

Slope instability risk assessment along the Almada municipality coastline, Portugal

Évaluation des risques d'instabilité des pentes le long du littoral de la municipalité d'Almada, Portugal

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ABSTRACT: The Portuguese continental coastline extends for 987 km, centralizing around 75% of the national population in just 25% of the territory, generating 85% of the gross domestic product (GDP). Approximately 30% of the coastline is considered a protected area and included in the National Network of Protected Areas, with around 50% including areas belonging to the Rede Natura 2000. The exponential growth that has occurred in recent decades, resulting in increased demographic pressure on the coastal strip, has been promoting the occupation of dangerous zones subject to possible landslides. It is known that the adulteration of the physical landscape, in the name of development, has reached alarming proportions. The loss of territory and damage to coastal infrastructure are visible consequences of human intervention on the coast. As a result, it is crucial to investigate the mass movements of cliffs. This type of movement is difficult to predict due to its lack of warning signs and displacement speeds that occur in seconds. Once the movement begins, it is impossible to contain it, making it necessary to identify potential weaknesses in cliffs and minimize inherent risks by understanding rupture mechanisms. With this communication it is intended to present the geomechanical study of the stability of several cliffs of the municipality of Almada.

RÉSUMÉ: Le littoral portugais s'étend sur 987 km, centralisant environ 75% de la population nationale sur seulement 25% du territoire, générant 85% du produit intérieur brut (PIB). Environ 30% du littoral est considéré comme une zone protégée et inclus dans le réseau national des zones protégées, avec environ 50% comprenant des zones appartenant au Rede Natura 2000. La croissance exponentielle survenue au cours des dernières décennies, entraînant une pression démographique accrue sur la bande côtière, a favorisé l'occupation de zones dangereuses sujettes à d'éventuels glissements de terrain. On sait que la falsification du paysage physique, au nom du développement, a atteint des proportions alarmantes. Les conséquences de l'intervention humaine sur le littoral sont visibles, à savoir la perte de territoire et les dommages aux infrastructures de protection côtière. Cependant, les mouvements de masse sur les falaises doivent être considérés comme l'un des principaux axes d'étude en raison de leur irrégularité temporelle. Ce type de mouvement se caractérise par des vitesses de déplacement de l'ordre de la seconde, pas toujours précédées de signes avant-coureurs et, de ce fait, considérées comme difficiles à prévoir. Une fois de mouvement amorcé, il devient impossible de le contenir, ce qui nécessite de comprendre les mécanismes de rupture pour identifier les signes de faiblesse potentielle des falaises et minimiser le risque inhérent. Avec cette communication, il est prévu de présenter l'étude géomécanique de la stabilité des différentes falaises de la municipalité d'Almada.

Keywords: Risk assessment; rock cliffs; slope stability.

1 INTRODUCTION

The incorporation of stability studies of Portugal's coastline zones in land planning and urbanism policies is a recent development that started in the 90s. This change in mentality demonstrates an awareness of the potential risk to people and property caused by cliff movements. This is due to an increase of the Portuguese coast occupation rate.

Ten study locations were selected along the Almada municipality coastline for risk assessment, using information provided by the Almada municipality, namely:

- Olho-de-Boi (Poente)
- Banática
- Pica Galo
- Abas da Raposeira
- Foz do Rego

- Porto Brandão
- Arriba Fóssil da Costa de Caparica
- Arriba Fóssil do Bairro do Fóni
- Arriba Fóssil – Via Panorâmica Pablo Neruda
- Quinta da Arealva.

2 METHODOLOGY

Initially, the applied methodology consisted of a semi-quantitative risk assessment to promote a simple and quick prioritization of risks identified. This was achieved by determining the Risk Index (RI), using the following equation:

$$\text{Risk Index (RI)} = \text{Probability of Occurrence (PO)} \times \text{Magnitude (M)} \times \text{Potential Damage (PD)} / \text{Response Capacity (RC)} \quad (1)$$

where (PO x M) defines the dangerousness (D) and (PD/RC) represents the vulnerability (V).

This methodology is adapted from Costa et al. (2009). Each term in the equation was categorized on a scale of 1 to 5 (respectively: not significant, reduced, average, high and very high). Equation (1) calculates the risk values associated with the hazard in question. The matrix used to calculate RI values for all possible scenarios was recalculated for the interval [0;1], instead of [0.2;1], for better perception of the obtained values. The calculated values were divided into 5 classes of equal amplitude.

The danger calculated by this methodology must be understood as an apparent danger, differing from the concept proposed by Varnes (1984). This is because it is not based on the probability of an occurrence, but rather on a weighted calculation that relies on available information and on the expert assessment of geological-geotechnical factors that affect cliff stability (refer to Figure 1). Even though this assessment has some degree of subjectivity, when well-founded, it is generally more valuable than mere numerical calculations, namely in Geotechnics (Schubert, 2004). Furthermore, an expedited initial assessment allows the concentration of more detailed studies in places that require priority intervention.

In the second phase, the behaviour was measured through geomechanical analysis of the cliffs wherever $RI \geq 0.80$ was obtained, based on the geotechnical characterization of the rock mass and on identifying rupture mechanisms (Brissos, 2013; Brissos et al., 2014).

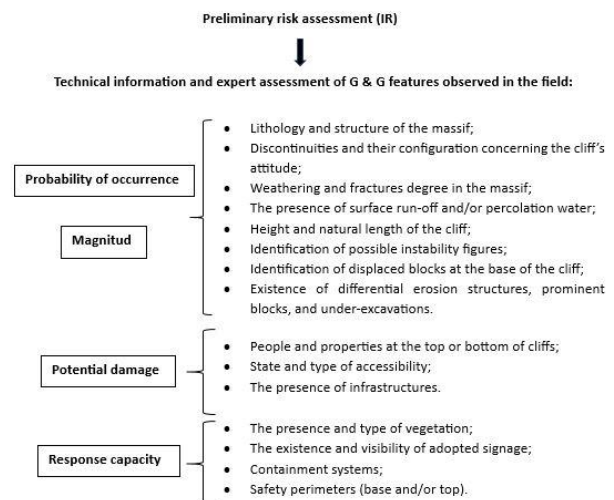


Figure 1. Schematization of the preliminary risk assessment methodology.

3 RESULTS

3.1 Preliminary risk assessment (1st phase)

Table 1 presents the values attributed to the different variables of equation (1), as well as the calculation of the Risk Index (RI) associated with the problem under analysis.

The cliffs in the Almada municipality represent a risk due to the lithological and weathering characteristics of the rock mass. These conditions can lead to frequent instabilities caused by differential erosion of the existing rock masses. Figure 2 shows the panoramic view of the fossil cliff in Bairro do Fóni, with houses adjacent to the cliff's crest, figure 3 shows a fallen limestone block from Banática cliff near two parked cars, figure 4 represents a panoramic view of the fossil cliff in Olho de Boi, with Almada Cemetery behind, and figure 5 shows the panoramic view of the cliff in Porto Brandão, with houses adjacent to the base of the cliff.

Table 1. Calculation of hazard, vulnerability and risk values for the identified locations.

Locals	Stations	Dangerousness			Vulnerability			Risk Index	
		PO	M	Final Value	PD	RC	Final Value	Preliminar RI	Classification
Olho de Boi	1	5	5	25	5	1	5	1,00	Very high
	2	5	4	20	3	3	9	0,16	Insignificant
	3	5	4	20	4	2	8	0,32	Reduced
	4	5	5	25	5	1	5	1,00	Very high
Quinta da Arealva	5	5	5	25	4	2	8	0,24	Reduced
	6	5	4	20	4	1	4	0,48	Moderate
Banática	7	5	4	20	5	1	5	0,80	Very high
	8	5	5	25	5	1	5	1,00	Very high
Porto Brandão	9	4	2	8	3	1	3	0,19	Insignificant
	10	4	4	16	1	2	2	0,06	Insignificant
	11	5	5	25	5	1	5	1,00	Very high
	12	3	2	6	5	2	10	0,12	Insignificant
	13	4	4	16	5	4	20	0,16	Insignificant
Abas da Raposeira	14	5	3	15	5	2	10	0,30	Reduced
	15	5	3	15	4	1	4	0,48	Moderate
	16	5	3	15	3	3	9	0,12	Insignificant
Pica Galo	17	5	4	20	5	1	5	0,60	High
	18	5	4	20	5	1	5	0,60	High
	19	1	1	1	5	5	25	0,01	Insignificant
	20	5	4	20	5	3	15	0,27	Reduced
	21	5	5	25	5	1	5	0,64	High
Arriba Fóssil Costa Caparica	22	5	5	25	2	2	4	0,20	Reduced
	23	5	5	25	4	2	8	0,40	Moderate
	24	5	5	25	2	2	4	0,20	Reduced
Via Panorâmica Pablo Neruda	25	5	5	25	3	1	3	0,20	High
	26	5	4	25	5	3	15	0,42	Moderate
	27	5	4	20	2	1	2	0,32	Reduced
	28	4	4	16	2	1	2	0,26	Reduced
	29	5	4	20	2	1	2	0,32	Reduced
	30	4	4	16	2	1	2	0,26	Reduced
	31	2	3	6	5	1	5	0,24	Reduced
Estrada da Foz do Rego	32	3	3	9	3	1	3	0,36	Reduced
	33	4	4	16	4	1	4	0,51	Moderate
	34	5	4	20	4	1	4	0,64	High
	35	4	3	12	5	1	5	0,48	Moderate
	36	4	3	12	5	1	5	0,48	Moderate
	37	4	3	12	5	1	5	0,48	Moderate
Arriba Bairro do Fóni	38	5	4	20	4	1	4	0,80	Very high
	39	5	4	20	5	1	5	0,80	Very high
	40	3	3	9	3	1	3	0,22	Reduced
	41	5	5	25	4	1	4	0,80	Very high
	42	2	2	4	2	1	2	0,06	Insignificant
	43	4	4	16	2	1	2	0,26	Reduced
	44	5	4	20	5	1	5	0,80	Very high

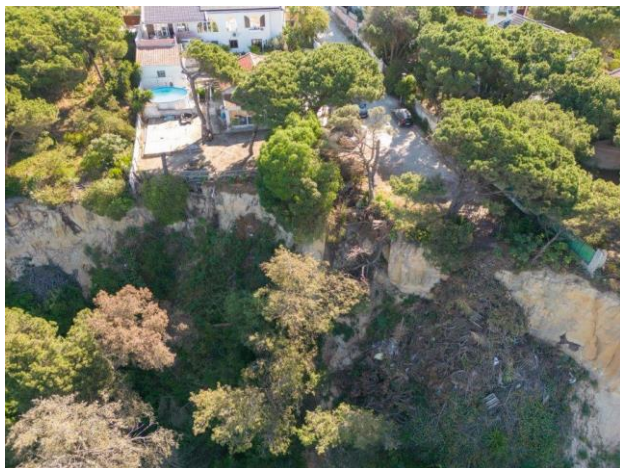


Figure 2. Panoramic view of the fossil cliff in Bairro do Fóni with houses adjacent to the cliff's crest (June, 2023).

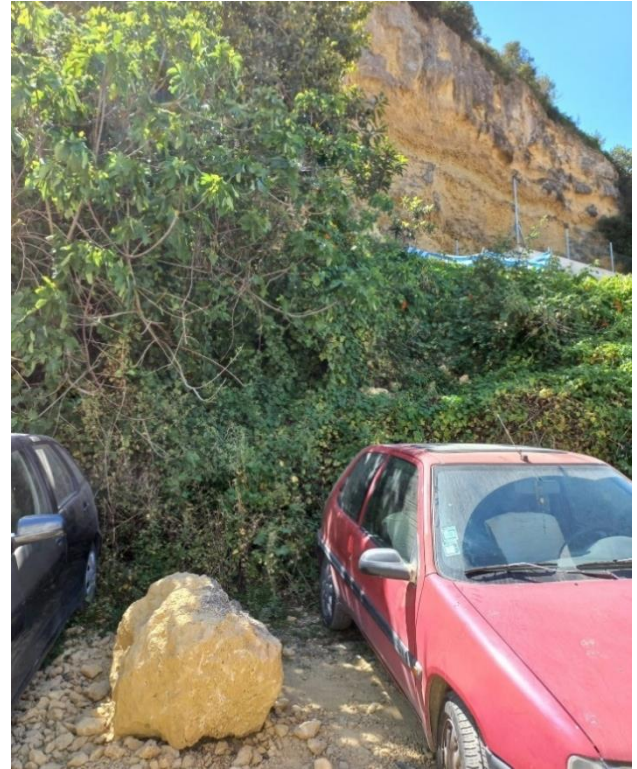


Figure 3. Limestone block from Banática Cliff near parked cars (June, 2023).



Figure 4. Panoramic view of the fossil cliff in Olho de Boi with Almada Cemetery behind (June, 2023).

Table 1 shows that certain locations have a higher risk index due to the greater height of the cliffs, the history of incidents and the possibility of large blocks being mobilised from these locations (as shown in Figure 3).

This higher risk index, in specific cases like Olho-de-Boi, Banática, Porto Brandão and Bairro do Fóni, is associated with poor conditions caused by their close proximity to urban areas with constructed infrastructure both at the top and at the base of the cliffs.



Figure 5. Panoramic view of the cliff in Porto Brandão with houses adjacent to its base (June, 2023).

For example, the landslides and rock fall events observed at the Olho-de-Boi cliff occurred at the base of the slope, leading to an overhang at the top. This indicates that the layers with the least resistance are located at the bottom of the cliff, while the ones with the most resistance are at the top. It is observed that the most weathered and the less weathered layers are divided by tension cracks parallel to the cliff and subvertical fractures visible at the top of the cliff.

In Banática, the houses are located near the slope (between 2.0m and 10.0m) and there is no protection against slope movements. This is a scenario of maximum damage potential and no response capacity.

In Porto Brandão, there are several residential and commercial buildings occupying the foot of the cliff with no safety distance. This represents a very high vulnerability, as there is minimum response capacity and maximum potential damage.

In Bairro do Fóni, there is a very sharp cliff retreat with evidence of significant ravines. There are buildings located on the top of the cliff, with emphasis to an overhanging reinforced concrete structure at risk of structural failure.

Considering the above, it became evident that stability studies must be conducted in these areas. This is necessary not only because of the geomechanical conditions that favour instability phenomena, but also due to the high vulnerability associated with human occupation at both the base and the top of these cliffs.

3.2 Reassessment of risk and proposal mitigation measures mitigation (2nd phase)

The preliminary risk evaluation in this study was reassessed based on the geological-geotechnical

characterization of each cliff and the geotechnical zoning. The estimated retreat rates and the simulation of the trajectories of falling blocks from the studied cliffs also contributed to the reassessment of the preliminary risk.

The risk reassessment also considered the current and future of the areas of influence (crest and base), with the results presented in Table 2.

It appears that in general the values remained the same in practically all locations. The exception occurred at a station 38 on fossil cliff in Bairro do Fóni.

After the risk reassessment, the Risk Index (RI) is maintained based on the occurrence of falling blocks in the past, the number of people using the access paths to the top or base of the cliffs, and the annual retreat rate of the cliffs.

Table 2. Risk reassessment and comparison with the preliminary risk evaluation.

Locals	Stations	Dangerous ness			Vulnerability			Risk Index		
		PO	M	Final Value	PD	RC	Final Value	Final RI	Preliminar RI	Classification
Olho de Boi	1	5	5	25	5	1	5	1,00	1,00	Very high
	4	5	5	25	5	1	5	1,00	1,00	Very high
Banática	7	5	4	20	5	1	5	0,80	0,80	Very high
	8	5	5	25	5	1	5	1,00	1,00	Very high
Porto Brandão	11	5	5	25	5	1	5	1,00	1,00	Very high
	38	5	4	20	4	1	4	0,64	0,80	High
Arriba Bairro do Fóni	39	5	4	20	5	1	5	0,80	0,80	Very high
	41	5	5	25	4	1	4	0,80	0,80	Very high
	44	5	4	20	5	1	5	0,80	0,80	Very high

Based on this reassessment, a proposal for a short-term risk mitigation plan was presented (Table 3). The adopted approach focuses on reducing long-term vulnerability by reinforcing appropriate signage and placing physical fences to prevent access to the top of the cliff.

The dismantling of some larger, potentially unstable blocks, must be considered using appropriate dismantling methodologies, as well as, the fixing of metal nets to control blocks that may detach from the cliff face.

Subsequently, nailing should be carried out, possibly associated with cables and steel mesh, pulled and anchored to the massif, to fix the larger volume consoles. The use of shotcrete, always accompanied by the execution of drainage holes, could be an alternative. The installation of ridge ditches allows the collection of runoff water, making infiltration and washing of fractures more difficult. The effective implementation of a monitoring plan is still considered necessary for long-term prevention perspective.

Table 3. Risk mitigation plan proposed for the case study.

Risk Mitigation				
Structural		Protection measures	Drainage	Non-structural
Stabilization measures				
Correction	Reinforcement			
Dismantling of rock blocks; Cliff re-profiling	Nails; Metal mesh associated with steel cables / shotcrete	Nailed/anchored metal mesh	Cliff crest ditch	Implementation of appropriate danger signs in clearly visible locations (foothills and crests); Restriction and prohibition lanes with respective signs and fences, at the base and on the crest and foothills; New Jersey-type barriers in areas that require protection against blocks that could roll from the top of the cliff to homes

4 CONCLUSIONS

The methodology used for instability risk assessment of the studied cliffs relies heavily on subjective methods, rather than quantitative analysis. However, this methodology demonstrates higher reliability in establishing a preliminary risk zoning. This allows to hierarchise the most critical cliffs, which are in need of detailed stability studies, implementation of risk stabilization and mitigation measures, and their respective monitoring.

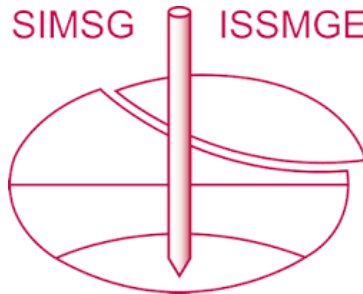
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