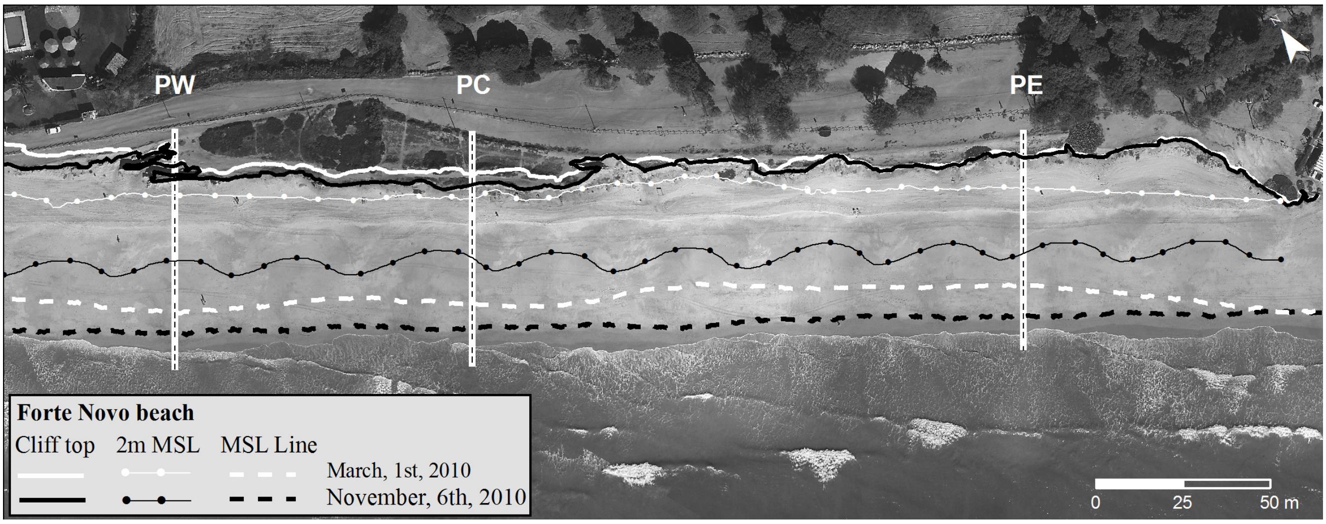

Figure 3. Retreat of the cliff top, MSL contour and 2 m MSL contour. Location of the profiles analyzed in the text.

period (Figure 4). Analysis of the profiles reveals two important points: (i) the continuous lowering of beach height between surveys, a dynamic common to all profiles; and (ii) the higher impact of storms recorded during the second and third term causing significant erosion, even though the corresponding conditions do not match the highest values of H_s and sea levels recorded during the monitoring period (Figure 2). PW demonstrates how the retreat of the cliff-beach system occurred in the westernmost part of the study area (Figure 4). Concurrently with a beach lowering of 1.8 m, the shoreline receded 10.6 m and the system lost 47 m^3/m in the first term (Table 1). The cliff top began to register a noticeable retreat rate in the second term with lower energy storm conditions. In the third term, storm height continued to decrease, although a further 13 m^3/m were lost from the cliff-beach system and the shoreline receded a further 6.4 m (Table 1). The central profile (PC), located at the area of the greatest protrusion, illustrates the most significant changes of the study area with a total cliff top retreat of 3.5 m, a reduction of 3.3 m of beach height and a loss of 89 m^3/m of volume from the cliff-beach system. The evolution pattern is characterized by a continuous lowering of beach height and shoreline retreat through all the surveys (Table 1). The amount of volume lost from the cliff-beach system was similar in the first and last term (38m^3/m, Table 1), although the wave conditions were significantly more energetic during the first term. The easternmost profile (PE), demonstrates the evolution of the most stable sector of the study area (Figure 3). Nevertheless, beach height lowering still reached a total of 2.1 m, from which 1.5 m was recorded in the first term together with the loss of 34 m^3/m and a shoreline retreat of 9 m (Table 1). Despite being the most stable profile, PE has recorded in the second term, a shoreline retreat of 6 m and loss of 20 m^3/m. PE was also the profile registering the higher total shoreline retreat 19.2 m (Table 1), which was not followed by significant cliff retreat (~0.4 m). It is possible to observe that the first storm group (term I), was mainly responsible for beach height lowering, beach volume change and shoreline retreat, while at the second storm group (terms II and III), the dominant process was cliff erosion and retreat (Table 1).

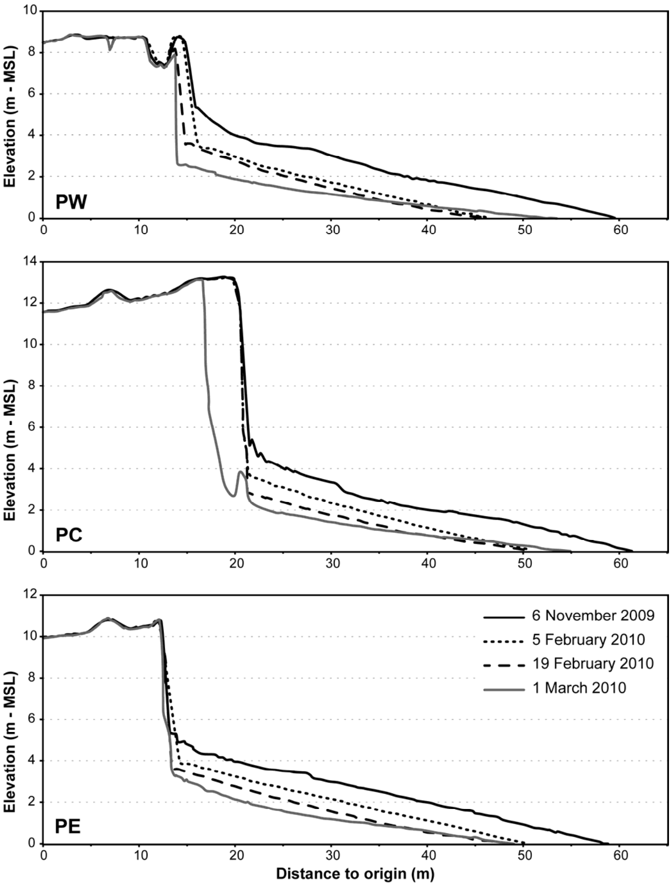

Figure 4. Cliff-beach profiles changes between surveys.

Table 1: Measurements of cliff top retreat, beach height change, shoreline retreat and volume change between surveys. Bold values indicate the dominant term at each variable.

Variable	Profile	I Term	II Term	III Term	Total
Cliff top retreat (m)	PW	-0.3	-1.0	-0.2	-1.5
	PC	-0.4	0.0	-3.1	-3.5
	PE	-0.3	-0.1	-0.1	-0.4
	Average	-0.33	-0.37	**-1.1**	-1.8
Beach height change (m)	PW	-1.8	0.0	-0.9	-2.7
	PC	-1.4	-0.9	-1.0	-3.3
	PE	-1.5	-0.3	-0.3	-2.1
	Average	**-1.57**	-0.4	-0.73	-2.7
Shoreline retreat (m - 2 m MSL)	PW	-10.6	-1.8	-6.4	-18.9
	PC	-7.5	-4.8	-3.7	-16.0
	PE	-9.0	-6.0	-4.3	-19.2
	Average	**-9.03**	-4.2	-4.8	-18.03
Volume change (m^3/m)	PW	-47	-13	-13	-72
	PC	-38	-13	-38	-89
	PE	-34	-20	-11	-65
	Average	**-39.7**	-15.3	-20.7	-75.3

DISCUSSION AND CONCLUSION

The coastal system studied in this research appears to be in a state of unstable equilibrium, responding to disturbances by adjustment to a new state (Chorley and Kennedy, 1971). Previous studies (*e.g.* Correia, Dias and Boski, 1995; Oliveira *et al.*, 2008), have demonstrated the downdrift impact of the Vilamoura marina jetties and Quarteira groin field construction on the dynamics of the system due to the disruption of the sediment supply and consequent cliff-beach system erosion. That impact is obvious even at the studied smaller scale, as demonstrated here, since these structures restrain sediment nourishment by longshore drift, leading to sediment scarcity and a lack of beach recovery between storms (Figure 4).

The presence of a beach provides cliff protection assuring the dissipation of wave energy on the foreshore. When a wide berm exists, wave attack at the cliff foot may be infrequent and only related to a combination of high tides and large waves (Lee and Clark, 2002). Storm waves can be extremely effective in causing cliff recession, especially on sandy cliffs (Lee and Clark, 2002). In the study area, the succession of four storms in a period of 23 days with storm peak H_s between 3.6 m and 5.2 m and sea levels between 0.9 m and 1.9 m above MSL promoted beach depletion. The grouping of storms resulted in a cumulative impact on the coastal system where beach recovery was prevented by the magnitude and frequency of the storm events (Ferreira, 2006). The recorded storm data and subsequent geomorphological change has led to an increased vulnerability of the system. The continuous lowering of beach height (Table 1), and the absence and/or rapid cliff foot debris removal, demonstrates the significant beach erosion caused by storms. This in conjunction with the associated sediment disruption in the study area caused by the westward structures, allows marine erosion to attack the cliff base and promote cliff retreat and the consequent sediment loss from the cliff-beach system. This was particularly evident at terms II and III when a second storm group reached the area (Figure 4, Table 1).

The distinctive profile retreat observed in the Forte Novo cliffs (Figure 4), reveals important variations within the study area. The central, most protruding profile, had the minor fronting beach, hence the higher cliff top retreat. The easternmost profile is located at a re-entrant position and farthest from the groins explaining the beach lowering and the reduced cliff retreat. The results confirm the assumption that the longshore variation in beach levels are reflected in the longshore variation in cliff recession rates (Lee, 2008). From the short-term perspective of the present study, Forte Novo cliffs have retreated with a rectilinear pursuit pattern, as the greatest erosion occurred where the cliff protruded the most. At re-entrant sites (near profile PE), the cliff retreat was smaller even when the shoreline retreat reached the highest values. It is therefore possible to presume that longshore retreat on soft cliffs will depend greatly on the degree of exposure to wave attack after beach depletion has taken place.

The results presented here demonstrate how a combination of the magnitude and frequency of extreme events coupled with coastline development, particularly through hard engineering structures, has led to increased cliff recession. The present work clearly demonstrates the importance of understanding the combined dynamics of cliff-beach systems.

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