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Sea cliff instability susceptibility at regional scale: a statistically based assessment in southern Algarve, Portugal

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Abstract

Mass movements of different types and sizes are the main processes of sea cliff evolution and also a considerable source of natural hazard, making its assessment a relevant issue in terms of human losses prevention and land use regulations.

To address the assessment of the spatial component of sea cliff hazard, i.e. the susceptibility, a statistically based study was made to assess the capacity of a set of conditioning factors to express the occurrence of sea cliff failures affecting areas located along their top.

The study was based on the application of the bivariate Information Value and multivariate Logistic regression statistical methods, using a set of predisposing factors for cliff failures, mainly related with geology (lithology, bedding dip, faults) and geomorphology (maximum and mean slope, height, aspect, plan curvature, toe protection) which were correlated with a photogrammetry based inventory of cliff failures occurred in a 60 yr period (1947–2007). The susceptibility models were validated against the inventory data using standard success rate and ROC curves, and provided encouraging results, indicating that the proposed approaches are effective for susceptibility assessment. The results obtained also stress the need for improvement of the predisposing factors to be used in this type of studies and the need of detailed and systematic cliff failures inventories.

1 Introduction

Slope mass movements, which include rock falls, toppling and different types of landslides, are the dominant and also the more visible process of sea cliff retreat (Trenhaile, 1987; Sunamura, 1992), and, in consequence, a significant source of natural hazard and a constraint for human activities and safe land use in cliffed coastal areas (e.g. Moore and Griggs, 2002). The extent and economic significance of this problem tends to increase along time, due to a general context of growing occupation of coastal areas and the large extent of cliffed and rocky shorelines, which correspond to 3/4 of the world coastlines (Emery and Kuhn, 1982; Bird, 2000). The economic value of land in coastal areas tends to be very high, as a result of increasing demand for exceptional location building areas for houses and beach and leisure resorts, and locations over the cliffs are no exception. There are also issues related with the presence, near the cliff top, of consolidated urban areas and also the conservation of archaeological and historical heritage (e.g. Bromhead and Ibsen, 2006; Carrasco et al., 2007). In spite of the obvious economic and social relevance of the problem, sea cliff and rock coasts have received comparatively low research attention in comparison with fast evolution sandy shorelines (Naylor et al., 2010).

Cliffs with global average retreat velocities (retreat rates) in the range of a few decimetres per year to several meters per year are the most commonly covered in the literature, with lower retreat rate cliffs receiving much less attention, partly due to the difficulties in monitoring an episodic, comparatively low frequency event based process, located in highly irregular and frequently inaccessible locations. In fact, most low retreat rate sea cliffs correspond also to difficult access, highly irregular and steep slope surfaces, poorly represented in aerial photographs and maps, making its accurate monitoring a difficult task.

There is some evidence supporting the need of a separation between soft cliffs (e.g. Dong and Guzzetti, 2005; Marques, 2008) with mean cliff retreat rates typically higher than 0.1 $\mathrm{m\,yr^{-1}}$, and strong to intermediate strength cliffs, with mean retreat rates lower than 0.1 $\mathrm{m\,yr^{-1}}$. The former are mainly composed by overconsolidated soils or very soft rocks as chalk (e.g. Dornbush et al., 2008) with failures occurring frequently in direct relation with periods of cliff toe direct attack by waves, while the latter are mainly composed of rock masses, where direct wave attack is not directly related or followed by cliff failure. This division implies that soft cliff evolution is strongly dependent on the sedimentary budget of the near shore, while in the stronger cliffs, the protecting role of beaches or other coastal features as sand or shingle beaches, or abrasion platforms, may only be effective at intermediate or large time scales.

Some attempts have been performed to provide conceptual frameworks for evolution prediction, to improve the more common approaches which rely on simple extrapolation of past cliff or shoreline evolution data to the future, but focusing mainly on fast retreating cliffs (Lee et al., 2001, 2002; Hall et al., 2002; Walkden and Hall, 2005). For low retreat rate cliffs hazard estimation or assessment, the published work is very scarce and includes expert based classification of indicators of near future instability (e.g. De Pippo et al., 2008), attempts to characterize the role of sets of conditioning factors, weighted and combined also according local experience or expert opinion (Del Río and Gracia, 2008; Nunes et al., 2009) and use of Bayesian probabilistic models to forecast future cliff evolution based on past cliff retreat data and expert opinion on a limited set of conditioning factors (Milheiro-Oliveira, 2007; Hapke and Plant, 2010). One of the common shortcomings of these approaches lies on the non-objective assessment of the relative importance of the selected conditioning factors or indicators of future instability. In spite of the difficulties of acquiring geotechnical data accurate enough to be representative of the strength variations of the rock masses that compose the cliffs, approaches have been made using slope stability physically based methods, including different types of cliff instability (e.g. Fall et al., 2006), or specifically for cliffs mainly composed of clays (Castedo et al., 2013). One of the most common shortcomings of these approaches lies on the limited or absent validation of results using standard methods.

While the recent developments in cliff evolution monitoring techniques, mainly based on terrestrial or airborne LIDAR and digital photogrammetry, are providing new and detailed cliff evolution data at local (Rosser et al., 2007; Young et al., 2009) and regional (Young et al., 2011) scales, regional based hazard studies which could support land use planning and hazard prevention measures are still at an undesirable qualitative and not objectively assessed level, which is not compatible with a straightforward management of coastal areas. In fact, the lack of standardized techniques and methods to support land use regulations in cliffed coastal areas, provides the ground for increased conflict potential between planning authorities and, land owners and real estate promoters.

According to their relative location, cliff failures impacts on structures and people may affect the areas located near the cliff top, the cliff face and, the areas located near the cliff toe. The processes affecting each one of these areas have significant differences, with the near cliff top retreat being the result of retrogression due to mass movement occurrence, while the near toe areas are mainly affected by failure debris or blocks motion. The cliff faces may be affected by combination of the two processes (e.g. Young et al., 2009).

The hazards induced in cliff faces and near the toe are very important especially for beach support structures and people, but are restricted to the areas where these elements are present, being very small or negligible in plunging cliffs or difficult access cliff faces and toe. As examples of strong negative impacts, in Portugal, in 2006, two tourists were killed by a low height cliff toppling failure and, in 2009, an also low height (13 m) cliff toppling failure at Maria Luísa beach (Algarve), caused 5 fatalities (Teixeira, 2009; Marques and Andrade, 2009), and two month later, in Tenerife, a cliff rock fall caused another fatality. In common in these accidents, is the relatively small scale of the failures, but which had high impact in terms of life losses. The hazards induced near the cliffs top may affect mainly structures, and is thus a concern for land use regulations and planning, both at regional and local scale, and apply to the whole extension of cliffs in a given region.

Besides being frequently highly irregular difficult access morphological features, sea cliffs tend to be formed also by soil and rock masses with complex strength variations, which make the application of physically based hazard assessments a very arduous and expensive work to be carried at regional scale of analysis. As an alternative, and considering the relevance of the problem for hazard prevention and risk mitigation, a statistically based approach seems a more convenient approach, due to the inherent complexity of the natural environment to study.

For landslides in non-coastal areas, a complete hazard assessment includes the space, time (Varnes, 1984) and magnitude components (Guzzetti et al., 2005), with the first, designated as susceptibility, being usually the less difficult to deal with and the one which is more frequently assessed. Transposing this concept to sea cliffs results that the susceptibility of the occurrence of cliff failures corresponds to the propensity of a given area to be affected by these phenomena, based solely on terrain conditions (Soeters and Van Westen, 1996), without any implication of the time component, i.e. time frequency or recurrence periods. In statistically based approaches, the terrain conditions correspond to a set of predisposing factors which statistically correlate with the occurrence of landslides, with the correlations being assessed using various bi-variate or multivariate statistical techniques (Guzzetti et al., 2005).

To address the problems involved in the assessment of the spatial component of sea cliff hazard in low retreat rate cliffs, i.e. the susceptibility of a given sector of cliffs being affected by failures which cause cliff top retreat, based solely on the spatial predisposing factors and without implications on magnitude or time components of the phenomena, a statistically based study was performed along the top of the sea cliffs of the Burgau-Lagos coastal section (Southwest Algarve, Portugal). The study was based on an aerial digital photogrammetry systematic inventory of cliff retreat events covering a 60 yr period (1947–2007), which included special procedures to enable the extraction of accurate data from old aerial photos, and validated by systematic stereo photo interpretation, helped by oblique aerial photos observation and field surveys, and a complete set of conditioning factors which are obtainable with a degree of labour compatible with studies at regional scale. The statistical methods selected for this study, which have been applied with success to landslide susceptibility assessment, were the simple bi-variate information value method (Yin and Yan, 1988) and the multi-variate logistic regression method. The results obtained are compared with the inventory data using standard success rate curves, which enable an objective assessment of the adequacy of the susceptibility models computed.

2 Setting

The 15 km long Burgau-Lagos coastal section is located in SW Algarve (Portugal) (Fig. 1) and is composed of a 10.8 km long WSW–ENE, W–E and WNW–ESE trending section exposed to SW and SE main directions of storms, and a 4.1 km long highly irregular coastline N–S section which is more sheltered and only affected by SE storm waves. The cliffs in the studied coastal section have a widely variable morphology, expressed in cliff height, cross profile and plan contour variations, and also lithological composition. The geology and geomorphology of the cliffs is described in detail in Marques (1997), together with a systematic inventory of cliff failures for the period 1947–1991, compiled using aerial photo based simplified methods (Marques, 2006). From west to east (Fig. 1), the cliffs sections are composed by (Rocha et al., 1983): (a) Cretaceous (Barremian) marls, alternating marls and marly limestones; (b) Cretaceous (Aptian) sandstones, marls, and marly limestones alternating with marls cut by a late Cretaceous basaltic pipe; (c) Miocene weak calcarenites with karst features filled with Plio-Pleistocene silty sands.

The geological structure is mainly tabular, horizontal or gently dipping to E or SE. The structure in the area near Burgau is the most disturbed by tectonics: westwards of the village, the predominantly marly beds are folded and cut by faults, while eastwards, along one hundred meters, the alternating beds of marly limestones and marls are cut by faults and dip up to 25° to SW. To eastwards and until Praia da Luz, the Cretaceous beds structure corresponds to a monocline sloping 6–10° to SE. Eastwards of Praia da Luz the Cretaceous marls and marly limestones alternating with marls beds slope generally less than 6° to E. Eastwards of Porto de Mós the Cretaceous alternating marly limestones and marls which form the lower part of the cliffs, are near horizontal but cut by several faults, and the overlying Miocene calcarenites are near horizontal but deeply affected by old karst features, mainly sinkholes which were filled by Plio-Pleistocene (PQ) reddish silty sands that form also an extensive cover in the eastern part of the study area (Fig. 1).

The cliff height varies between 6 m and more than 100 m, with varied cross profile slopes, from approximately 30° sloping near linear profiles in marls, to with a general slope of 60–90° in the alternating marly limestones and marls, and near vertical with frequent overhanging sections in the Miocene calcarenites and Cretaceous sandstones. The plan contour of the cliffs is quite regular in the Cretaceous rocks, while in the Miocene calcarenites the karst sinkhole exhumation by marine erosion caused an extremely complex plan contour, with succession of stacks, capes and very small bays.

3 Methods

The statistical methods used in this study include the bivariate Information Value Method (Yin and Yan, 1988) and the multivariate Logistic Regression method (Cox, 1958; Hosmer and Lemeshow, 2000), applied to a set of predisposing factors, mainly related with geology and geomorphology, which were correlated with an inventory of past cliff failures. The predisposing factors were selected considering the need to provide a complete description of geological and geomorphological constrains which are usually considered as relevant in conditioning the occurrence of sea cliff failures and, simultaneously, could be obtained with an acceptable level of work at a regional scale. According with these conditions, the predisposing factors selected included geological and geomorphological aspects (major lithological units; geological structure, i.e. bedding dip in relation with the cliff faces; presence of faults; presence and type of cliff toe protection) and morphometric aspects derived from a 2 m grid DTM (cliff height; mean cliff slope angle; maximum cliff slope angle; aspect, plan curvature).

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3.1 Susceptibility assessment

3.1.1 Information value

The sea cliff failure inventory relations with the conditioning factors selected were assessed first using a simple bi-variate statistical method of Bayesian inspiration, the Information Value Method (Yin and Yan, 1988), which has been applied successfully for landslide susceptibility assessment (Yin and Yan, 1988; Wu et al., 2000; Zêzere, 2002). The use of this method requires that each factor is divided in classes, with each one corresponding to a variable. The information value I_i of each variable X_i is (Yin and Yan, 1988):

$$I_i = \log \frac{S_i/N_i}{S/N}, \qquad (1)$$

where S_i is the number of terrain units with cliff failures of a given type in the units with the variable X_i, N_i is the number of terrain units with the variable X_i, S is the total number of terrain units with cliff failures of the same type, and N is the total number of terrain units in the study area. The positives values of I_i indicate that the variable is positively correlated with the possibility of occurrence of cliff failures, the negative ones indicate that the variable (or property) is associated with low susceptibility: for example, a very strong rock mass with widely spaced discontinuities is likely to have a strong negative I_i, being a lithological group with the less susceptibility to cliff failure. The near zero values indicate that the variable is not significant in terms of susceptibility ranking.

The total information value I_j for a given terrain unit j is:

$$I_j = \sum_{i=1}^{m} X_{ji} \cdot I_i \,, \tag{2}$$

where m is the number of variables, X_{ji} is 0 if the variable is not present in the terrain unit j, or 1 if the variable is present.

This statistical method enables an objective assessment of the susceptibility, based only on the spatial distribution of the predisposing factors classes (variables) and on the presence or absence of cliff failures in each terrain unit. The main limitation of this method results from its bi-variate character, i.e. it does not take into account correlations that may exist between variables.

3.1.2 Logistic regression

The sea cliff failure inventory relations with the conditioning factors selected were also assessed using the multi-variate logistic regression method (Hosmer and Lemeshow, 2000), which consists of the regression of a dichotomic dependent variable (0 without instabilities, 1 with instabilities) with a set of explanatory independent variables which may be continuous, categorical or dichotomic. The relation between instability occurrence in a given terrain unit and the set of explanatory variables is:

$$S = \frac{1}{(1 + e^{-\Psi})} \quad 0 \leq S \leq 1 \,, \tag{3}$$

where S (from 0 to 1) is the probability of a given terrain being in the group of the units affected by instabilities. Ψ Is the logit, which is linearly related with the independent variables

$$\Psi = \log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 v_1(r) + \beta_2 v_2(r) + \ldots + \beta_m v_m(r) + \varepsilon \tag{4}$$

where $\beta_0, \beta_1, \ldots, \beta_m$ are the unknown parameters of the Logistic Regression, $v_0, v_1, \ldots v_m$ are the independent variables in each terrain unit and ε is the error associated to model fitting. The logistic regression computations were performed using IBM SPSS Statistics v20 which performed the regression of the input data and returned the β and ε values. A model was built using the complete set of cliff instability predisposing factors and another model using the forward conditional approach, in which after the regression computation, the factors with all its variables are added to the model, one by one and in decreasing order of relevance, until reaching a state where the factors remaining are not relevant for the model.

4 Data acquisition and processing

4.1 Inventory of cliff failures

Inventories of past cliff failures are a fundamental piece of information for application of statistically based methods. Aerial photo based cliff evolution monitoring and cliff failure inventory compilation, while usually less accurate and less convenient than other recent techniques (e.g. airborne LIDAR), especially when using old aerial surveys for which there are no camera calibration data, enables much longer monitoring periods, which may extend to the 1940's, to the older aerial photo surveys available in many sea cliff dominated coastlines. These much wider monitoring periods are very convenient to get a wider sampling window of the cliff retreat phenomena, which is highly irregularly spaced in space as in time, and in consequence enable much more representative samples of the cliff retreat events. It must be stressed that the photogrammetric monitoring using archival aerial photos is only able to detect the larger cliff failures, which cause cliff top retreat larger than approximately 1.0–1.5 m, with the smaller but much more frequent failures (Marques, 2008) remaining mostly undetected.

In this study, the cliff failure inventory was compiled using multi-temporal aerial digital photogrammetric methods, using aerial photographs of 1952, 2002, and 2007. Special techniques were used to enable the use of old aerial photos without camera calibration data (Redweik et al., 2008, 2009). The photogrammetric techniques did not provide satisfactory results in the processing of the older aerial survey available dating from 1947, mainly because the photos were made with non-metric reconnaissance cameras. These photos were used for photointerpretation comparison with the 1952 photos for the identification of cliff failures occurred between 1947 and 1952. The photogrammetric processing involved several aerotriangulation steps, generation of pseudo-camera data for the older aerial photos without camera calibration information, stereo plotting of the cliff top, ridges and toe, and automatic generation of digital terrain models (Redweik et al., 2008, 2009). The results were validated by systematic stereo photo interpretation, helped by oblique aerial photos and field surveys.

This study enabled the detection and characterization of 137 cliff failures that occurred between 1947 and 2007 along the 15 km long cliffs. However, some of these failures occurred in sea stacks or correspond to block quarrying in low rocky parts of the coast which do not correspond to the sea cliffs. For this study, were only considered 119 cliff failures or groups or failures which occurred in the same place and could not be separated due to the wide time gap between aerial photo surveys, which causes an inevitable degree of data amalgamation (Dong and Guzzetti, 2005). The cliff failures caused a net loss of 11 195 m^2 of horizontal area at the level of the cliffs top.

The distribution of failures and failure size along the cliffs sections of the studied coast is quite variable, and is expressed by the cumulative number of failures and of horizontal area lost at the cliff top against the length of cliff top (Fig. 2). Using these plots and considering also the lithology of the cliffs it is possible to separate sub sections with some degree of homogeneity of retreat behaviour. The slope of the linear regression of the selected plot sections expresses the average cliff retreat for the 60 yr monitoring period, that divided by the number of year provides estimates of the mean cliff retreat. Computed mean retreat rates varied within one order of magnitude from 7×10^{-3} m yr^{-1} in lower Cretaceous strong sandstones and alternating marly limestones and marls to 4×10^{-2} m yr^{-1} in Miocene calcarenites with frequent karst sinkholes filled with Plio-pleistocene silty sands (Fig. 2b). The dominant cliff failures in calcarenites and silty sands caused local cliff top retreat from 3 m to 16 m, with a maximum recorded retreat of 26 m, while in Cretaceous rocks the more frequent values varied between 1 m and 2.4 m, with the larger values up to 9 m (Fig. 3). Most of the larger local retreat cliff failures occurred in Plio-Pleistocene silty sands and weak Miocene calcarenites dominated cliffs. Field evidence indicates that, with the exception of the larger failure recorded occurred at Praia do Canavial cliffs, the larger cliff top retreat values correspond to successions of failures occurred as a consequence of heavy rainfall frequently associated with sea storms, which increase the possibility of a near saturation of the toe of the slopes, but that could not be separated because of the large time periods separating the different aerial photo surveys used.

The cliff failures identified correspond to steeply sloping failure plane planar slides (58 %) mainly in Cretaceous alternating limestone and marls and sandstones, toppling failures (17 %) mainly in Miocene calcarenites, slumps (15 %) in Plio-Pleistocene silty sands, and the remaining 10 % correspond to complex movements, rockfalls and not determined cases. The failures correspond mainly to the mobilization of comparatively thin slabs of the cliff faces, with most of the larger cliff top retreat events corresponding to series of failures rather than unique failures. The only exception is the larger cliff planar slide, located at Praia do Canavial cliffs, which caused the larger cliff top retreat of 26 m and the larger single horizontal area lost at the cliff top (Fig. 2), and was a failure mainly driven by a local long term water pipe rupture. However, this slide occurred near to the place where a comparatively large cliff failure had already occurred a few years before. The plot of maximum local cliff top retreat against cliff height shows that there are no clear relations between these two variables (Fig. 4).

Considering that the cliff failures cross section does not show strong variations in the inventory, it is assumed a certain convergence of causes, mechanisms and triggering factors, giving support to an analysis which includes all data without failure type separation.

The length of cliff top affected by failures varied within a large range (Fig. 5), from less than 4 m to approximately 100 m, with the values lower than 30 m corresponding to circa 80 % of the inventoried cases.

4.2 Terrain units

One important aspect for this type of studies is the definition of the divisions of the study area in portions which properties that may be assumed as nearly constant in terms of the different cliff instability predisposing factors, i.e. the terrain units or domains to consider for application of the statistical methods. In the case of sea cliffs, a pixel based approach, in spite of its convenience in use, is affected by several drawbacks which include: some predisposing factors mapping (e.g. toe protection) cannot be extended to all unit cells that cover a given cliff face; the cliff stability is dependent of the predisposing factors present along the entire cliff face and not in an pixel per pixel basis; grid cells located landwards of the cliff top but with limits very close to it would produce low susceptibility values due to very small values of slope and other morphometric derived factors, but this result will be misleading because its susceptibility is mainly dependent on the adjacent cliff top cells values. Considering these problems a terrain unit approach was selected.

Following a preliminary trial using 50 m long sections of the cliff top line, the mapping and analysis of the factors was made in ArcGIS 9.3, using terrain units defined along 25 m long sections of the cliff top line, smoothed with a 25 m radius of tolerance line. This size corresponds also to the limit of the majority of the values of length of cliff top affected by retreat and is a good balance between the detail of the mapping of the different predisposing factors and the number of resulting terrain units and their possible use for planning purposes.

At the ends of each 25 m smoothed cliff top line segment, the lateral limits of terrain units were drawn in directions approximately perpendicular to the cliff contour lines, crossing thus the manually digitized lines of the cliff top and toe. This approach was slightly modified in the highly complex cliff plan contour of the eastern coastal section studied, which corresponds to the cliffs cut in the Miocene calcarenitic rocks and the Plio-Pleistocene overconsolidated silty sandy soils. In this coastal section, located eastwards of Praia do Canavial, the limits of the terrain units were manually adjusted to provide a better representation of cliff morphology, namely the aspect and plan curvature.

To enable a complete sampling of the morphometric properties of each terrain unit, 1 m buffers were created along the cliff top an toe lines, i.e. one half of the DTM grid cell used, and these buffer areas were added to the cliff terrain units. The study cliffs were then divided in 595 terrain units containing approximately 25 m long sections of cliff top line, which corresponds to approximately 14 875 m of cliff top length.

4.3 Sea cliff failure predisposing factors

The predisposing factors considered were those that were susceptible to bear relations with cliff failure occurrence and which could be obtained with acceptable level of work and detail compatible with a regional scale study.

The geological and geomorphological factors considered were: (a) major lithological units including the 16 following classes by order of dominance in each class except when indicated: Basalt; Calcarenites; Calcarenites and marly limestones; Calcarenites and silty sands; Calcarenites, silty sands and marly limestones; Marls; Marls over marly limestones (subordinated); Marly limestones; Marly limestones (subordinated) over marls; Marly limestones over marls; Marly limestones over marls (subordinated); Marly limestones and calcarenites; Marly limestones and silty sands; Sandstones; Silty sands; Silty sands and calcarenites. (b) Geological structure in terms of bedding dip relation with the cliff faces expressed in four classes: horizontal (less than 10°) and against cliff face dipping (against slope); Beds dip direction outwards of the cliff face (i.e. nearly parallel to cliff face dip) but dip lower than cliff face slope angle (Inferior to slope); Igneous rock masses with no visible structure (massive); Beds dip direction roughly parallel to the cliff face with dip higher than 10° (parallel to slope). (c) Presence or absence of faults. (d) Presence and type of cliff toe protection against direct wave attack including 18 classes: plunging cliffs with no protection (no protection), cliff toe protection by debris accumulations of large cliff failures older than 1947 and not included in the inventory used in this study (talus deposits) and blocks fallen from the cliffs mainly corresponding to already existing features in 1947 (blocks), sandy beach wide, sandy beach narrow, boulder beach (gravel beach), wave cut platforms (platform), large sea stacks (sea stacks), or various combination of these features. These factors were mapped at 1 : 2000 scale using existing geological maps, field surveys and vertical and oblique aerial photo analysis.

The aspects related with the cliffs morphometry were derived from a 2 m grid DTM obtained from a 1 : 2000 aerophotogrammetric survey carried out by the national water authority (INAG), with source data (1 : 8000 scale aerial photographs) obtained between 2001 and 2003. The maps in vector format were object of systematic checking and correction of errors in order to enable the production of an accurate DTM. The cliff top and toe lines which were the basis for the terrain units definition were manually digitized using the topography (contour lines and slope) information and orthophotomaps.

The topography used in this study was made after the occurrence of most cliff instabilities recorded in the inventory. This implies that, especially for slope assessments for each terrain unit, the obtained values represent post failure conditions and not pre failure conditions. In the cases of the cliff failures which caused the smaller values of cliff top retreat, the cross profile of the cliff did not suffer large variations of slope, and the same happened with the failures that affected mainly the sandy cliffs, which caused near parallel retreat of the cliff face. In the larger failures however, the morphometry of the cliff suffered changes which were not considered in this study. However, this problem cannot be easily solved because the topographic survey used is the older which is accurate enough to carry this type of studies (more accurate previous maps were only at 1 : 25 000 scale).

The morphometric factors used obtained by processing of the 2 m grid cell DTM include: (e) cliff height which corresponds to the maximum elevation value in each terrain unit, (f) mean cliff slope angle which corresponds to the mean slope angle of all slope grid cells in each terrain unit, and (g) maximum cliff slope angle recorded in each terrain unit.

For aspect and curvature assessment the information derived from a 2 m DTM reflected very small local variations which were not representative of the global terrain conditions in each terrain unit. After several trials with DTMs with grid cells with 2, 4, 6, and 10 m, the 6 m grid cell DTM was retained for the computing of aspect and plan curvature, since it provided an adequate balance of detail and smoothing of small local sharp variations in the topography which did not reflect the general character of each terrain unit. The several attempts made to obtain reasonable results for the profile curvature from the DTMs were unsuccessful and in consequence this factor was not considered in this study.

The 6 m grid cell DTM derived factors were: (h) aspect (direction of cliff face exposure) which corresponds to the mean direction of exposure of the cliffs that bears some relations with the perceived intensity of the wave regime in the different parts of the study area; (i) mean plan curvature of the cliff faces obtained by classification of the computed plan curvatures in each terrain unit in four classes separated by curvature values of −3.0, −0.5, 0.5, 3.0 in order to avoid the heavy influence of cells with very low (negative) or high curvatures which would otherwise have an excessive influence on the mean values computed for each cell. The mean values of the reclassified plan curvature values were retained and expressed in a qualitative scale which includes 5 terms: strongly concave; slightly concave; plan; slightly convex; strongly convex. The results were object of a systematic checking to detect eventual errors of aspect and curvature assessment.

Considering that the shape of most cliff failures corresponds to the detachment of relatively thin and high slabs of rocks or soils, separated by steeply dipping failure surfaces of planar, slump or toppling failures, the analysis of the inventory data was made including all events recorded, and the dependent variable level is composed of terrain units with cliff failures (186) in a total number of 595 terrain units. The data

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processing for the production of the mapping and distribution of predisposing factors in all terrain units was performed in ArcGIS 9.3.

In the categorical factors processing (lithology, bedding dip, toe protection, faults) were retained the classes which were mapped along the study area. The numerical factor aspect was classified according the 8 general directions and the plan curvature in 5 classes (strongly concave; slightly concave; plan; slightly convex; strongly convex).

The classification of the numerical predisposing factors cliff height, maximum slope and mean slope in classes followed a near quantile approach in order to enable a near homogeneous distribution of terrain units in each variable of each factor (Table 1).

5 Results, validation and discussion

The results obtained in the computing of the Information Value for each variable are in Table 1. For the Information Value computation were considered two variables, "Marls over marly limestones (sub)" of factor "Lithology" and "Sea stacks" of factor "Toe protection", with zero cliff instabilities. These variables are meaningful in the context of the studied coast and to enable the computation an artificial value of 0.999 for cliff failures was considered, in order to prevent an excessive increase of the resulting I_i negative values.

A global analysis of the results indicates that the larger positive or negative I_i values correspond mainly to variables of the factors "Toe protection" and "Lithology", with minor contributions of variables of factors "Aspect", "Cliff Height", "Mean slope" and "Maximum slope". The relative importance of each factor was tentatively analysed by computing the area under the curve (AUC) for the success rate curves of each of the factors analysed separately, and also by comparing the mean of the absolute values of the Information Value for each factor (Table 2).

The forward stepwise conditional logistic regression analysis indicated that the relevant factors for model construction were, from step 1 to step 6, "Lithology", "Toe protection”, “Cliff height”, “Mean slope”, “Plan curvature” and “Aspect” (β and ε values in Table 1).

The success rates curves for the models produced with the results of the logistic regression considering all factors and forward conditional with 6 factors, and the Information Value with all factors is in Fig. 6, together with an ideal model for this situation, i.e. a model in which there would be no false positive values and all cliff failures were captured in the leftmost part of the curve. The AUCs are in Table 3 and suggest that the results obtained for the success rate are acceptable because in this study area, where there is a large proportion of terrain units with cliff failures (186 in 595, 31.3 %) the “ideal model” for this situation, that could predict only terrain units with cliff failures in the higher susceptibility values, would only provide a AUC value of 0.844, making the results of the model much more meaningful. It seems also clear that the logistic regression provided a significant improvement of the results over the Information Value, especially considering all factors. A different perspective of the results is obtained using the false positive against the true positive curves and correspondent AUCs (Fig. 7), as in this type of curves the “ideal model” corresponds to an AUC = 1. In Fig. 8 there is the comparison of the maps of the inventory and of the results obtained with the best model in this study, the logistic regression with all factors, to enable a visual confirmation of the adequacy of the model.

The I_i values also indicate that models that do not include faults and bedding dip have a slightly better performance, suggesting that these factors are not relevant for model construction under the particular circumstances of the studied area, which is also confirmed by the rejection of factors produced by the forward stepwise conditional logistic regression.

Lithology is one of the most important factors, mainly because reflects the cliffs rock mass strength, together with toe protection which plays a major role in controlling wave erosion and attack at the cliffs toe. Aspect is probably the third factor in terms of relevance, because it partially reflects the main aspects of the intensity of the wave action in this particular coastline. The remaining factors (mean and maximum slopes, height and plan curvature) played a minor role but nevertheless contributed for the increase of the success rates of the computed models.

The relative importance of the different factors considered in this study is probably conditioned in an uncertain degree by the specific geological and geomorphological context of the cliffs and coastline analysed. Studies carried out in other types of cliffs may produce different results and in consequence, it seems advisable to test the models performance with all factors before discarding the least relevant for describing the cliff failure processes.

The models produced in this study show good agreement with the inventories that were used to build them, and in consequence, the validation stage corresponds to success rates. The predictive capacity of the models was not analysed due to limitations of the inventory, which was compiled with very wide and extremely different time periods between aerial photos used. In fact, the 2002–2007 last monitoring period was atypical of the general evolution of the cliffs, and provided only 4 small cliff failures. The models construction with the 1947–2002 inventory produced results close to the global models presented, but the 2002–2007 inventory data was clearly not sufficient to enable a meaningful model predictive capacity assessment.

6 Conclusions

The statistical methods used in this study, specially the logistic regression, provided models which enable an objective assessment of the relations between a set of predisposing factors related with geology and geomorphology of the cliffs, which are compatible with studies carried out at a regional scale, and the occurrence of sea cliff failures.

The predisposing factors of sea cliff failure used were effective but their improvement is desirable in order to obtain variables with stronger relationships with the actual cliff failures.

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The use of success rate curves is an objective way of validating the results of the models, but the significance of the area under the curve (AUC) should take into account the proportion of terrain units with failures in relation with the total terrain units of the study area.

The methods used in this study showed a good potential for the assessment of the susceptibility of sea cliff failures for planning purposes and, in consequence, a step towards the objective sea cliff hazard assessment.

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Table 1. Information Value (I_i) and Logistic Regression (Constant, B values) results.

		Information Value			Logistic Regression	
Factors	Variables	(S = 186; N = 595)			All factors	Forward stepwise
		S_i	N_i	I_i	β	β
	Logistic regression constant ε	–	–	–	−21.0573	−22.2740
Cliff Height	6–17	22	66	0.0642	1.2429	1.2681
	17–24	19	60	0.0129	0.4662	0.4334
	24–30	28	70	0.2465	0.6455	0.7020
	30–34	20	55	0.1512	0.5502	0.6083
	34–39	19	79	−0.2622	−1.2440	−1.1980
	39–42	22	64	0.0950	0.1975	0.2325
	42–46	19	64	−0.0516	−0.8633	−1.0266
	46–74	13	71	−0.5349	−1.7791	−1.9397
	74–106	24	66	0.1512	0.0000	0.0000
Mean slope	28–35	12	56	−0.3776	−2.2276	−1.9344
	35–39	22	68	0.0343	−1.4428	−1.2071
	39–41.5	19	59	0.0297	−1.9744	−1.5568
	41.5–43.5	20	56	0.1332	−1.4118	−0.9103
	43.5–46.5	21	58	0.1469	−0.7548	−0.3732
	46.5–49	23	52	0.3471	−0.0080	0.3215
	49–51.5	21	70	−0.0412	−0.7292	−0.4878
	51.5–54.5	19	57	0.0642	−0.1091	0.1147
	54.5–58	11	53	−0.4096	−0.0564	0.0617
	58–67	18	66	−0.1365	0.0000	0.0000
Aspect	N	3	16	−0.5112	−2.1334	−2.3084
	NE	8	38	−0.3953	−2.6951	−2.7757
	E	21	72	−0.0693	−1.5065	−1.7546
	SE	34	130	−0.1784	−0.8556	−0.9341
	S	80	240	0.0642	−0.3098	−0.4528
	SW	30	75	0.2465	−0.3461	−0.4974
	W	9	22	0.2690	0.0000	0.0000
	NW	1	2	0.4697	−20.6799	−19.9799
Plan curvature	Strongly Concave	21	45	0.4007	2.2219	2.0000
	Lightly Concave	23	77	−0.0455	0.0184	0.0218
	Plan	101	346	−0.0685	0.1160	0.1031
	Lightly Convex	31	86	0.1425	0.7514	0.6961
	Strongly Convex	10	41	−0.2482	0.0000	0.0000
Lithology	Basalt	2	7	−0.0899	0.3824	0.4676
	Calcarenites	16	137	−0.9846	1.0178	0.3180
	Calcarenites, marly limestones	3	13	−0.3035	0.9729	0.7889
	Calcarenites, silty sands	35	84	0.2873	3.6573	2.8564
	Calcarenites, silty sands, marly limestones	4	4	1.1628	23.1595	22.5443
	Marls	15	25	0.6520	5.5645	5.3866

Table 1. Continued.

Factors	Variables	Information Value			Logistic Regression	
		(S = 186; N = 595)			All factors	Forward stepwise
		S_i	N_i	I_i	β	β
	Marls over marly limestones (sub)	0*	8	−0.9176	−14.9728	−16.3829
	Marly limestones	13	30	0.3266	1.7924	2.1454
	Marly limestones (sub) over marls	33	78	0.3026	4.4144	3.7155
	Marly limestones over marls	6	25	−0.2643	0.3523	0.5610
	Marly limestones over marls (sub)	21	104	−0.4371	0.8852	1.0269
	Marly limestones, calcarenites	5	8	0.6928	2.9241	2.5536
	Marly limestones, silty sands	3	6	0.4697	2.6485	2.3599
	Sandstones	12	45	−0.1589	0.0000	0.0000
	Silty sands	9	10	1.0575	8.8960	7.5963
	Silty sands, calcarenites	9	11	0.9621	6.7038	5.5824
Toe protection	Blocks	27	92	−0.0631	20.3754	20.6081
	Blocks Gravel beach	9	23	0.2245	19.4296	19.6496
	Blocks Gravel beach Talus deposits	2	4	0.4697	20.7828	20.8601
	Blocks Platform	15	53	−0.0994	21.1748	21.6191
	Blocks Talus deposits	11	37	−0.0502	20.6619	20.5737
	Gravel beach	1	7	−0.7831	17.3871	17.6927
	No protection	11	80	−0.8213	19.5409	19.6550
	Platform Sea stacks	6	17	0.1214	21.4936	22.0698
	Sandy beach narrow	31	94	0.0535	20.8057	20.9498
	Sandy beach narrow Blocks	21	32	0.7416	22.3400	22.4244
	Sandy beach narrow Blocks Gravel beach	4	7	0.6032	18.0943	18.5671
	Sandy beach narrow Blocks Platform	3	7	0.3155	20.9666	21.5188
	Sandy beach narrow Platform	2	3	0.7573	20.0850	20.1637
	Sandy beach narrow Sea stacks	1	7	−0.7831	16.2115	16.9278
	Sandy beach wide	37	109	0.0824	20.6562	20.6239
	Sandy beach wide Blocks Platform	3	7	0.3155	19.5484	19.8746
	Sandy beach wide Sea stacks	2	2	1.1628	55.8467	54.6495
	Sea stacks	0*	14	−1.4863	0.0000	0.0000
Maximum slope	44–68	18	55	0.0459	−1.4738	–
	68–72	25	68	0.1622	−0.3518	–
	72–75	26	60	0.3266	−0.5477	–
	75–77	14	51	−0.1300	−0.8297	–
	77–79	24	85	−0.1018	−0.6844	–
	79–81	15	76	−0.4599	−1.3168	–

Table 1. Continued.

Factors	Variables	Information Value (*S* = 186; *N* = 595) S_i	N_i	I_i	Logistic Regression All factors β	Forward stepwise β
	81–83	17	67	−0.2087	−0.6287	–
	83–85	23	76	−0.0324	−1.0010	–
	85–88	24	57	0.2978	0.0000	–
Faults	No faults	165	537	−0.0172	−0.3727	–
	Faults	21	58	0.1469	0.0000	–
Bedding dip	Horizontal, Against slope	102	347	−0.0615	−0.6537	–
	Inferior to slope	25	70	0.1332	0.6999	–
	Massive	2	7	−0.0899	0.0000	–
	Parallel to slope	57	171	0.0642	0.0000	–

[*] No cliff failures identified in the terrain units of the variable. For calculation the 0 was replaced by 0.999 to prevent an excessive increase the resulting I_i negative values.

Table 2. Predisposing factors relevance based on I_i.

	I_i absolute values mean	Success rate curve AUC
Lithology	0.5668	0.6935
Toe protection	0.4963	0.6415
Aspect	0.2754	0.6355
Maximum slope	0.1961	0.5650
Plan curvature	0.1811	0.6650
Cliff Heigth	0.1744	0.5614
Mean slope	0.1720	0.5556
Bedding dip	0.0872	0.6667
Faults	0.0821	0.7885

Table 3. Success rate Area Under the Curve (AUC) for the different models.

Model	AUC (success rate)
Ideal model for this situation	0.8437
Logistic regression with all factors	0.7509
Logistic Regression FwCond: Lithology, ToeProt, Height, Mean slope, Plancurv, Aspect	0.7425
I_i model with all factors	0.7017
I_i: Lith, ToeProt, Aspect, MaxSlope, PlanCurv, Height, MeanSlope, BedDip	0.7021
I_i: Lith, ToeProt, Aspect, MaxSlope, PlanCurv, Height, MeanSlope	0.7029
I_i: Lith, ToeProt, Aspect, MaxSlope, PlanCurv, Height	0.6989
I_i: Lith, ToeProt, Aspect, MaxSlope, PlanCurv	0.6859
I_i: Lith, ToeProt, Aspect, MaxSlope	0.6805
I_i: Lith, ToeProt, Aspect	0.6734
I_i: Lith, ToeProt	0.6667
I_i: Lith	0.6583

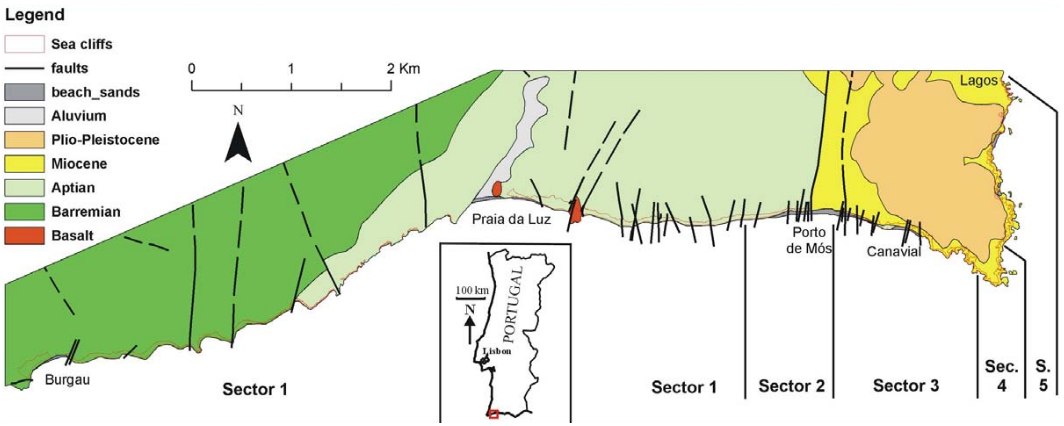

Fig. 1. Localization and geological units, faults and sea cliff extent in the study area, with sectors defined according space frequency of cliff failures and corresponding horizontal area lost at the cliff top.

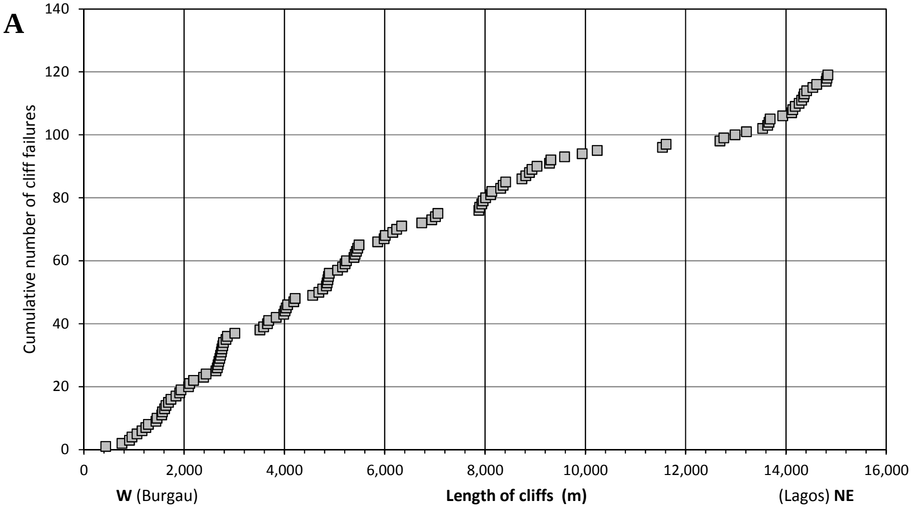

Fig. 2. Spatial distribution of cliff failures. **(A)** Cumulative number of cliff failures along the cliffs length (from west to east). **(B)** Cumulative horizontal area lost at the level of the cliffs top, along the length of cliffs (sector extent in Fig. 1). The slope of the linear regressions corresponds to the mean retreat in meters for the 60 yr long period of monitoring for each sector defined according the frequency of cliff failures, horizontal area lost and geological units affected.

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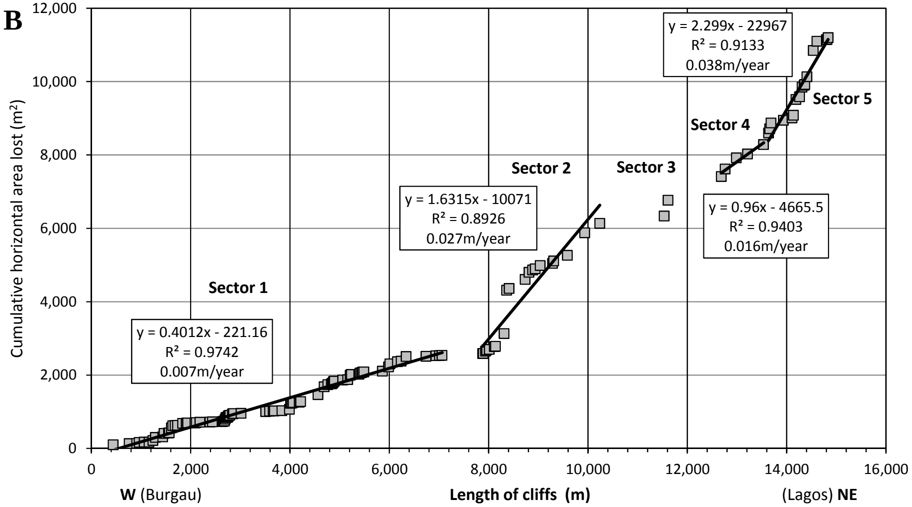

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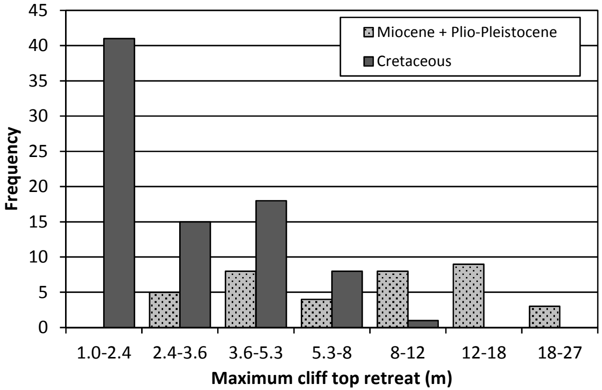

Fig. 3. Variation of maximum cliff top retreat caused by cliff failures in Cretaceous, and Miocene plus Plio-Pleistocene formations. Size classes defined according a quantile basis.

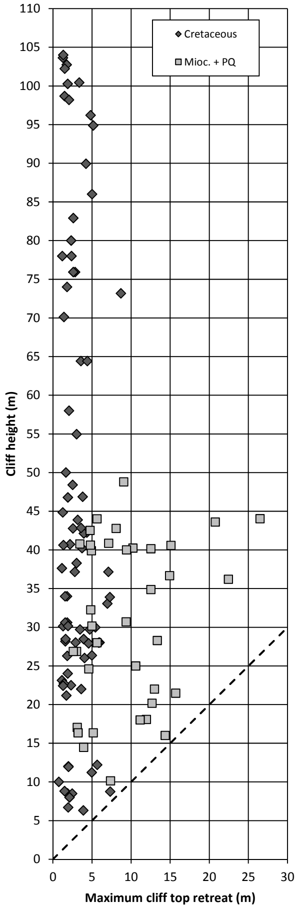

Fig. 4. Variation of maximum cliff top retreat caused by cliff failures in Cretaceous and Miocene plus Plio-Pleistocene formations against cliff height.

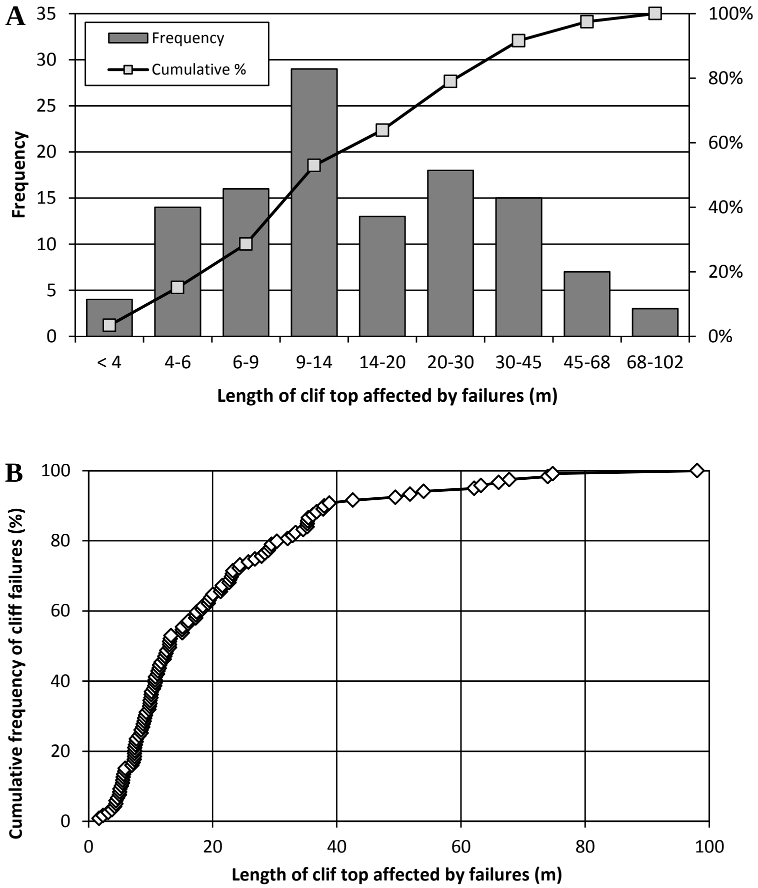

Fig. 5. Length of cliff top affected by sea cliff failures ordered by increasing order of values. **(A)** Histogram of cliff top length affected by cliff failures (quantile based) and corresponding cumulative frequency curve. **(B)** Cumulative frequency plot (continuous) of cliff top length affected by cliff failures.

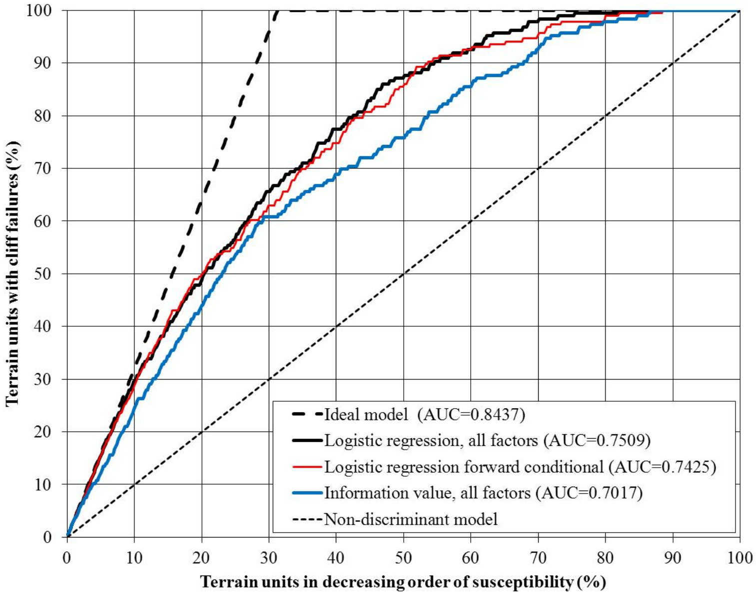

Fig. 6. Success rate curves of the models produced in this study.

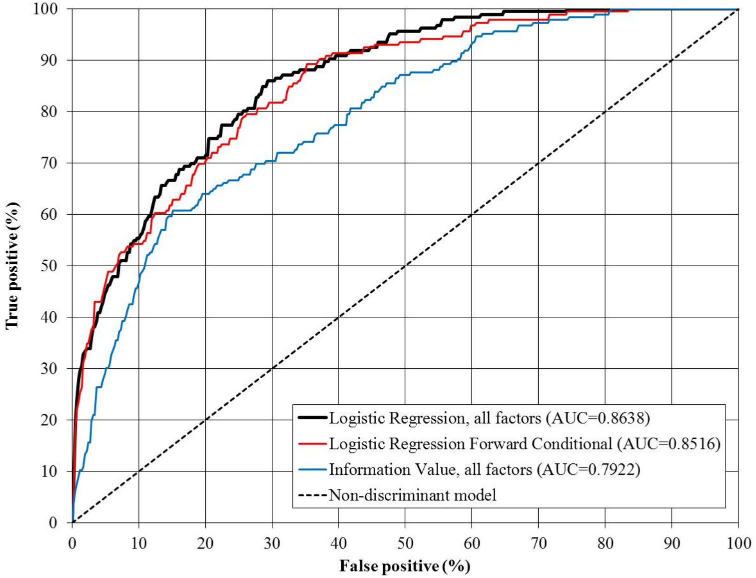

Fig. 7. Receiver operating characteristic (ROC) curves of the models produced in this study including the corresponding areas under the curves (AUC).

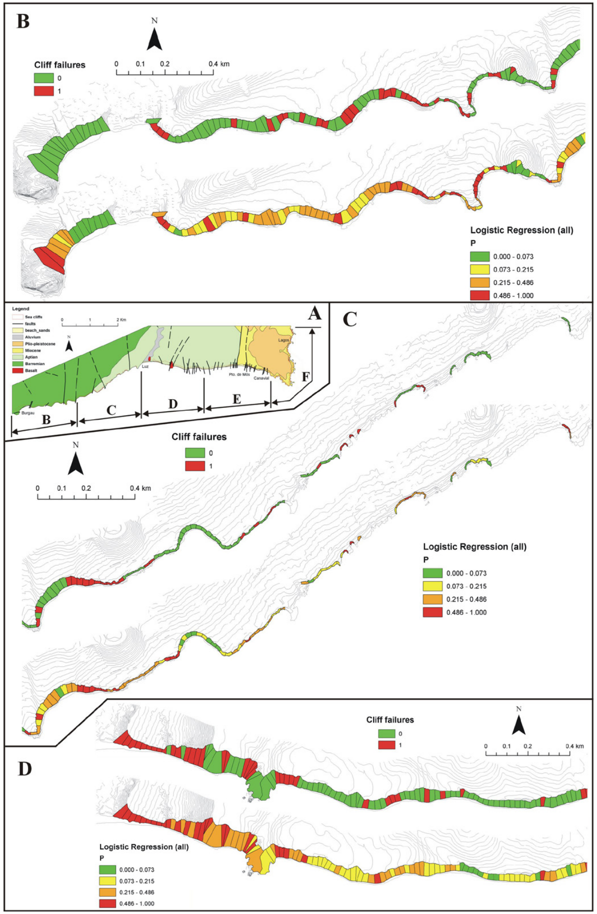

Fig. 8. Comparison of the terrain units with cliff failures and the logistic regression model with all factors. Classification of logistic regression probability values in quantile based classes. **(A)** Localization of the coastal sections **(B)**, **(C)**, **(D)**, **(E)**, and **(F)**.

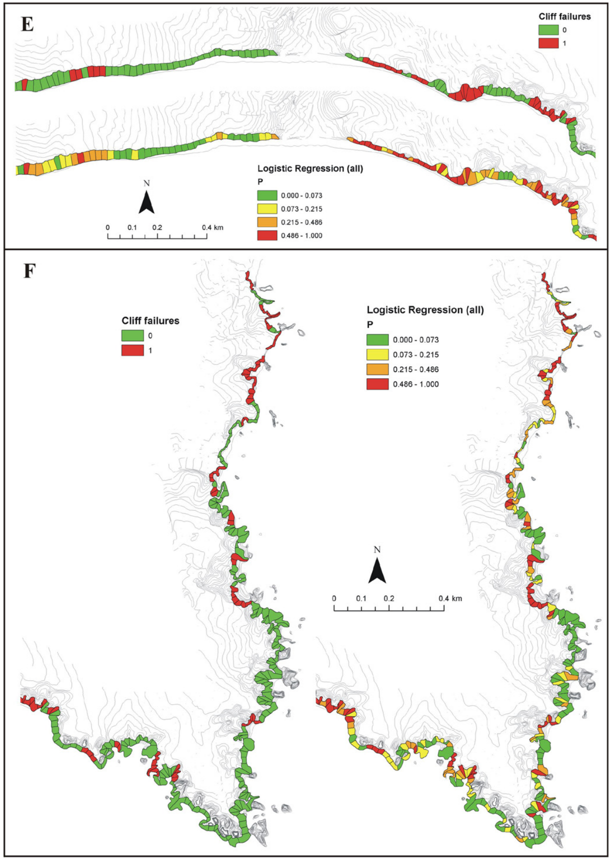

Fig. 8. Continued.