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Analysis of Coastal Retreat and Slope Movements on Rocky Coastal Cliffs: A Distributed Natural Hazard in the Safi Region, Morocco

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Abstract: The coastal area of Safi between Cap Beddouza and Jorf Lihoudi is dominated by different forms of marine cliffs forming the coastline, with rock formations ranging from Jurassic to Quaternary. The main coastal geological risk is the instabilities of these cliffs due to falls and collapses of blocks as well as landslides. The aim of this paper is to give detailed information on the rate of cliff summit recession for the last 66 years, obtained by applying the DSAS model, in parallel with the identification of unstable elements, including their different parameters such as size, abundance, activity in time and their effect on the recession of the cliff top, which are fundamental information for the evolution models of sea cliffs. These phenomena constitute a significant economical, social, and environmental risk.

Keywords: coastal cliffs; recession; instability analysis; DSAS; Morocco

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1. Introduction

Coastal cliffs are geological-geomorphological features that form great landscapes, and also, have scientific, cultural, and social value all, around the world [1–3]. Unfortunately, this geomorphological heritage is subject to continuous degradation induced by instabilities that are considered to be the main and most damaging coastal geological hazards [4,5]. These instabilities pose risks to people and their property at the base and top of cliffs, which account for 80% of the world's ocean shoreline [6]. More than 1.2 billion people in the world live within 100 km of the coastline, and less than 100 m above mean sea level [7].

Landslides are the most predominant risk on rocky coast. It provide, in some cases, protective deposits accumulated in the base of the cliff and thus slow down mechanical waves erosion [8]

Mass movements on steep cliffs are instantaneous phenomena that provide virtually no warning, they are triggered and amplified by a variety of marine and subaerial processes [9], including waves [10], groundwater flow [11], mechanical and chemical weathering [12], and precipitations [13]; while cliff lithology [14], coastal geometry [15] and structural features [16] are acting as conditioning factors. Over the past decade, we have witnessed several accidents caused by cliff collapses and landslides, which have killed or injured people and destroyed several buildings.

A series of modern techniques exist for monitoring coastal cliff evolution [17], such as terrestrial laser scanning [18], digital photogrammetry, video monitoring technique

[19] and LiDAR [20,21], which provide very detailed data on cliff evolution. However, these monitoring techniques are fairly new and can only provide monitoring results for limited periods of time, at most on the order of a decade, which is a considerable limitation for monitoring a discontinuous and event-driven process with low temporal frequency [22]. Aerial photographs were, until recently, a major source of cliff movement data, and although they are capable of providing much less precise and accurate data than newer techniques, they have the advantage of allowing follow-up long periods of more than half a century, which can provide a more meaningful sampling of larger but less frequent cliff movements [23].

At this stage, it is an increasingly necessary to improve our knowledge of these areas in order to better manage them, taking into account human safety, but also the preservation of these geological heritages. The rate and modalities of cliff recession are interesting informations to understand how this specific form of ablation works. Thus, to determine the appropriate protection method, it is essential to master the scientific object before any management action. In this study, our interest is focused on the determination of recession rate of coastal cliffs in the region of Safi in relation to masse movements type, their distribution, size and frequency which depend, in large part, on the type of rocks composing the cliff.

1.1. Topographical and Geological Context

The coastline of the region of SAFI, is part of coastal meseta of Morocco. This coastline has an unique character dominated by a cliff morphology. They, are real cliffs which owe their existence to the marine action [24]. The study area approximately whose length is about 48 km long, extends from Cape beddouza (32° 40'00''; 09°20'00'') in the north to Jorf lihoudi (32° 00' 00'' ; 08°40'00'') in the south. The height of the cliffs can reach more than 150m in Borj Nador and be reduced to 15 m near the cliff of jorf n''am Figure 1.

The geological formations of the study area range from the Jurassic to the Quaternary [25,26]: Plio Quaternary sandstone, clay and sandstone (Hauterivian), Limestone of Dridrat (Upper Hauterivian), Clays of Safi (Lower Hauterivian), Lower limestone (Valanginian) and limestone with clay and gypsum (Upper Jurassic).

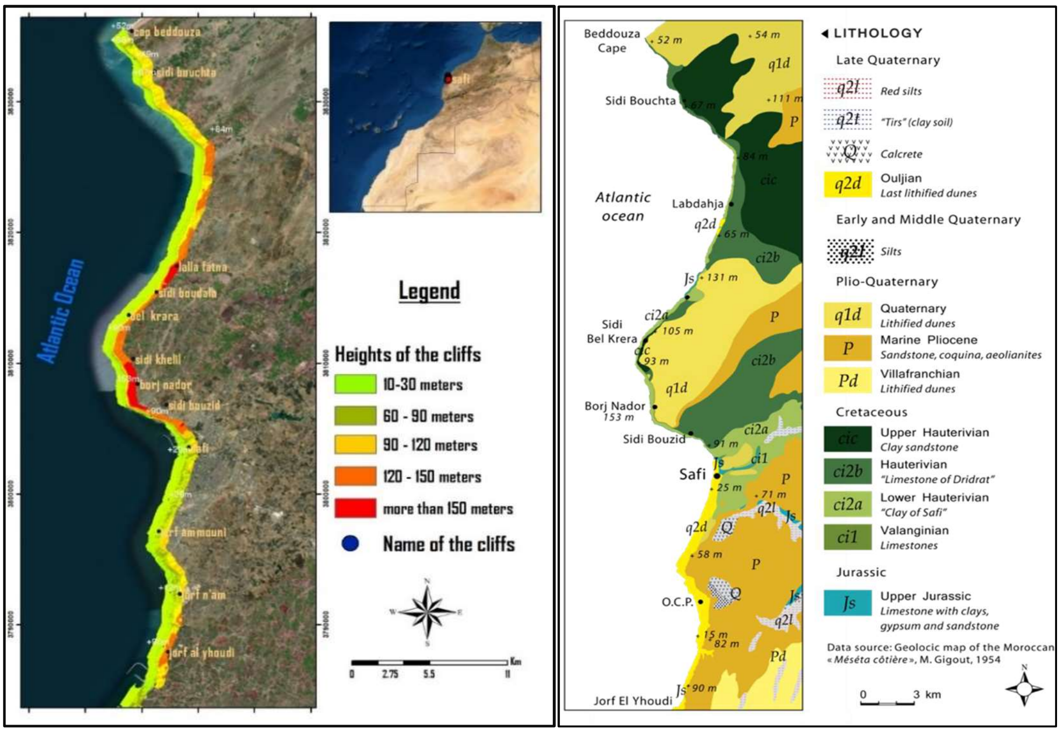

Figure 1. Location and geological map of the study area [8].

2. Materials and Methods

Two methods of analysis were used to carry out this work:

First, a quantitative diachronic approach whose objective is to study the evolution of the tops of coastal cliffs from several reference dates in order to define the rate of recession of these cliffs. The diachronic approach should be based on documents that give the widest possible observation period of in order to seek temporal relevance to the phenomenon studied. In the present work this condition is available based on aerial photographs for the determination of the recession rate of coastal cliffs in the Safi region. The quantitative approach is a classic protocol including (i) the collection of photographic documents, (ii) the georeferencing and digitization (under GIS software) and (iii) the calculation of evolutions by the DSAS model - Digital Shoreline Analysis System.

Before any diachronic study of a coastline, the question of the choice of the reference line arises, according to the authors [27]. There are more than a dozen reference lines materializing the position of the coastline [28]. It must be legible on all documents used. For cliff coasts, the morphological reference indicator is the foot or the top of the cliff, depending on the authors [21]. The cliff top is frequently chosen because it is more easily observed in vertical shots. Our interest is focused on determining the recession rate of the top of the coastal cliffs. This choice is dictated by the fact that only the decline of the summit part is important insofar as this decline affects the developments (buildings, roads, power lines, agriculture, ...). The cliff slopes in the northern part, because the southern part is a rocky cliff, are also undergoing a great deal of change, but these areas are generally not the subject of any development.

The coastline of each series, represented by the top of the cliff, was manually digitized at the selected dates (1954, 1983 and 2020) with a standardized scale to ensure greater homogeneity. The approach to quantifying the recession of cliff shores is to compare the position of the top of the cliff, according to a previously established reference line, between two given dates and to conclude recession values according to a spatial and temporal relevance. The method known as the Digital Shoreline Analysis System (DSAS)[29], which simplifies quantification and change trends by several analytical techniques, the most important of which is the End Point Rate (EPR) which estimates the rate of erosion or accumulation by dividing the distance of shoreline movement by the number of years between the two positions (Equation (1)).

$$\mathrm{EPR} = \frac{L_1 - L_2}{t_1 - t_2} \quad (1)$$

Secondly, the geomorphological approach consists of analysising unstable elements based on the diachronic analysis of mass movements affecting the cliff (modalities of cliff recession), observable geomorphological markers, previously georeferenced aerial photographs and field investigations. This approach collected data on the different types of land movements and mapped their frequency, intensity and spatial distribution.

3. Results

In this analysis the term "shoreline" will represent the digitised position of the cliff top (edge of the cliff) and the term will be used a synonym for the DSAS tool. The cliff top was extracted from aerial photographs from 1954, 1983 and 2020 covering a period of 66 years. The rate of shoreline change was calculated using the DSAS model and two different statistical analysis: End Point Rate (EPR) and Net Shoreline Movement (NSM). Baselines were built offshore and parallel to the general shoreline trend with a 5-meter-wide transects.

Rocky cliff shorelines are unique in that they constantly erode and change slowly with time and space. Moreover, the rate of change often varies from zero for stability, to less than zero in case of recession. One of the critical issues for the study area, is the retreat rate and the mass movement type of the cliffs, especially for the area between Cap Beddouza in the north and Jorf lihoudi in the south (about 48 km long). To define the recession severity, a qualitative analysis is performed, using the NSM model along the northern and southern sectors, Figure 2.

The delineation of recession severity and stable transects indicates that the northern and southern area of Safi experienced a recession for the period 1954–2020 with a visible difference between the North and South. In addition, cliff recession rates are quantified spatially and temporally for each sector using the statistical model of the EPR (Figure 3). The results of this study are compiled in Table 1, and present the local average recession rates of the top of the cliffs and the percentage of transects eroded for the two sectors. Nearly 4561 transects out of 5492 in the northern sector and 1608 out of 3078 in the southern sector show erosive characteristics, with an average recession rate of −0.08 m/year for the northern shoreline and −0.04 m/year in the southern one, Figure 3, Table 1.

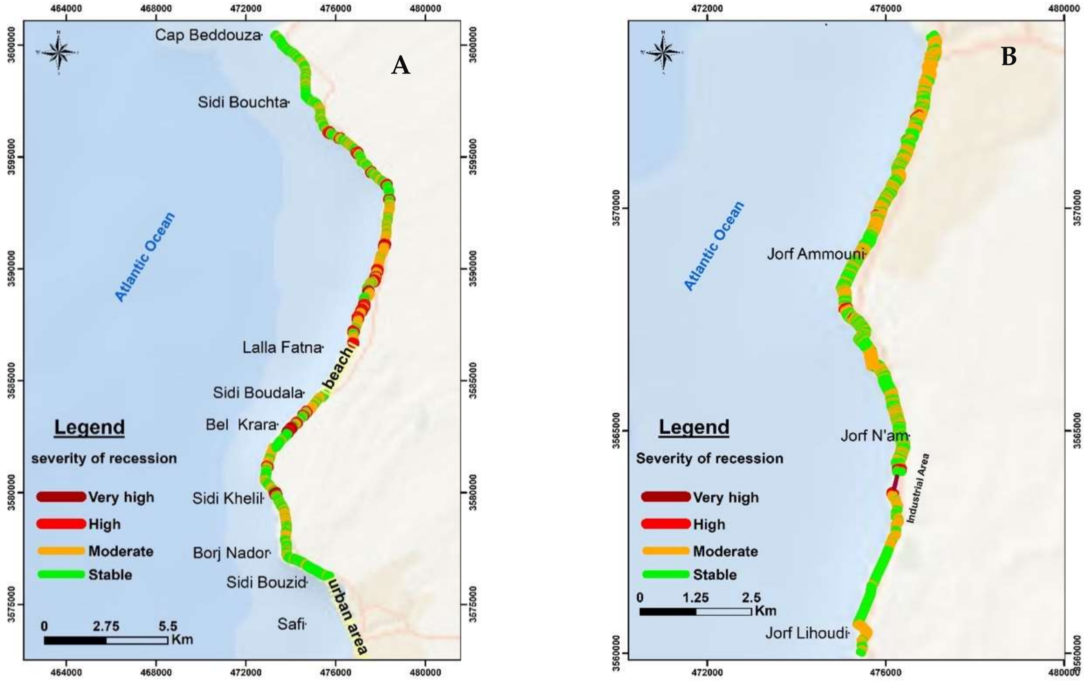

Figure 2. Spatialization of recession severity in the high cliffs for the northern (**A**) and southern (**B**) sectors.

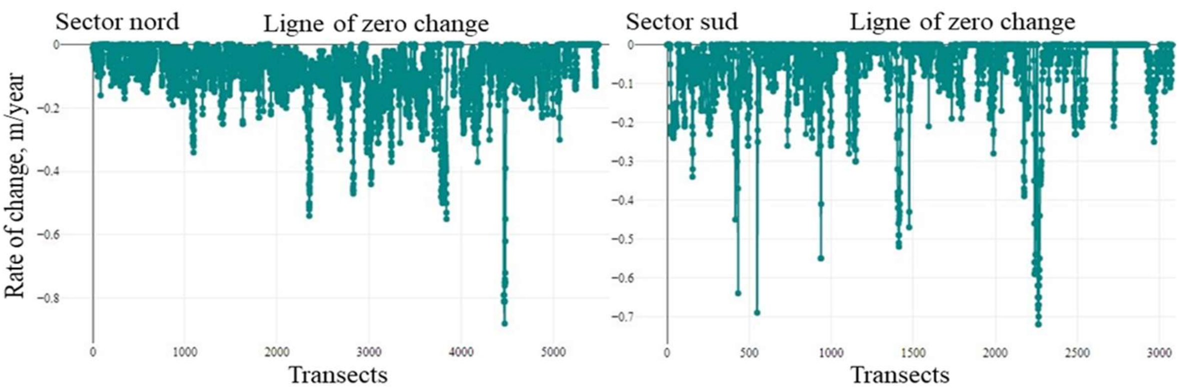

Figure 3. Evolution of the position of the high cliff line between 1954 and 2020 (erosion/stable), EPR Statistical analysis.

Table 1. Global statistical synthesis of the northern and southern zone during (1954 -2020).

	Northern Sector	Southern Sector
Total transect number	5492	3078
Total transects that record erosion	4561	1608

Total transects that record stability	931	1470
percent of transects with erosion data	83%	52%
percent of transects with stable data	17%	48%
Shoreline length (km)	27 km	17 km
Mean regressive shoreline change rate (m/year)	−0.08 (m/year)	0.04 (m/year)

Beyond the recession rates, it is also fundamental to understand the spatial distribution and the type of the mass movements activity. To do this, the mass movements visible on the ground have been counted and annalyzed.

This inventory has the advantage To provide information on the Type, Size, Abundance, Activity and recession rate. A continuous erosion with an abrupt localized recession characterizes the evolution of Safi coastal cliffs.

The recession occurs over a long period of time, followed one day by a sudden major event. A total of 280 mass movements whose traces are still visible have been identified in field between Cap Beddouza and Jorf Lihoudi.

These recorded events are spatially unevenly distributed from north to south. In this area, the study has allowed us to distinguish roughly four types of dominant mechanisms. The instabilities are related to the dynamics of rocks from either sliding, toppling or falling.

The inventory of these movements allows us to study their spatial distribution. A predominance of rockfall phenomena along the entire coast (north and south sectors) can be distinguished to from other fossil processes, discontinuous and limited. However, the size of landslides by rotation is very high. On the contrary, overturning and translational landslides extend at most over a few tens to a few hundreds of meters. These mass movements can also be classified in term of their activity-type according to the typology of Varnes in [30], and are from the largest to the smallest:

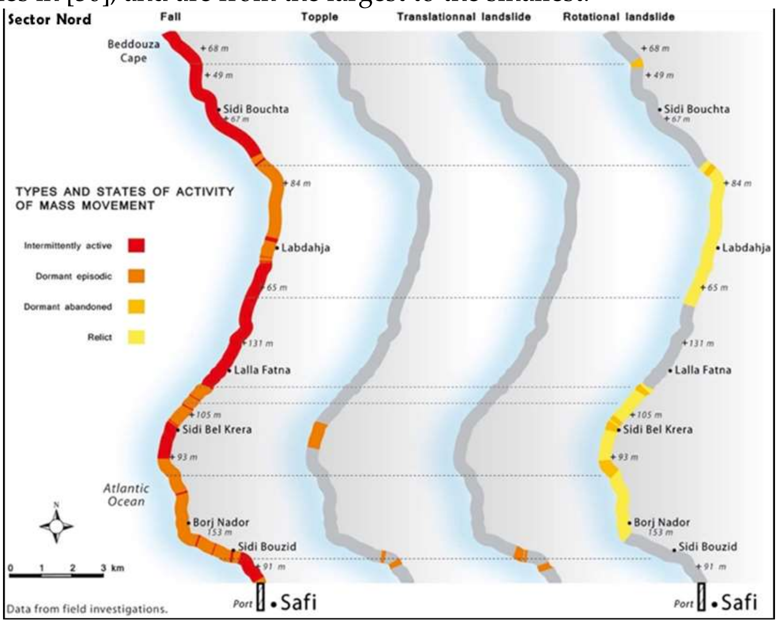

Figure 4. Spatialization of mass movement types and activity states in the northern sectors.

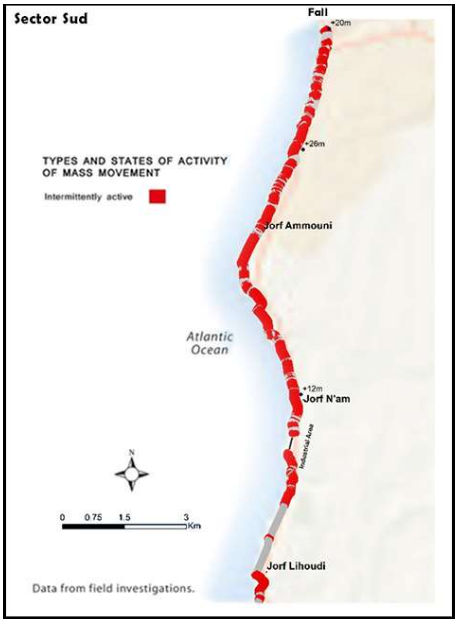

Figure 5. Spatialization of mass movement types and activity states in the southern sector

The abandoned dormant type defined as inactive but is no longer affected by the initial activating causes by they have reached a certain stability. The forms are fossile and vegetation is beginning to cover the movement. Rotational landslides are punctually attributed to this state, including the Sidi Khelil landslide (north of Borj Nador) whose length is 480 meters with a volume of 1.2 million m^3 Figure 4.

Dormant episodic movements are related to other types of movements whose triggering conditions can recur and be easily reactivated such as translational and collapse slides. They are not considered active as no significant movement appears to have occurred in the last ten years. Note that some areas listed as episodically dormant have been subject to rockfall, but in minor proportions that indicate very little instability activity Figure 4.

Finally, intermittently active movements, with sporadic events over the last 10 years, which correspond to block falls. In contrast to dormant movements, active movements are exerted under the simple effect of gravity Figure 5.

The different types of mass movements are characterized by different criteria, namely size, abundance, activity over time, and their effect on shoreline recession. It can be seen that block falls and collapses are active especially on the cliff crest and have a net effect on a top- cliff line recession, while large-scale slides affecting cliff slopes are fossilized and cause top-cliff line recession. They also provide accumulated protective deposits at the base of the cliff and thus slows down mechanical erosion when waves cannot remove all deposits. Table 2

Table 2. analysis of different types and parameters of movements and their effect on shoreline recession.

Type	Size	Abundance	Activity-type
Fall			Active
Topple			Active intermittent
Translational landslides			Intermittent to fossil
Rotational landslides			Fossil

4. Discussion

In response to natural processes and anthropogenic actions, rocky cliff shorelines change and evolve over time and space [31–34]. Changes in shoreline position by recession and mass movement can be drastic and expensive, as they apparently affect marine human activities [31]. The results of this study on recession rates and analysis of associated recession patterns show a significant difference from north to south. The northern part is an area marked by large translational and rotational landslides, with an average recession rate of −0.07 m/year greater than that of the southern sector, The reconciliation between the recession rate and the associated mode shows that areas with a low recession rate are characterized only by rockfall instability, while very high and high recession rates are associated with lands of very large mass movements such as rotational and translational slides. Of all the observations, the reason for the difference between the dynamics of the northern and southern sectors can be explained by sector-specific criteria that can be summarized in the characteristics of rock lithology and morphological factors, often mentioned in the literature as likely to influence the regressive dynamics of the cliffs. The northern part between Cap Beddouza and the port of Safi, where the cliffs are of complex morphology consisting of cornice, slope and cliff foot, has clay formations on a large part of their profiles. On the other hand, it is the highest part of the coastline (Figure 1), and according to field observations it presents a complex and diverse dynamics in terms of cliff movements. The southern part from the town of Safi to Jorf-Lihoudi has rocky-cliffs of medium height with quaternary formations composed entirely of limestone rocks and a total absence of clay. These differences are therefore sufficient for the behavior of these coastal cliffs to be different from north to south. Thus, from all the above observations and descriptions and as a conclusion to this discussion, we can confirm that cliff lithology plays an important role not only on the recession rate but also on the recession mode. Thus, the clay formations with little resistance are conducive to large-scale gravitational movements such as rotational landslides, and this is particularly visible in the northern part which has led to a significant regression of the top-cliff line, while the southern part characterized by an outcrop of plio-quaternary types, with a total absence of clay and entirely composed of limestone rocks, gives movements of collapses and rockfall type.

5. Conclusion

The cliff coasts are everywhere characterized by erosion phenomena. The management of cliff-coasts along the world's coasts, which combine high landscape and cultural value with increasing visitor appeal, requires the development of specific characterization strategies to assess their vulnerability to instability and to implement management strategies that ensure safety. Over the last decade, and within the study area we have witnessed several cliff collapses and slides. At this point, it is increasingly necessary to manage these spaces taking into account the safety of visitors, but also the preservation of these geological heritages. The rate of recession of the high cliffs and the analysis of the modalities of their recession are interesting information, for the understanding of the functioning of this specific form of ablation. Thus, to determine the appropriate protection method, it is essential to master the scientific object before any management action. In this context, this article focuses on the problem associated with the evolution of the position of the cliff top along the coast of Safi from Cap Beddouza in the north to Jorf Lihoudi in the south during the period from 1954 to 2020 and the analysis of mass movements type associated with this retreat that affects this area of natural and socio-economical importance. During 66 years, the position of the top of the cliffs has changed significantly, with a clear landward migration from north to south with different mass movements recorded in these sea cliffs whose lithological and morphological characteristics play a major role in the spatialization of the types of these movements.

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