

MODELLING THE LONG TERM EVOLUTION OF ROCKY COASTS IN CENTRAL PORTUGAL

Modelización de la evolución a largo plazo de las costas rocosas en el litoral centro de Portugal

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Resumen: El estudio de la dinámica geomorfológica de una sección con 13 km de largo, situada en la costa oeste de Portugal, entre la Foz do Arelho y Praia da Gralha, permitió la identificación de 83 deslizamientos profundos que originaran retrocesos muy significativos de la parte superior de los acantilados. El conocimiento de las fechas de ocurrencia de uno de estos eventos llevó a la identificación del ritmo de los posibles factores desencadenantes. Aprovechando el hecho de que las secciones costeras con similares características geomorfológicas, como es el caso, pueden proporcionar información espacial esencial para identificar las diferentes fases del ciclo temporal de evolución, hemos utilizado los datos recogidos para elaborar un modelo que se ajuste a los procesos predominantes en esta franja costera. Dadas las características de los deslizamientos identificados, se alerta también para la ubicación inadecuada de infraestructuras humanas cerca de los acantilados.

Key words: rocky coasts, landslides, coastal evolution, Portuguese Estremadura

Palabras clave: costas rocosas, deslizamientos, evolución costera, Estremadura Portuguesa

1. INTRODUCTION

Rocky coasts have cycles of erosion in which dominant processes can change over long periods of time, effectively making significant modifications impossible to observe over the human lifespan. However, coastal stretches with similar geomorphological characteristics often make excellent surrogates for time, where the different stages of the evolution cycle can be easily observed at locations close by. The coastal stretch of *Foz do Arelho-Praia da Gralha*, 13 km long, located on the West coast of Portugal (Fig. 1), has such characteristics.

2. MATERIAL AND METHODS

A 2004 orthophoto map (0.5 m resolution), together with land and aerial photos of the studied area, was analysed in order to carry out a preliminary identification of the main processes of coastal evolution.

Afterwards, fieldwork allowed: (i) validation and classification of the slope movements identified by photo interpretation; (ii) improvement of the location limits of each movement; and, (iii)

identification of the geological characteristics of the outcrops and of the fault systems.

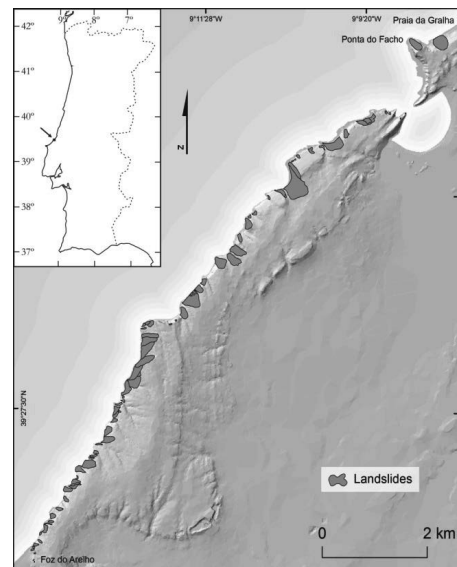


Fig. 1 – Location of landslides at Foz do Arelho-Praia da Gralha coastal stretch.

The relation between the compressive strength of the rocks at the base of the cliffs and the erosive force applied there by

the waves was calculated using methodology described in Neves *et al.* (2002).

Although restricted by the scarce existing data, the research on the possible preparatory and triggering factors (namely, wave climate, rainfall and seismic events) of the landslide events with a known exact time of occurrence was accomplished. Following methodology described in Zêzere *et al.* (2005), the daily and the cumulative absolute antecedent rainfall for 1, 5, 10, 15, 30, 45, 60, 75 and 90 consecutive days prior to the date of the landslide events were analysed.

3. LANDSLIDE ACTIVITY, CONDITIONING AND TRIGGERING FACTORS

In the coastal stretch of *Foz do Arelho-Praia da Gralha*, 83 large deep-seated translational landslides were identified through photo interpretation, and later validated in the field (Fig. 1). These landslides have an average dimension of *c.* 13,000 m² and affect a total area of over one million m².

The geological structure shows an alternation of layers of Upper Jurassic age, with different permeability and resistance, fine grain sandstones and marls, interleaved by limestone and clay layers. The outcrops dip 21-26° to N330-333°, therefore presenting a seaward-dipping attitude (Fig. 2).

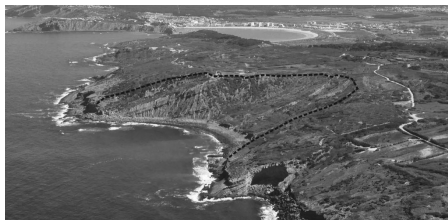


Fig. 2 – Large landslide in the coastal stretch Foz do Arelho-Praia da Gralha (dotted line). Note the seaward-dipping attitude of the geological structure.

On the west coast of Portugal, waves have a prevailing (about 80%) NW origin, with an average height of 2.5 m, frequently

exceeding 6.0 m in storm conditions (Pires, 1989).

The models, which evaluate the global strength of the cliff rocks against the erosive force of the waves, point to a higher susceptibility of the outcrops with lower results. Whilst marls can be affected by waves higher than 2 m, softer sandstones can only be destroyed by wave storms 7 m high (Tables I and II).

Table I – Rock Mass index (RMI) values of the lithological unities at Foz do Arelho-Praia da Gralha stretch.

	RMI (ton m ⁻²)		
	minimum	average	maximum
Sandstones	39.,7	502.8	1057.8
Marls	10.2	53.2	112.1

Table II – Pressure applied on the cliff base by the incoming waves according to their height. A 0.1 m water depth is considered at the cliff base.

Wave height (m)	Maximum pressure	
	Height above sea level (m)	Pressure (ton m ⁻²)
1.82	from 0 to 1.4	10.17
2.30	from 0 to 1.8	12.78
2.78	from 0 to 2.2	15.45
3.26	from 0 to 2.5	18.19
3.74	from 0 to 2.9	20.99
4.23	from 0 to 3.3	23.85
4.71	from 0 to 3.7	26.77
5.19	from 0 to 4.0	29.74
5.67	from 0 to 4.4	32.77
6.15	from 0 to 4.8	35.84
6.63	from 0 to 5.2	38.96
7.11	from 0 to 5.5	42.13
7.59	from 0 to 5.9	45.34
8.08	from 0 to 6.3	48.60
8.56	from 0 to 6.7	51.89
9.04	from 0 to 7.0	55.23

According to Neves (2004, 2006), from January to March 1954, at *Ponta do Facho*, a slope movement displaced an estimated 171,000 m³ volume of material and made the top of the cliff retreat between 120 and 200 metres (Fig. 3). The slip surface was located at a depth of 23 metres. The local morpho-structural characteristics and the geometry of the slope movement classify it as a deep-seated translational slide. The rate of deformation was moderate – according to the IUGSWGL (1995) classification – and the landslide activity extended for two months.

Records showed no seismic activity in the

starting day of the event or the previous days.

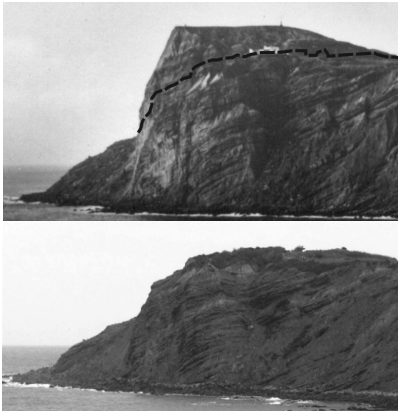


Fig. 3 – Ponta do Facho in: upper–1952/53 (©Foto Beleza); lower–September 2003 (©MNeves). At photo 1, the dashed line indicates the present topography

This landslide occurred in a period with low or null records of rainfall. The 40 days cumulative rainfall is the parameter that best adjusts to the beginning of the instability period at Ponta do Facho cliff (Fig. 4).

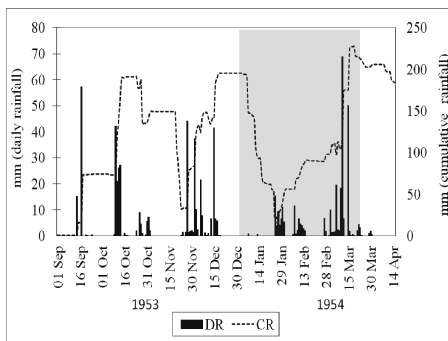


Fig. 4 – Daily rainfall (DR) and cumulative rainfall for forty days (CR) at Alfeizerão between September 1, 1953 and April 15, 1954. The shadow area indicates the activity period of the 1954 Ponta do Facho landslide

The evaluation of the wave influence on the triggering of the 1954 landslide event is very limited because, at that time, there were no wave buoys on the Portuguese coast. The only existing information is merely qualitative, obtained from newspapers, indicating that there were

several sea storms in December and in early January.

Landslide reactivations were identified subsequently at Ponta do Facho (Neves, 2004). An import event was recorded in February 1996, affecting the crown of the 1954 movement which suffered a retreat of 24 m in a retrogressive slump. Again, there was no intense rainfall in this period but the 40 and 60 days cumulative rainfall have return periods longer than 60 years.

4. LONG TERM COASTAL EVOLUTION

Given the relative homogeneous geological setting and the identical coastline orientation throughout the stretch of Foz do Arelho-Praia da Gralha, the comparison of different sectors offers a good insight of the evolution stages of the entire studied coastal zone and, therefore, allows us to develop a dynamic model that combines them all.

Thus, in a first stage, the cliff cut in a rocky substratum with resistant outcrops (sandstone or limestone), is subject to the excavating action of the waves on its base, leading to increasing slope instability. Lithology and geological structure clearly control the susceptibility to the occurrence of deep-seated translational slides. Due to the seaward-dipping attitude of the sedimentary layers, the persistence of wave erosion action widening and deepening the pre-existent discontinuities in the sandstone and limestone layers, and exploiting the fragility of the marl and clay layers underneath, contributes to a retreat of the cliff base. As a consequence, there is a gradual increase on the shear stress of the rest of the slope, which promotes the conditions required for the occurrence of translational landslides.

The gap between the rainfall events and the start of landslide movement, as the one which occurred at Ponta do Facho, is in accordance, amongst others, with the conclusions of Van Asch and Nieuwenhuis (1994) who state that, in deep landslides,

this gap may last weeks, being controlled mainly by the permeability of the superficial layers and the depth of the slip surface.

After a landslide event, the types of geomorphic processes tend to diversify: the landslide crown becomes susceptible to small retrogressive rotational slides; wave action is directed to the remobilization of the landslide deposit that covers the base of the cliff; and the landslides flanks, cut in the sandstone or limestone layers, tend to evolve mainly by rockfalls, whilst the original slip surface, carved in marls or clays, is progressively destroyed by rill erosion. In a subsequent phase, the erosion of marls and clays leads to the exposure of the underlying sandstone and limestone layers while the deposit, at the base of the cliff is completely redistributed by wave action. At this point, waves can reach again the rock substratum, preparing the conditions required for the occurrence of a new large landslide event, thus starting a new geomorphic cycle.

5. CONCLUSIONS

The geological framework at the coastal stretch *Foz do Arelho-Praia da Gralha*, presenting a seaward-dipping attitude of layers with different permeability and resistance, and with important clay or marls outcrops in the system, is an important predisposing factor to the occurrence of deep-seated translational slides. Wave action at the base of the cliff, exploiting the lower resistance of some outcrops, increases the shear stress on the upper part of the slope, operating as a landslide preparatory factor. Finally, accumulated rainfall for periods of several weeks, can act as a triggering factor. No evidence was found for landslides triggered by seismic activity.

The deep-seated translational landslides registered at the studied coastal stretch are responsible for large cliff retreats. Subsequently, different erosion processes

provide again the conditions necessary to the occurrence of a new landslide event.

The time of completion of each geomorphic cycle is generally long but remains unknown. Nevertheless, the susceptibility to deep-seated landslide events on this coast should be a major concern, since results suggest that the top of the cliff tends to retreat several tens of metres at each event. Therefore, expanding urban areas near the top of the cliffs, as found for instance at *Ponta do Facho*, are located in areas of increasing risk.

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