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Anthropogenic modifications in the erosional rhythm of a coastal cliff. Rocha do Gronho (western coast of Portugal)

Cambio antropogénico del ritmo erosivo de un acantilado costero. Rocha do Gronho (litoral oeste Portugués)

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Abstract

The beach-cliff system "Rocha do Gronho" is a stretch of the west coast of Portugal that marks the southern limit of a coastal lagoon – The Obidos lagoon. The cliff is cut in sedimentary material and the elongated beach is generally narrow being almost submerged by the spring tides. Existing documents show that, in almost all of the second half of the twentieth century, there has been a state of equilibrium of the beach-cliff system because the abundance of sediments proceeding from the lagoon and carried south by the longshore current (predominantly N-S) provided a covering of the cliff base that protect it from the assailing force of the waves. The cliff face evolved mainly by small magnitude rockfall events. Between 1958 and 1995, a rate of retreat of 0.15m (±0.02m) year−1 was recorded. Afterwards, the frequency and the magnitude of the occurrences of mass movements had changed. Five events leading to a 33.6m retreat of the cliff top have been recorded. The type of movement, the affected length of the top of the cliff, the maximum retreat, the lost area of the top of the cliff and the volume of material displaced were estimated for each event. The identification of the processes involved as well as the evaluation of the potential triggering factors allowed an assessment of the influence of human intervention in the lagoon (changing the main draining paths and consequently the patterns of sediment transport) in the modifications of the "Rocha do Gronho" evolution.

Keywords: coastal cliff, slope movements, rate of retreat, anthropic influence, Portuguese west coast.

Resumen

El sistema playa-acantilado costero de "Rocha do Gronho" es una parcela del litoral oeste de Portugal que establece el límite sur de una laguna costera, la laguna de Obidos. El acantilado está tallado en material sedimentario y la larga playa es generalmente estrecha siendo frecuentemente cubierta durante las mareas altas. Los documentos existentes demuestran que, en casi toda la segunda mitad del siglo XX, ha habido equilibrio en el sistema playa-acantilado porque la abundancia de sedimentos que procedían de la laguna y eran transportados hacia el sur por la corriente litoral (predominante N-S) proporcionaba una cobertura de la base del acantilado que la protegía contra la fuerza erosiva del oleaje. El frente del acantilado evolucionó principalmente por episodios de desprendimientos rocosos de pequeña magnitud. Entre 1958 y 1995 se obtuvo un índice de retroceso de 0,15 m (±0,02 m) año Posteriormente, la frecuencia y la magnitud de los movimientos de ladera cambiaron. Se han registrado cinco eventos que causaro 33,6 m de retroceso del acantilado. El tipo de movimiento, la extensión afectada, el retroceso máximo, el área perdida de la cin del acantilado y el volumen de material desplazado fueron calculados para cada acontecimiento. La identificación de los proceso así como la evaluación de los factores potenciales determinantes permitió establecer la influencia de una intervención humana en laguna (cambiando las principales líneas del trayecto de drenaje y, por consiguiente, los patrones de transporte de los sedimentos modificando el ritmo evolutivo de la "Rocha do Gronho".

Palabras clave: acantilado costero, movimientos de ladera, índice de retroceso, influencia antrópica, litoral oeste de Portugal.

1. Introduction

In the centre of the west coast of Portugal, there is a stretch that extends alongshore 7.2 km from NE to SW and which is entirely exposed to the predominant NW waves in a mesotidal environment (maximum amplitude 3.5-4.0 m). This stretch is characterized by a beach-cliff system, with an elongated and narrow beach that in several locations is completely submerged particularly during spring tides. The cliffs are cut in Cretaceous sandstones and conglomerates dominated by quartzose sediments bound either by a siliceous or by a kaoliniferous cement which are cross-stratified. The conglomerates are generally badly sorted and are composed mainly of rounded or sub-rounded clasts. These materials have a 11º to 14ºN245º dip almost parallel to the coastline.

The 35 m high cliff that marks the northern limit of this stretch is named "Rocha do Gronho" or simply Gronho. It is adjacent to a 6 km^2 coastal lagoon – the Obidos lagoon – which is aligned at right angles to coastline (Fi 1). A 250/300 m width and 1500 m length sandy barri partially isolate this lagoon from the sea, with the ma connection being by a channel normally located in th central part of the barrier.

This cliff of Gronho also forms a barrier to the N winc promoting the development of a very high (35-40m) a tive dune that limits the SW margin of the lagoon's te minal area. Since the 1960's, holiday houses have bee constructed, partially over the dune, and now form a vi lage of more than 120 buildings (Fig. 2).

This paper is based on research that aimed, not only characterize in detail all the processes of evolution of Gro ho cliff, but also to identify the main triggering factors.

The understanding of the dynamic of this coastal are beyond its scientific interest, is essential to the evaluatic of its natural hazards, and as a first step to the delimit tion of restricted or even forbidden areas, near the cli top and base where the risk is higher.

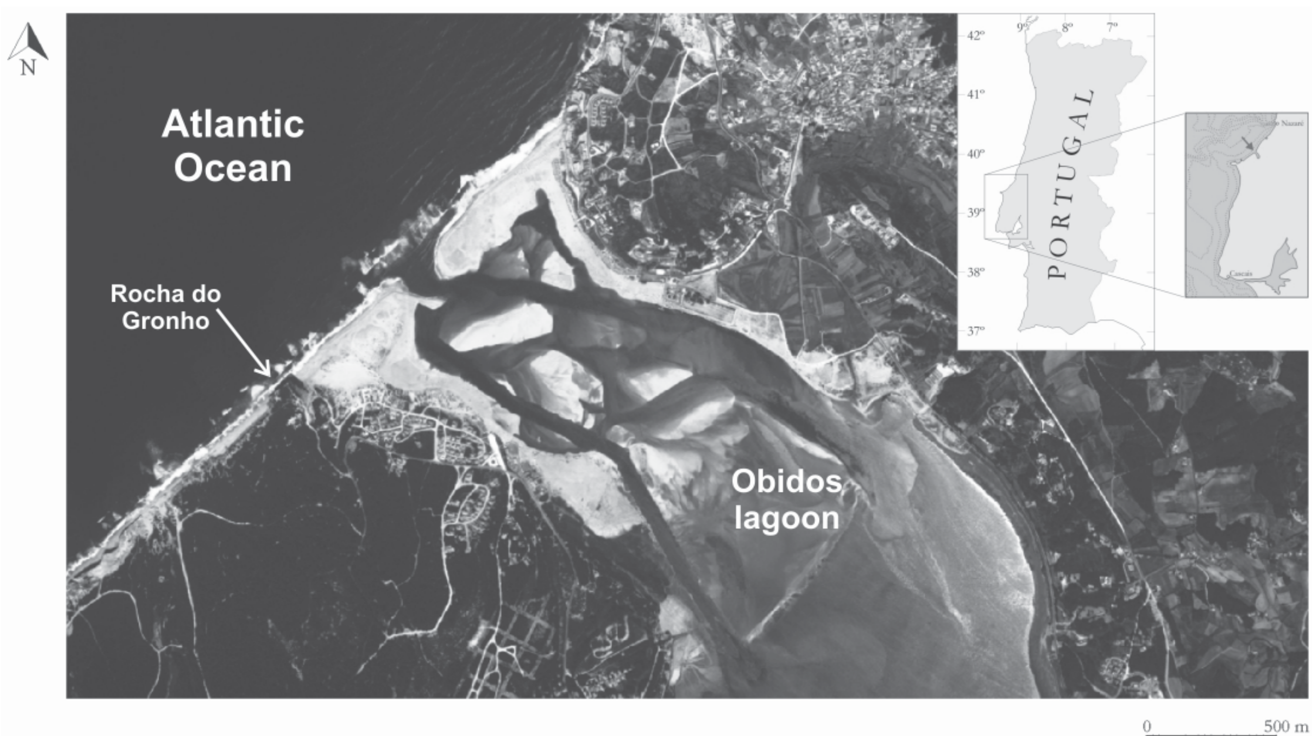


Fig. 1.- Obidos lagoon and "Rocha do Gronho" beach-cliff system
Fig. 1.- La laguna de Obidos y el sistema playa-acantilado costero de "Rocha do Gronho"

Fig. 2.- A climbing dune covers the Gronho cliff to NE. Remark the village over the dune.
Fig. 2.- Una duna cubre el sector NE del acantilado del Gronho. Nótese el pueblo sobre la duna.

2. Methodology

The study on the present evolution of the Gronho cliff and the Obidos lagoon was based on the analysis of aerial photos and ortho-photos of the area and fieldwork. Older documents, such as the 1957 aerial photos, were digitized with high definition – 2400 ppp - allowing the amplification of the images up to 15 times with sufficient definition to clearly identify the top of the cliff. After 1997, the positions of the cliff-top were obtained by fieldwork using a hand-held laser meter and fixed marks on the ground. These measurements allowed the calculation of the cliff-top area lost using SIG software. The slope angle prior to the movement was used to calculate the volume of material displaced.

The geological characteristics of the outcrops were also identified and data was gathered to allow the strength calculation of the different lithological units that compose the cliff in the studied area. This evaluation was obtained using the *Rock Mass index* created by Palmstrom (1996a, b) that considers the Compressive Strength of the rocks and a group of jointing parameters – density, roughness, alteration and size.

The maritime characteristics near the coastline were obtained: namely the tide levels in relation to the cliff base and the area reached by the waves particularly during storm situations. In the west coast of Portugal there are only two buoys which function regularly – Sines, at the Alentejo coast and Leixoes, north of the river Douro mouth. Nevertheless, malfunctions are relatively frequent and consequently there is no wave data for some periods. Very recently, a new buoy was installed in front of the Obidos lagoon, but its data it is still unavailable. According to Pires (1979), along this stretch of the Portuguese west coast the wave climate is very similar to Sines and therefore the available data from this buoy was used. The pressure applied by the waves at the cliff base was calculated using the ALFA model (Neves *et al.*, 2002) which considers the height of the deep water waves, the bottom slope near the coastline and the water-depth at the base of the cliff.

Also, the rainfall data was analysed, not only for the period immediately prior to the events, but also the accumulated rainfall of the previous days. The respective return period was calculated. Taking into account the nature of the rocks, particularly its texture, the fault system, and the period of the year in which the slope movements occurred, it was considered that there was a retention factor of the rainfall water in the rock mass of 5 days. Accordingly, the weight of this water in unstable blocks was calculated.

3. "Rocha do Gronho" cliff dynamics between 1958 and 2004

Despite the few fixed references in the field, the aerial photographs analysis allowed the evaluation of the evolution of the studied coastline. Marques (1997b), comparing aerial photos of 1947 and 1991, obtained a rate of retreat of 0.1 m year^{-1}, for the entire 7.2 km stretch of coast cut in sandstones and conglomerates.

In this research, another pair of aerial photos taken in June 1958 and June 1995 (Fig. 3) was used, and the comparison gave, just for the cliff of Gronho, an average rate of retreat of 0.15 m (±0.02 m) year^{-1}, with maximum values attaining 0.27 m year^{-1} (Neves, 2004), i.e. not significantly different from the rest of the coast with similar geomorphological characteristics.

However, this rhythm was about to change in the next decade with the occurrence of five slope movements that affected an area of nearly 1650 m^2, and led to a maximum retreat of the top of the cliff of 33.6 m and the dislodgment of a calculated volume of almost 62000 m^3 of rock (Table 1 and Fig. 4).

In consequence, the rate of retreat of the top of the cliff increased significantly to 3.4 m year^{-1} (Table 2) and if only the more active period of 1997-2000 is considered, the rate of retreat rises to 8.9 m year^{-1}.

Elements obtained regarding the geomorphological characteristics of Gronho cliff and particularly its evolution in the period 1995-2005 allow the identification of

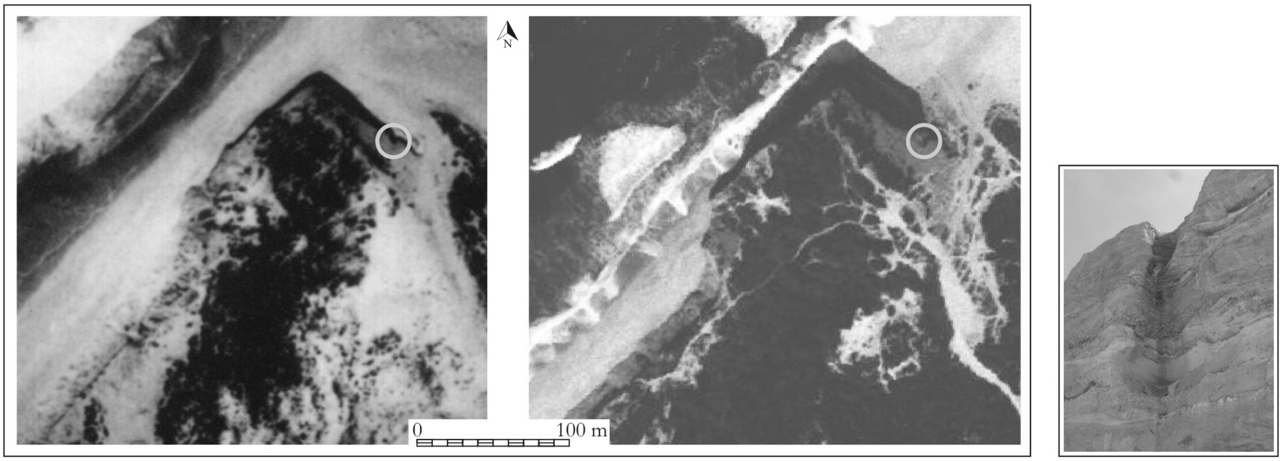


Fig. 3.- Cliff of Gronho in 1958 and in 1995. The natural well seen in the photo to the right is clearly visible in the prior photos (circle) and was used as a reference mark.

Fig. 3.- Acantilado del Gronho en 1958 y 1995. El pozo natural que se observa en la foto de la derecha es claramente visible en las fotos anteriores (señalado con un círculo) y fue usado como punto de referencia.

a group of common and specific factors related to each event of slope movement that are essential to understand the genesis and development of the main geomorphological processes that controlled the evolution of this stretch of coast, during this phase.

The first movement of this period occurred in the beginning of 1997. On the night of 8 January, a rockfall affected the overhanging profile which can be regarded as a natural response of the system to a long period of inactivity of the top of the cliff. The new cliff face had a perfect sub-vertical profile. This was at the beginning of a spring-tide period with high tides reaching 3.0 m above chart datum.

Records obtained in the Seismographic Stations, indicate that on January 4, that is 3 days before the rockfall, two earthquakes occured with a few hours gap, both with 2.2 magnitude in the Ritcher scale and with epicentre at approximately 26 km from the Gronho cliff (Fig. 5). As Zellmer (1987), Bull *et al.* (1994) and Vidrih *et al.* (2001), quoted by Dorren (2003), concluded, seismic activity is a frequent cause of rockfalls. In the studied location, the indicated earthquakes could have increased the fracturing of the rock mass, particularly on the cliff sector close to the equilibrium limit.

Rainfall in the preceding 15 days was relatively limited, but the 30 days total had a return period of 11 years. Considering the 5 days retention period of rain water, the weight increase in the dislocated block was calculated as 36.7 kN.

At July 1999, Andrade (1999) noticed that the debris from the 1997 fall had been completely removed and a 2 m depth x 15 m long notch had been formed in the NW base of the cliff near its NE corner. On the 24 September, a new rockfall occurred in the Gronho cliff which affected the part above this notch.

The average wave-height on the Sines buoy did not show any unusual values, fluctuating between 1.7 and 2.4 m. Yet,

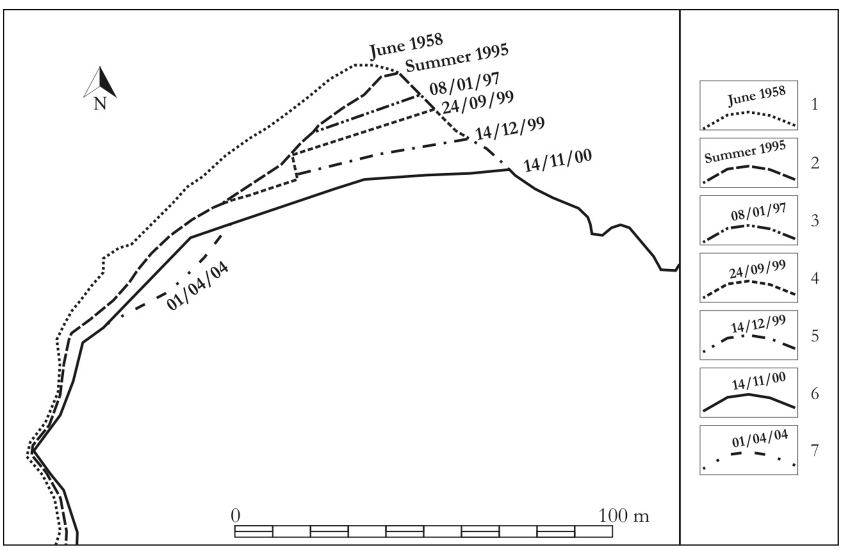


Fig. 4.- Top of the cliff retreat between June 1958 and April 2004. Top of the cliff location: 1-in the aerial photo of June 1958; 2-in the orthophoto of summer 1995; 3/4/5/6/7-after slope movements events in the indicated dates.

Fig. 4.- Retroceso del alto del acantilado entre Junio 1958 y Abril 2004. Localización del alto del acantilado: 1- en la foto aérea de Junio 1958; 2-en el ortofoto de Junio de 1995; 3/4/5/6/7-después de los movimientos de ladera en las fechas indicadas.

Type of movement	Date	Cliff length affected (m)	Highest retreat (m)	Top area lost (m^2)	Volume dislocated (m^3)
Rockfall	08-01-1997	30.9	6.9*	115.3*	3746.9*
Rockfall	24-09-1999	61.7	4.4	219.2	8221.3
Rockfall/Topple	14-12-1999	61.7	10.5	310.8	12589.2
Rockfall	14-11-2000	86.7	12.3	848.0	33919.6
Rockfall	01-04-2004	44.3	5.4	156.0	3358.0
TOTAL	**1995-2005**	--	33.6	1649.3	**61835.0**

Table 1.- Data on cliff length affected, highest retreat, top area lost and volume of material dislocated in the slope movement events at Gronho cliff.

Tabla 1.- Datos sobre la extensión del acantilado afectado, el retroceso máximo, el área perdida de la cima del acantilado y el volumen de material dislocado en los movimientos de ladera en el Gronho.

Time interval	Highest retreat rate (m y^{-1})	Top area lost rate (m^2 y^{-1})	Volume dislocated rate (m^3 y^{-1})
06/1958 to 06/1995	0.3	22	394
06/1995 to 06/2005	3.4	165	6184

Table 2.- Annual rates of retreat in the Gronho cliff

Tabla 2.- Índices de retroceso anual en el acantilado del Gronho

it was a spring tide period with high tide reaching 3.2 m.

Once again, it is possible to see evidence of significant seismic records of the days preceding the fall event. At the beginning of nightfall September, 20 a 4.0 Richter magnitude earthquake occurred in the continental shelf south of Cascais. This earthquake had an intensity II in the modified Mercalli scale at Caldas da Rainha (9 km east of Gronho). Two days after, a new earthquake occurred, with a magnitude 3.5 Richter, and with its epicentre 37km NE of Gronho (Fig. 5).

Rainfall, in the previous days, was scarce as is normal for this time of year. However, the larger cliff-top area affected allowed a greater weight increase when compared with that of the 1997 movement. Considering again, the 5 day retention period of rainwater, this increase could have reached 59.1 kN.

Field surveys, immediately after the fall, detected a subvertical fracture, parallel to the cliff face, that extended from the top (where the gap between the rock faces had a maximum width of 11 cm) to approximately half the cliff height (Fig. 6). This rupture was perhaps connected to the earthquakes of 20 and 22 September or to the vibration induced by the 24 September fall. The installation of fixed marks at both sides of the fracture made it possible to periodically check any modification of its width. Until the end of November, there was no movement of the individual separated blocks. This could indicate that the main fall had not been preceded by small readjustment movements, but instead indicated a rapid and single movement.

The debris produced by the September fall rapidly destroyed and mobilized by the waves and, by the end of November, there was already a 1 to 2 m deep notch at the base of the cliff.

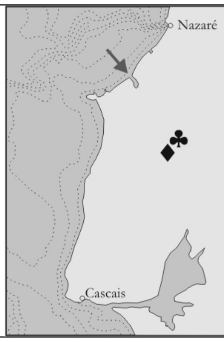
On the December, 14 1999, a new movement took place on the Gronho cliff that included, as could be expected, the more unstable sector, exploiting the discontinuity which already existed. It dislodged almost 12600 m^3 of rock, affecting more than 300 m^2 of the area at the top of the cliff where it produced a maximum retreat of 10.5 m.

The seismicity records of the 8-15 December week, revealed that the majority of earthquakes occurred on the oceanic floor to south and SW of Portugal, and that all were less than 3.0 magnitude. There was no information about any of these having been felt in the Gronho region

This event happened in a neap-tide period when high tides reached 2.93 m at Peniche, and a low-wave climate with waves around 2 m high. Rainfall was limited in the preceding 30 days, but the weight increase, due to the retention period of the rain water, in the unstable block could have reached 89.9 kN.

In the particular case of the 14 December event, the existence of another discontinuity, transverse to the cliff face, allowed the separation of two blocks. Each of which was affected by a different type of movement. The WSW block was displaced, due to a fall, with the debris cove-

	08/01/97	24/09/99
same day	none	none
5 previous days	♦ 04/01 (02:28h) magnitude 2.2	♥ 20/09 (21:54h) magnitude 4.0
	♣ 04/01 (09:54h) magnitude 2.2	♠ 22/09 (10:12h) magnitude 3.5
15 previous days	none	none



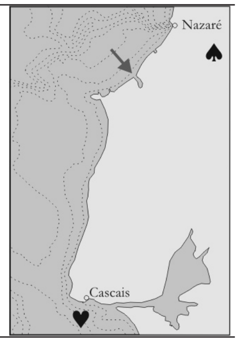


Fig. 5.- Seismic activity in the Gronho region at the day or at the preceding days of the January 1997 and the September 1999 cliff movements (magnitude values in Richter scale).

Fig. 5.- Actividad sísmica en la región del Gronho en el día o en los días precedentes a los movimientos de ladera de Enero 1997 y de Septiembre 1999 (valores de magnitud en la escala de Richter).

ring the base of the cliff, while the ENE block suffered a topple in a lateral movement relative to the cliff face. The debris from this movement dispersed over an area 63 m in length (Fig. 7). This topple and particularly the direction of the movement was possible because the notch was more profound at the base of the cliff facing NE than that facing NNW. According to Dikau (1996), a block will topple when:

$$b/h < \text{tg}\ \alpha$$

(b/h being the width-height ratio of the block and α the angle of the block base).

The unstable block was 38.0 m high, 10.3 m wide and there was a notch of 1.8 m depth. In agreement with these values, an angle of the block base greater than 15.2º would have been sufficient for the topple to have taken place. This discontinuity resulted in the connection between the notch and the transverse fracture that separated the toppled block (Fig. 8).

One of the main characteristics of the Gronho cliff movements – either fall or topple - is the high fragmentation of the material affected which facilitate the rapid and easy destruction of the debris and its distribution by the waves. At the end of August 2000, less than eight months after the December 1999 events, the greater part of the debris produced by those movements had disappeared, with only a few blocks remaining to protect the base of the cliff from wave attack (Fig. 9).

In September and most of October, the sea remain calm in the area with Sines buoy indicating significant wave heights of less than 2 m. However, in the last days of October and in the first week of November the same buoy registered NW waves with a significant height of greater than 4.0 m and maximum heights of between 6.0 and 8.0 m.

On 14 November a new movement took place at Gronho cliff which disrupted 87 m of its NNW face. A maximum retreat of more than 12 m occured. This fall-type

Fig. 6.- ENE sector of the Gronho cliff in the last trimester of 1999, with a vertical fracture.

Fig. 6.- Sector ENE del acantilado del Gronho en el último trimestre de 1999, con una fractura vertical.

Fig. 7.- ENE sector of Gronho cliff affected by a topple at 14 December 1999. **1 and 2**-Full lines - main fractures; dotted line - probable fracture lines; ellipse - notch at the cliff base; the arrow points out the topple direction. **3-** Photo taken 4 days after the slope movements; the topple debris were dispersed to NE.

Fig. 7.- Sector ENE del acantilado del Gronho afectado por un balanceamiento el 14 de Diciembre de 1999. **1 y 2**- Líneas continuas - fracturas principales; líneas discontínuas - fracturas probables; elipse - muesca en la base del acantilado; la flecha indica la dirección del balanceamiento. **3-** Foto tomada 4 días después de los movimientos de ladera; los escombros del balanceamiento fueron dispersados hacia el NE.

movement dislodged about 34000 m^3 of rock and affected a cliff-top area of almost 850 m^2 (Fig. 10). In the preceding days, rainfall was scarce and there were no seismic records in the region.

A comparison between pictures taken before and after the November event shows a clear difference, not only in the cliff-face, but also in the climbing dune beyond. Despite the short period, the episodes of rough sea were

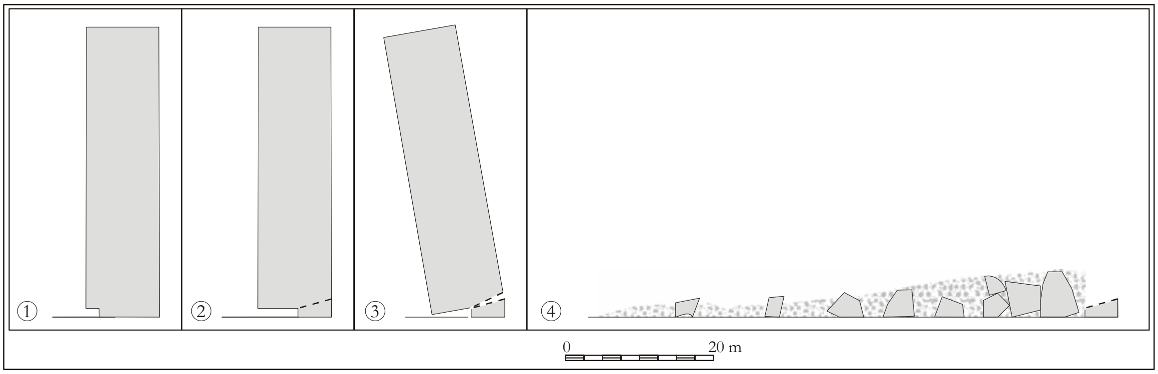


Fig. 8.- Evolution model of the toppled block at Gronho.
Fig. 8.- Modelo de evolución del bloque balanceado en el Gronho.

capable of a very rapid excavation of the cliff base, destabilizing the rest of the slope, and they forced a significant retreat of the dune.

Storms in December 2000 and January 2001 (with significant waves reaching 6 to 8 m in height for severel days; in January, 2 the maximum wave at Sines reached 13 m) remobilized almost all the debris from the previous fall (Fig. 11).

In the following 3 years, several storms with significant wave heights greater than 5 m were recorded (namely in February and March 2001, January and February 2002 and all of the period between November 2002 and March 2003).

Fieldwork in the Summer 2003 revealed that, at the base of the cliff, 8 notches had been formed, the deepest of which was almost 13 m long. These notches affected mainly the base of the cliff exposed to NNW and formed 80% of the total base of the cliff extension. The average rate of retreat of the base of the cliff, between November 1999 and June 2003, was 1.3 m year^{-1}, rising to 1.7 m year^{-1} in the sector exposed to NNW.

Finally, in April, 1 2004, a new fall occurred moving more than 3000 m^3 of rock from the top of the cliff whichsuffered a maximum retreat of 5.4 m and lost an area of 156 m^2. This fall took place precisely above the deepest notch (Fig. 12).

There were no records of seismic activity in the preceding days and the weight increase due to rainwater in the unstable block was calculated as the smallest of all the cliff events – 23.2 kN. In the two preceding months, the

Fig. 9.- Gronho cliff base: **1**-in 18 December 1999, covered by the debris from the movements that occurred 4 days earlier; the circle indicates a man, for scale; **2**-in 24 August 2000, only a few blocks remained. Arrows points to a common feature in both pictures.
Fig. 9.- Base del acantilado del Gronho: 1-en Diciembre 1999, cubierta por los escombros resultantes de los movimientos ocurridos 4 días antes; el circulo indica un hombre que sirve de escala; 2-el 24 Agosto 2000, solamente permanecían unos pocos bloques. Las flechas indican marcas comunes en ambas las fotos.

Fig. 10.- Part of the debris produced by the November 2000 rockfall. Photo taken in December 2000.

Fig. 10.- Parte de los escombros resultantes del desprendimiento ocurrido en Noviembre 2000. Foto tomada en Diciembre 2000.

point, there was a tendency for the development of vertical fractures that crossed, without significative variations, the different lithological units of the Gronho outcrops. The seismic events can also be related to the creation of these discontinuities, as suggested by the data from January 1997 and September 1999. The debris protected the base of the cliff for a very short period. With the destruction and the transportation of these sediments, this sector was once again exposed and vulnerable to wave attack.

The situations described correspond to phases of a repetitive cycle that, although with a different rhythm, can be adapted to the rocky coast south of Gronho that is also cut in outcrops of detrital rocks (Fig. 13).

Rainfall and drainage of rainwater as erosive agents are irrelevant in the cliff evolution. Yet, either by the weight of water over the unstable block, or by hydrostatic pres-

Fig. 11.- Evolution of the cliff and the dune in the fall and the beginning of winter 2000/2001. The arrows point to a common features in both pictures. Full line: cliff face after the November 2000 fall; dotted line - dune front before the erosive episodes of this period. Photos of 24 August 2000 and 17 January 2001.

Fig. 11.- Evolución del acantilado y de la duna del Gronho en el otoño y el invierno de 2000/2001. Las flechas indican marcas comunes en ambas fotos. Línea continua - frente del acantilado después del desprendimiento de Noviembre 2000; línea discontinúa - frente de la duna antes de los episodios erosivos de este periodo. Fotos de 24 de Agosto y de 17 de Enero 2001.

wave climate had been weak with significant waves of less than 3 m in height.

4. Discussion

The facts collected allows the identification of the main conditions and triggering factors of the processes that control the present-day evolution of the Gronho cliff. In all the described situations, wave action was fundamental in the destruction of the soft outcrops. This action was increased by the permanent presence of sand that allowed abrasion to be effective and such erosive processes at the base of the cliff can be very efficient, as demonstrated before.

The enlargement of the notches gradually destabilized the top of the cliff to a point where the shear strength of the rock mass became insufficient to sustain it. At that point, there was a tendency for the development of vertical fractures that crossed

sure along the vertical fractures, as Bromhead (1992) and Flageollet and Weber (1996) suggested, it can contribute to trigger the slope movements which are already in a very unstable situation.

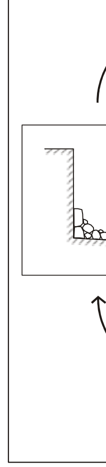
The influence of biological action in the present evolution of this rock coast is practically non-existent, since the colonization of the cliff by animals and plants is scarce. The absence of macro-species at the base of the cliff, if in a way, is a consequence of the continuous presence of sand, is also a clear indicator of the unstability of the outcrops.

After describing the present evolution of the Gronho cliff, the question arises: Why had the rate of retreat of the top of the cliff increased so dramatically after 1997? Can it be explained by natural causes?

It is possible to state that particularly in 1998 and 1999 there were a considerable number of storms conditions.

Fig. 12.- April, 1 2004 rockfall. **1**-cliff before the rockfall event; remark the well developed notches at the cliff base; **2**-cliff after the rockfall event (Photo **1**-August 2003; Photo **2** - April, 2004).

Fig. 12.- Desprendimiento de 1 de Abril de 2004; **1**-acantilado antes del desprendimiento; notar las muescas bien desarrolladas en la base del acantilado; **2**-acantilado después del episodio de desprendimiento de rocas (Foto **1**-Agosto 2003; Foto **2**-Abril, 2004).



However, the significant waves heights registered, according to Pires e Pessanha (1986), had a return period lower than 5 years, i.e. none of these events was a very strong storm situation and more important, periods like those are not rare on this coast. Yet, in the last 50 years, never were the consequences so remarkable. So, why were these storm situations more effective in causing a cliff retreat?

As Richards and Lorriman (1987) recognized, retreat of slopes, with the characteristics already described, depends upon the efficiency of the agents of erosion that act at the base of the cliff against the strength of the rocks at that level. But the efficiency of the erosive action of the waves does not depend exclusively on the wave energy or the presence of abrasive elements; it is also controlled by the water depth at the cliff base.

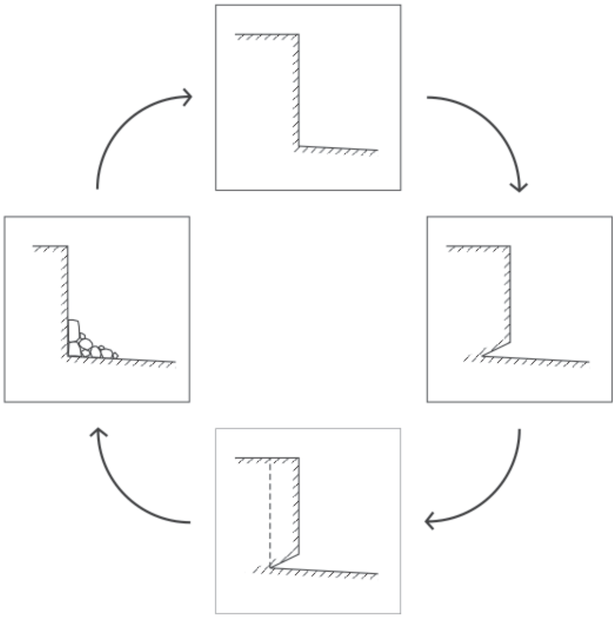


Fig. 13.- Evolution cycle of Gronho cliff.
Fig. 13.- Ciclo de evolución del acantilado del Gronho.

The base of the cliff at Gronho is covered by sand with a variable spatial and temporal thickness. This oscillation of the level of the beach sand is a normal characteristic that integrates the natural cycle of sediment exchanges between the beach and the nearshore zone which is controlled mainly by the wave climate and the nearshore currents. At Gronho, this oscillation is an essential factor that rules the dynamic of this rocky coast, because it influences the notch development. When the sand cover decreases, waves can reach the cliff base, particularly at high-tides, with higher energy causing greater erosion. On the other hand, when the sand cover near the base of the cliff rises not only do waves arrive at this level with less energy, but pre-existent notches are now filled with sand and, consequently, are protected from wave attack.

	RMi (ton m^{-2})		
	minimum	average	maximum
Clay	28.2	72.6	225.1
Fine kaoliniferous sandstone	32.5	163.2	466.9
Coarse ferruginous sandstone	70.8	202.4	605.3

Table 3.- *Rock Mass index* (*RMi*) values of the lithological unities at Gronho cliff.
Tabla 3.- Valores del *Índice de Masa Rocosa* (*RMi*) de las unidades litológicas del acantilado del Gronho.

In the particular case of Gronho, the sand cover at the base of the cliff is intimately dependent on the dynamic of the coastal system that integrates also Obidos lagoon. The estimation of the assailing force of the waves and the strength of the rocks that form the Gronho cliff was an essential step in the understanding of the events (Tables 3 and 4).

If the base of the cliff is only reached at high tides, only strong storm situations can cause erosion of the cliff. However, if we consider a 2.0 m water depth at high-tide, the model indicates that specially breaking waves are capable of destroying the more fragile parts of the clays, sandstone and some of the conglomerates. This was a frequent situation over these last few years. What could explain the sudden increase in the water depth at the cliff base?

Sea-level variation is normally a very important factor to be considered in coastal geomorphological research. For Cascais, on the western coast, Dias and Taborda (1992) calculated this to be 1.7±0.2 mm/year. It can be connected to a progressively increase in the rate of coastal retreat normally in very large temporal windows. However, in this case, a possible sea-level variation can be considered unimportant and irrelevant to the studied events, not only because the intensity and frequency of rockfalls/topple events which occurred at Gronho are not

Wave height (m)	Type of wave at the cliff base	Maximum pressure	
		Height above sea level (m)	Pressure (ton m^{-2})
2.3	breaking broken	1.6	81.35
3.1		from 0 to 2.4	14.75
3.7		from 0 to 2.9	19.53
4.3		from 0 to 3.3	24.50
4.9		from 0 to 3.8	29.67
5.5		from 0 to 4.3	35.00
6.1		from 0 to 4.8	40.50
6.7		from 0 to 5.2	46.13
7.3		from 0 to 5.7	51.91
7.9		from 0 to 6.2	57.81
8.5		from 0 to 6.7	63.83
9.2		from 0 to 7.1	69.96
9.8		from 0 to 7.6	76.20
10.4		from 0 to 8.1	82.54
11.0		from 0 to 8.6	88.98
11.6		from 0 to 9.0	95.51
12.2		from 0 to 9.5	102.14

Table 4.- Pressure applied on the cliff base by the incoming waves according to their height. It is considered a 2 meter water depth at the cliff base.
Tabla 4.- Presión aplicada contra la base del acantilado por las olas en función de su altura. Se considera una profundidad del agua del mar frente al acantilado de 2 m.

Fig. 14.- The groyne constructed in the Obidos lagoon near its northern margin. The arrow points to the location of the sand bags placed to reduce south dune erosion.

Fig. 14.- El dique construido en la laguna de Obidos próximo al margen norte. La flecha indica la posición de los sacos de arena colocados para reducir la erosión da la duna sur.

compatible with a slow variation of sea-level, but also because the rest of the 7.2 km stretch of coast with the same geomorphological characteristics did not show any change the last few years.

In 1998, an intervention took place in the interior of the Obidos lagoon. Along an East-West direction (i.e. in a transverse position as regards the general orientation of the lagoon) a 150 m groyne was built to prevent erosion on its northern margin (Fig. 14). This barrier completely changed the water circulation pattern in the outer part of the lagoon. The main consequence was the progressive deviation of the main channel to the south.

This change led to an increase in erosion of the dunes on the southern margin, partially occupied by a village, and which forced protective interventions in the following years. After the first emergency, installation of sand bags (each weighting a tonne) in 1998 was necessary, after 2000, to carry out an annual reinforcement (Fig. 14). The need for a periodic renovation of defences against erosion on the margin of the lagoon indicates that this measure was not sufficient and, therefore, the building of a groyne parallel to this margin is planned.

The connection between this lagoon and the sea is through a channel – called locally “Aberta” - which has a natural tendency to break through the centre of the sand barrier. However, in the last few years, due to the groyne, the “Aberta” has always been located in the southern sector (Fig. 15).

The modification of the flow of the main lagoonal waters to the south led to a reduction in the sand cover at the base of the Gronho cliff. The induced rise of the water depth near the cliff caused an increase of wave energy against the base of the cliff which overcame the strength of the rock mass and finally led to the marked retreat suffered by both the cliff and the dunes and explains why the retreat was more intense on the northern part of the cliff face (Fig. 4).

At the beginning of the XXI century, the need to prevent the gradual filling in of the lagoon by fluvial sediments led the National Coastal Authorities to dredge the main channel that connects the lagoon to the sea. This action was carried out in the spring of 2001, 2002 and 2003 and the sands removed (between 100 000m^3 and 150 000 m^3) were transferred to the beach in front of Gronho cliff.

As described earlier, after the 1999-2000 slope movements, the rate of retreat declined and there was only one event registered, in 2004, and what was noticeable was that the cliff sector affected in this event was exposed to the NW rather than the sector, where all the previous movements had taken place, which was clearly exposed to north.

It is still premature to conclude that the coastal system is attaining a new equilibrium or to state that the rate of cliff retreat has regained the previous level that existed before 1998 because: on the one hand, the sand nourishment of the beach close to the cliff helped to reduce the waves erosive capacity and, on the other, in the last few years, there were a ver small number of storm situations.

5. Conclusion

The dynamic of Gronho cliff in the last ten years has given significative clues to the processes and the main triggering factors involved in cliff erosion. The rhythm of events is connected with the efficiency of wave erosion at the base of the cliff, because it creates notches that destabilize the rest of the slope that eventually evolves by processes of fall or topple.

The efficiency of wave erosion is not simply controlled by the frequency and intensity of storms in high-tide periods but also by the water depth at the cliff base. The facts described prove that if the beach sand is removed by whatever process, the rate of erosion of the cliff is likely to increase.

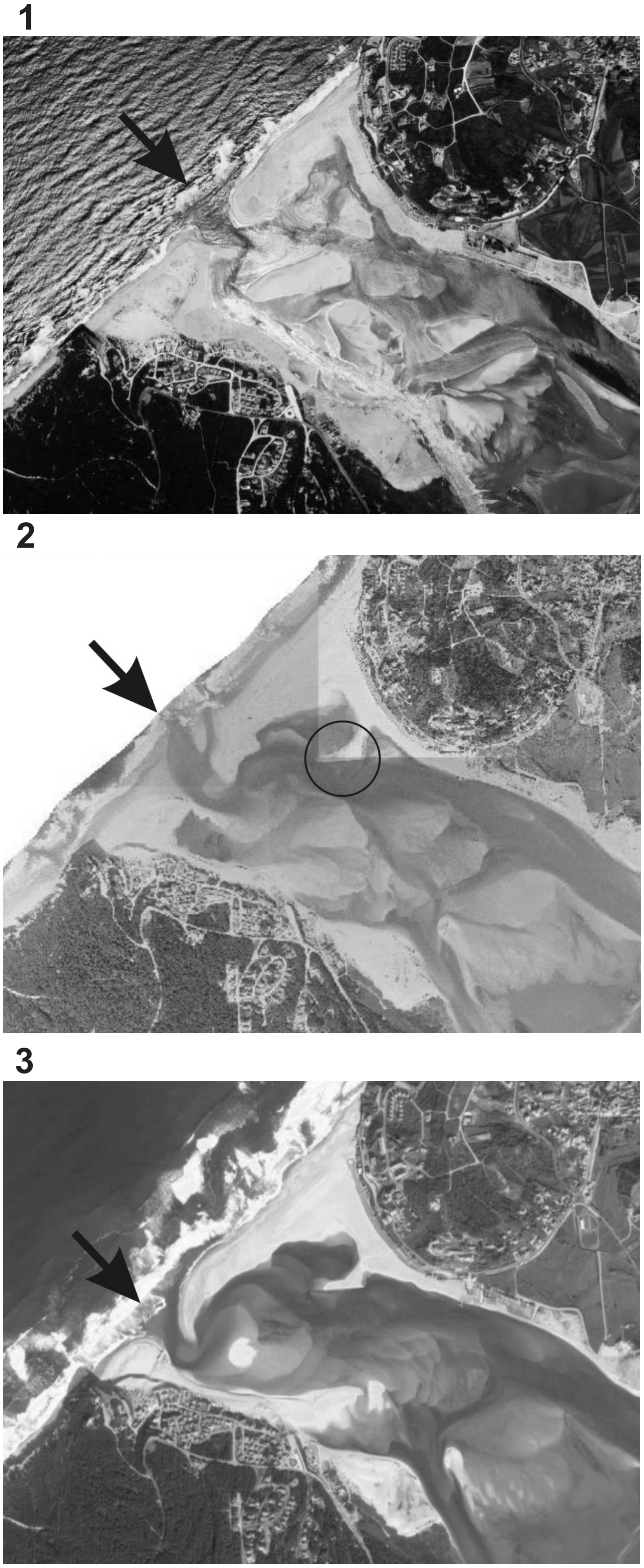


Fig. 15.- Obidos lagoon in: **1**-1995; **2**-2001; **3**-2004. The circle points out the position of the groyne. Note the change to SW in the position of the outlet to the sea.

Fig. 15.- La laguna de Obidos en: **1**-1995; **2**-2001; **3**-2004. El círculo indica la localización del dique. Nótese el desplazamiento hacia el SW del canal de salida de la laguna.

In the case of Gronho cliff, human intervention in an area close to a coastal lagoon, in 1998, led to a change in the drainage patterns that affected not only the dunes on the southern margin of the lagoon, but also to the distribution of sand at the base of the cliff. As a consequence, the rate of retreat of the cliff grew rapidly in the following two years. The nourishment of the beach in front of Gronho cliff in the subsequent years caused this to decelerate.

These conclusions can be applied, not only to the 7.2 km stretch of coast to which Gronho cliff belongs, but also to other locations on the Portuguese west coast with the same wave-climate and the same geomorphological characteristics, i.e. cliff-beach systems, where beaches are narrow, mostly intertidal beaches, and the cliffs cut into sandstones and conglomerates with a similar strength.

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