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Mapping of landslide susceptibility of coastal cliffs: the Mont-Roig del Camp case study

I. MONTOYA-MONTES[1,*] **I. RODRÍGUEZ-SANTALLA**[1] **M.J. SÁNCHEZ-GARCÍA**[1] **J. ALCÁNTARA-CARRIÓ**[2]
S. MARTÍN-VELÁZQUEZ[1] **D. GÓMEZ-ORTIZ**[1] **T. MARTÍN-CRESPO**[1]

[1] **Department of Biology and Geology, Universidad Rey Juan Carlos**
C/ Tulipán s/n. 28933, Móstoles, Madrid, Spain. Fax: (0034)916647490
Montoya E-mail: isabel.montoya@urjc.es Rodríguez E-mail: inmaculada.rodriguez@urjc.es
Sánchez E-mail: mariajose.sanchez@urjc.es Martín-Velázquez E-mail: silvia.martin@urjc.es
Gómez E-mail: david.gomez@urjc.es Martín-Crespo E-mail: tomas.martin@urjc.es

[2] **Institute of Environmental and Marine Sciences. Universidad Católica de Valencia**
C/ Guillem de Castro 94. 46001 Valencia, Spain. Fax: (0034)963153655.
Alcántara E-mail: javier.alcantara@ucv.es

*Corresponding author

ABSTRACT

The weathered and fractured conglomerate cliffs of Mont Roig del Camp constitute a rock fall hazard for the surrounding pocket beaches and, therefore, for the population that frequent them, especially over the summer. Landslide susceptibility of the cliff has been assessed using the Rock Engineering System method (RES). The determinant and triggering factors considered in this study include: wave exposure, shoreline variations, cliff height, cliff slope, geotechnical quality of the rocky mass, superficial runoff and cliff orientations favoring landslides. Geographic Information Systems (GIS) have been employed to facilitate the information analysis and generate new susceptibility maps. The quality of the rock mass and cliff orientation are the most interactive factors for the stability of the cliff. However, shoreline variations and surface runoff are the most dominant factors in the system. Thus, the quality of the rock mass has been determined to be a basic variable in the cliff characterization because of its high dependence on the variations of the remaining factors. The landslide susceptibility map depicts a predominance of surfaces with moderate degrees of susceptibility concentrated mainly in the headlands, where the combined actions of subaerial and marine processes control the weathering and eroding processes. Therefore, the landslide susceptibility assessment based on this methodology has allowed the identification of hazardous areas that should be considered in future management plans.

KEYWORDS | **Rocky coast. Cliff instability. Landslide susceptibility. Hazard. Geographic Information Systems.**

INTRODUCTION

Several researchers have reported that sea cliffs are found along 80% of the Earth's ocean coasts (Emery and Kuhn, 1982), although the amount of the world's shoreline that is rocky is questionable (Naylor *et al.*, 2010). Even if coasts with cliffs and rocky coasts have not been as extensively studied as beaches or sandy coasts, interest in researching this type of coast has increased in recent years (Naylor *et al.*, 2010), possibly as a consequence of the rapid development in these coastal areas. Wave action and physical-chemical weathering cause mass movements and progressive erosion of the coast, which increasingly threaten human lives and infrastructures. This conflict between human activity and the inherent instability of coasts with cliffs has become a problem of growing magnitude (Moore and Griggs, 2002). Thus, in a first order approach to the problem, it is essential to identify potentially unstable areas through a methodology that does not require substantial resources or time and that produces reliable results.

Landslide susceptibility assessments determine the distribution of potentially unstable areas. Susceptibility maps are useful to develop land management and mitigation plans (Mejía-Navarro and García, 1996) and are especially important for future damage reduction.

In the last few decades, great efforts have been made to develop methodologies related to the preparation of susceptibility models with the aim of analyzing landslide hazards (Brabb *et al.*, 1972; Carrara, 1983; Hansen, 1984; Corominas, 1987; Carrara *et al.*, 1991; Chung and Fabbri, 1993; Chung *et al.*, 1995; Van Westen *et al.*, 1997; Santacana, 2001; Bonaechea, 2006; Teixeira, 2006). Various factors influence instability processes in these areas and several authors have analyzed the occurrences of landslides and cliff retreats, emphasizing the need to quantify the influence of each factor in the process (Palmquist and Bible, 1980; Varnes, 1984; Brabb, 1984; Hutchinson, 1988; Turner and Schuster, 1995; Cruden and Varnes, 1996; González-Díez *et al.*, 1999; Zêzere *et al.*, 1999; Mateos, 2001; Nunes *et al.*, 2009; Budetta et al, 2008; Del Río and Gracia, 2009).

Three methods are proposed to calculate landslide susceptibility: statistical, deterministic and heuristic methods. Statistical methods determine the combinations of variables which have influenced past instability processes (Dai and Lee, 2001). Deterministic methods analyze slope stability using numerical modeling (Fall *et al.*, 2006; Godt *et al.*, 2008). The heuristic approach uses expert judgment to assess and classify the hazard, in addition to determining the causative factors of landslides (Barredo *et al.*, 2000; Foster *et al.*, 2008). The landslide susceptibility is categorized as "very high", "high", "moderate", "low" and "very low" (Fall *et al.*, 2006; Castellanos and Van Westen, 2008).

Uncertainty regarding the potential hazards in a coastal area leads to unknown consequences derived from such hazards. Thus, studying and analyzing the sensitive areas is essential to manage and plan adequate actions. Therefore, it is necessary to emphasize the importance of cartography and Geographic Information Systems (GIS) as tools for land management and map generation (Rodríguez *et al.*, 2009). Recently, the generation of susceptibility models has undergone important progress, as a result of the development of GIS and other techniques related to data spatial analysis (Carrara *et al.*, 1991; Chung and Fabbri, 1993; Van Westen, 2000; Irigaray, 1995; Baeza and Corominas, 2001; Remondo, 2001; Santacana, 2001; Fabbri *et al.*, 2003; Nunes *et al.*, 2009; Cruz de Oliveira *et al.*, 2008). GIS is useful in multi-factorial analysis, from the setting of the classes of parameter values to the final susceptibility map, undergoing the following phases: variable weighting, interpolation to obtain the value of each pixel, and the combination and reclassification of maps (Santacana, 2001).

The purpose of this work consists of developing a map of landslide susceptible areas for a section of the Tarragona coast (NE Spain) through the analysis of the factors that contribute to the instability of the sea cliff. The heuristic method is employed in the present paper, and one of the main difficulties encountered was the adequate weighting of each variable. In this work, we apply an approximation of the Rock Engineering System (RES) methodology proposed by Hudson (1992) to determine relevant variables influencing the cliff stability and the interactions between these variables (Hill and Rosenbaum, 1998; Budetta *et al.*, 2008).

STUDY AREA

The cliffs of Mont-Roig del Camp are located on the western Mediterranean coast of Spain (Fig. 1). They extend for 2.5km and reach a height of up to 19m. These cliffs have developed alluvial fans, which date from the Upper Pleistocene (125–300Ky BP) according to CSN (2001), formed from material from the Llabería and Pradell mountains and eroded by marine activity over high sea level periods, such as the present period (Fig. 1). The stratigraphy of the cliffs consists of three lithological units, related to alluvial fans, which are known as A, B, and C (Fig. 2A, B) (Montoya, 2008). Units A and C are conglomerates, which are associated with the proximal zones, showing large boulders, some degree of size sorting, and, occasionally, fine grained bodies. The intermediate unit B consists of clay, which is associated with the distal zones of the alluvial fan, with some conglomerate fragments and

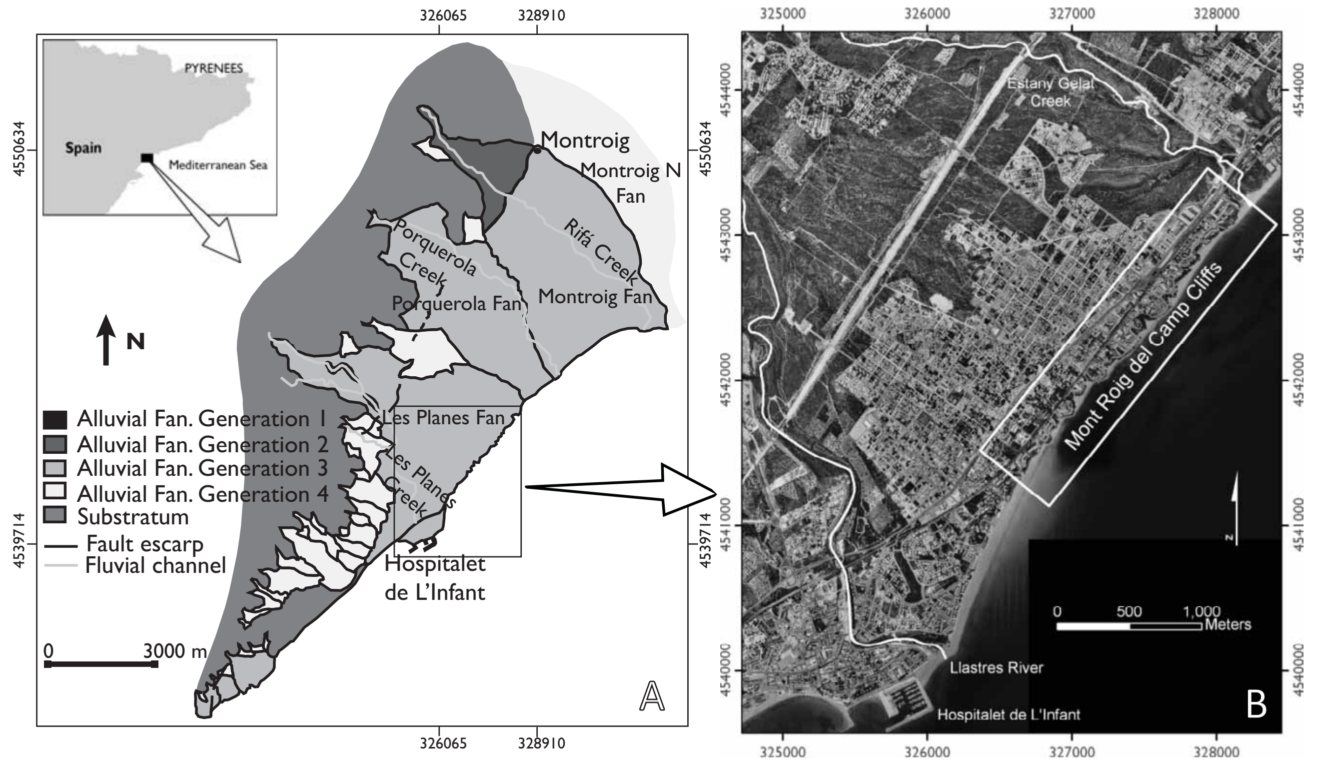


FIGURE 1 | Geomorphological map A) (modified from CSN, 2001) and orthophotograph (ICC, 2006) B) with the location of the study area (white box).

even some small lenticular bodies (Fig. 2C). The sharp and straight contact between the clays and the conglomerates, especially within unit C, is evidence of a period without any deposition. Moreover, certain levels present undulated and erosive contacts.

Masana (1995) concluded that this area underwent tectonic deformation during the Pliocene and the Quaternary from geomorphologic, tectonic, and paleoseismic indexes. The maximum compression axis was oriented from NNE-SSW to ENE-WSW during the Pliocene and changed to an orientation that varies from N-S to NE-SW during the Quaternary. This geologic evolution explains the position of mountain ranges and faults and agrees with the main joint orientations measured in the study area (Montoya, 2008): N10E, N70E, and N150E.

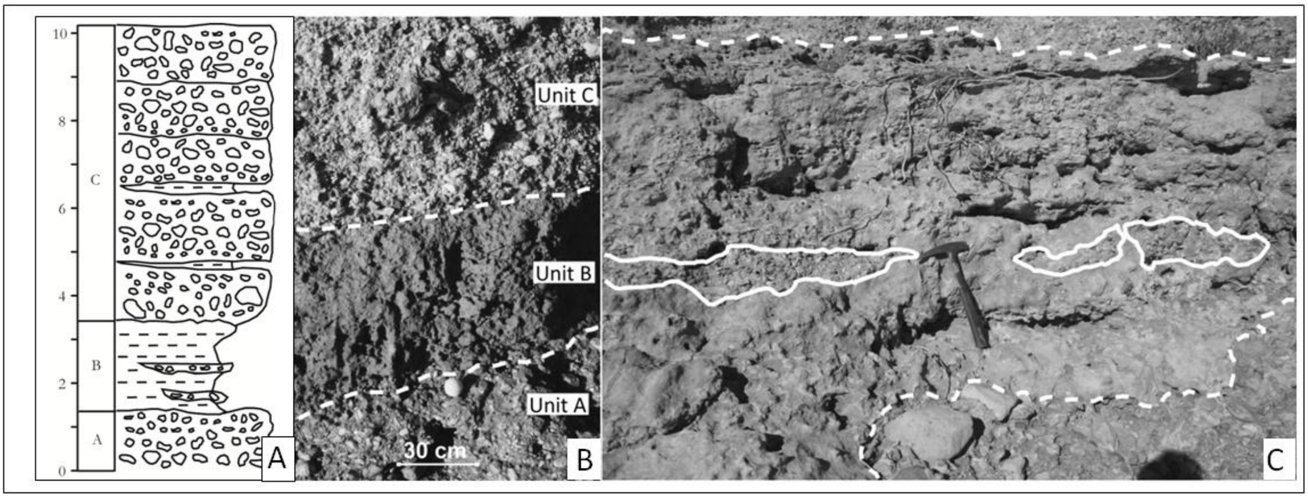


FIGURE 2 | A) Schematic stratigraphic column of sediments that form the cliffs. B) Sharp contact between clays (unit B) and conglomerates (units A and C). C) Characteristic distal alluvial fan facies (unit B) with lenticular bodies of thick material inside finer lithologies.

Streams and gullies are prominent features in the study area, which experiences the typical torrential rainfall of the Mediterranean. This storm events causes high runoff rates and floods (López-Bermúdez and Gomáriz-Castillo, 2006), and soil erosion during the flood events supplies large amounts of sediment to the coast. The area experiences moderate temperatures (15.5 to 17ºC) and an annual rainfall between 500 and 600mm. Rainfall occurs mainly during spring and autumn, with September being the rainiest month (Catalonian Meteorological Service, 2008).

Mediterranean coasts are microtidal, and the tide regime in the study area ranges from +50cm to -30cm (data from Cambrils port). The wave regime shows three predominant wave approach directions: E, S, and NW. The shoreline orientation indicates that the cliffs of Mont-Roig del Camp are mostly exposed to waves from the E and S, which also have the longest fetches (Jiménez *et al.*, 2000). The general bathymetry in the study area exhibits a narrow and steeped shelf in contrast with the broad shelf at Ebro Delta (Fig. 3).

At present, the top of the cliffs is densely developed (Fig. 1B), as a result of tourism during the summer. The base of the cliffs has a mixed character, with active zones alternating with inactive zones, because of the presence of several narrow pocket beaches, which are intensely used for recreation from June to September. The local government has established certain restricted areas because of rock fall hazards affecting the beaches as a consequence of high levels of weathering and degradation. Several studies related to littoral dynamics (Jiménez *et al.*, 2000; Mendoza, 2008), paleoseismicity (Masana, 1995; CSN, 2001; Perea *et al.*, 2003), hydrology (López-Geta *et al.*, 1989), and coastal management (MMA, 2002; HIDTMA, 2002; Villanueva and Galofré, 2002; Galofré, 2005) have been conducted in this area. However, none of them included an analysis of the possible factors that contribute to increases in cliff front weakness.

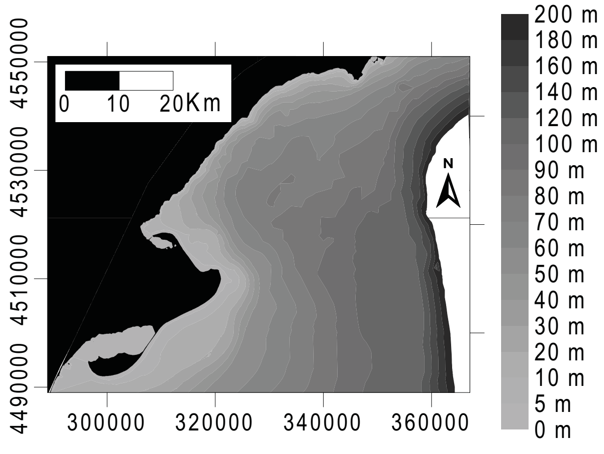


FIGURE 3 | Bathymetric map of the study area (white box) and location of the Tortosa buoy.

MATERIALS AND METHODS

The procedure to design the landslide susceptible map is based on the knowledge of the factors that cause instability in the study area. This heuristic approach is valid in zones with homogeneous conditions and of a medium scale (González de Vallejo *et al.*, 2002). The following steps have been completed: i) identification of factors causing instability, ii) assignment of values to each factor according to its contribution to the cliff instability, iii) weighting matrix generation with factors ordered and weighted according to their influence in the landslide formation process (Carrara *et al.*, 1995), and iv) establishment of a susceptibility map. Stages ii and iv were completed with ArcGIS software, which allowed the processing of information in addition to numerous analyses using different data combinations.

Identification of factors affecting the cliff stability

According to the geographic and geologic characteristics of the study area, the variables chosen to characterize the stability of the area include the following: wave exposure, shoreline variations, cliff height, cliff slope, geotechnical quality of the rock mass, superficial runoff, and cliff orientations favoring landslides. Each factor was rated in several classes depending on the influence of each factor in the landslide generation. Thus, classes with higher values will contribute to landslide occurrence in a higher grade than classes with lower values.

Wave exposure

To determine the wave exposure of the cliff, storm waves and run-up analyses were conducted. Wave data for a 17-year period (from 1990 to 2007) were obtained from the directional buoy located east of Tortosa (Fig. 3). From this database, 83 storm events were identified and classified according to the significant wave height (Hs) following the criteria of Mendoza (2008) for the Catalonian coast. The statistical analysis of these storms allows for the characterization of their typical ranges in approach direction, significant wave height (Hs), peak period (Tp) and frequency (Table 1).

The analysis of the wave propagation and impact for each approach direction was obtained by numerical simulations with the SMC software (GIOC, 2000), considering the bathymetry (Fig. 3) and defining three nested grids for each approach direction, with successive higher resolution coastward.

Several equations have been proposed to calculate the maximum elevation reached by waves over the emerged beach or wave run-up (*e.g.*, Iribarren and Nogales, 1949; Hunt, 1959; Holman, 1986; Mase, 1989). However, in this study, the more recent expression of Stockdon *et al.* (2006)

TABLE 1 | Typical values of storm wave events recorded in the buoy located eastward of Tortosa from 1990 to 2007

Approach direction	ENE to ESE	SSE to SSW	WNW to NNW
H_s (m)	2.5 to 4	2 to 3.5	2 to 3.5
T_p (s)	5 to 8	5 to 7	4 to 6
Events	1373	167	343
Annual frequency (%)	2.02	0.25	0.51

was used because it has been tested in a full range of beach conditions.

The topography of the pocket beaches was obtained using differential GPS (obtaining a total of 16,033 data values), homogenously distributed along the beach, with a distance of 1m between the profiles and with an accuracy of 25cm or less. These data were combined with the 1:10,000 digital map supplied by the Mont-Roig del Camp council to design the complete Digital Elevation Model (DEM) (cliff and beach) by the nearest neighbor interpolation method (Fig. 4).

Run-up was calculated using more than 53 beach profiles obtained from the DEM. Next, using GIS software, the elevation reached by sea water was represented on each beach profile. The areas where the wave run-up reaches the cliff toe during extreme storms were identified and mapped as active areas. According to the contribution of this variable in the cliff stability, an assignment of values for this factor was proposed, with a value of 0 assigned for no action of waves and a value of 1 for a cliff affected by waves.

Shoreline variations

Shoreline analyses at the medium/long term are commonly achieved through the comparison of aerial photographs from dates significantly separated in time, and with a similar scale (Moore, 2000; Cruz de Oliveira *et al.*, 2008; Lorenzo *et al.*, 2007). The comparison of aerial photographs taken in 1964 and 2003 allowed the identification of shoreline migration as a result of beach erosion and the accretion processes, which implies an increasing or decreasing wave exposure of cliffs, respectively. The assigned values to each class were a value of 1 for erosion, a value of 0 for equilibrium, and a value of -1 for accretion.

Cliff height and slope

From the cliff height data, obtained from the Digital Elevation Model, it was possible to digitize polygons along the slope with the value of the cliff top height in that portion of cliff. Next, to consider their influence in the landslide susceptibility, these polygons were ranked in five classes according to their height values: value 1 (h≤2m), value 2 (2<h≤5m), value 3 (5<h≤10m), value 4 (10<h≤15m), and value 5 (h>15m). Similarly, the slope map was reclassified into five classes: value 1 (0-20º), value 2 (21-35º), value 3 (36-50º), value 4 (51-65º), and value 5 (>65º).

Quality of rock mass

The quality of the rock mass was determined through the description of the rock matrix and discontinuities (field and laboratory), the resistance parameters calculation, and

FIGURE 4 | DEM of the cliffs at Mont-Roig del Camp. Pixel size: 1m. Orthophotograph base from ICC (2006).

obtainment of the quality indexes using geomechanical classifications.

In the first stage of the data acquisition during field surveys, the cliff front was divided into homogeneous sets, which were described geologically (Fig. 5). A detailed study of rock matrix properties (*i.e.*, lithology, surface alteration products, tectonic and sedimentary structures, fracture density, resistance, weathering degree, presence of water and sclerometer resistance) and the discontinuities (*i.e.*, type, dip direction, dip, spacing between joints, continuity, aperture, roughness, infilling) affecting the rock mass was conducted for each cliff front set. During a second stage at the geotechnical laboratory, 90 tests were conducted: a density calculation with mercury; the Point Load Test; and the Slake Durability Test.

Next, the resistance parameters were determined (*i.e.*, the angle of internal friction and cohesion), and finally, the quality indexes were obtained from the geomechanical classifications Rock Mass Rating (RMR) of Bieniawski (1989) and Q of Barton *et al.* (1974). Since lower quality values were obtained by the Q classification, this Q criterion was used. Next, the assigned coding to each class according to the Q values was as follows; value 1: excellent quality; value 2: good quality; value 3: moderate quality; value 4: poor quality; and value 5: very poor quality.

Surface runoff

The influence of surface water processes in rock weathering is determined through the calculation of the surface runoff flow following the method of MOPU (1990) modified by Témez (1991) and Ferrer (1993). This method has been applied to the different basins in the study area (Fig. 6), using the rainfall time-series (1994-2007) available for the Cambrils weather station.

The maximum surface runoff flow at the top of the cliff was estimated for different recurrence intervals and for a recurrence interval of 50 years. A value proportional to the contribution of every basin to the cliff stability was assigned: value 1 ($Q \leq 20m3/h$), value 2 ($20<Q \leq 40m3/h$), value 3 ($40<Q \leq 60m3/h$), value 4 ($60<Q \leq 80m3/h$), and value 5 ($Q>80m3/h$).

Cliff orientations favoring the landslides

The areas with the higher probability of potential fractures were defined to be more susceptible to cliff instability. Taking this into account and considering the pattern of preferred fracture orientation obtained from the characterization of the rock mass, different scenarios for probable planar and wedge failures

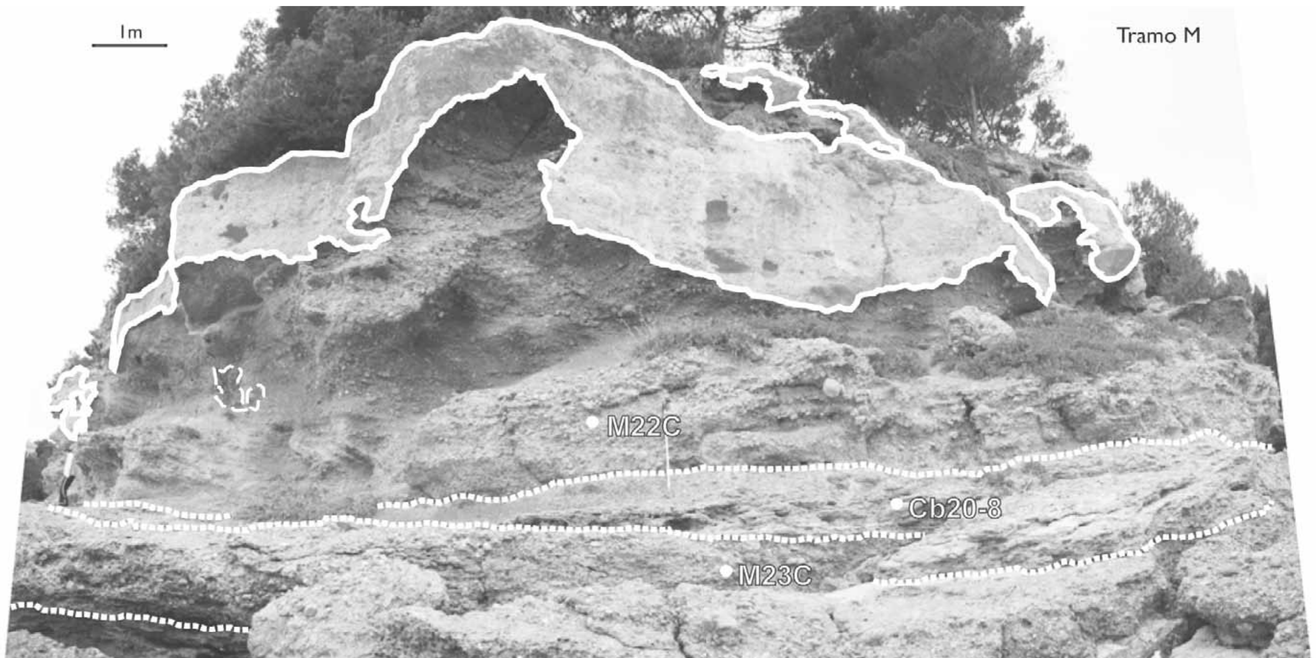
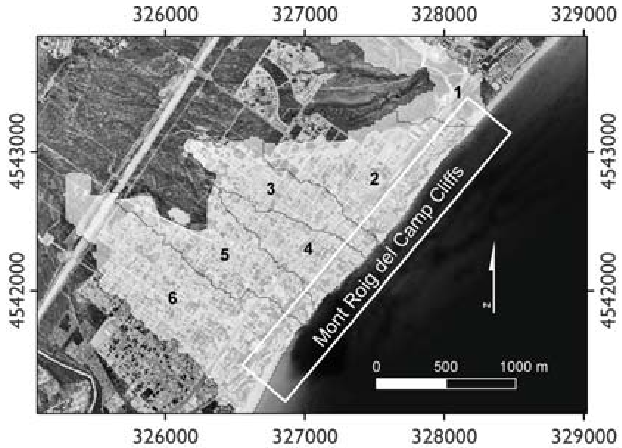


FIGURE 5 | Field scheme of the cliff front. The area covered by calcareous crust is shaded in grey. Dotted lines corresponds to contacts between different units. Location of rock samples is indicated.



Basin	Area (km^2)	Length (km)	Tc (h)
1	3.18	6.07	2.43
2	0.66	0.93	0.55
3	0.40	1.26	0.73
4	0.32	0.99	0.58
5	0.45	1.01	0.59
6	1.08	1.88	0.95

FIGURE 6 | Location of the studied basins and their main characteristics (area, length and time of concentration).

were simulated. From this simulation, the probable number of failures was obtained for the different orientations of the cliff wall. Therefore, the cliff orientations favoring the landslides were ranked into five classes, with values ranging from 1 (very low influence) to 5 (very high influence) according to the total number of potential fracture cases for each orientation (1 to 5 total potential fractures cases, respectively) (Table 2).

Variables weighting

The weighting of the influence of every factor affecting the cliff stability was obtained by the RES method (Hudson, 1992) to evaluate their interactions and avoid underestimating or overestimating any of the interactions. Therefore, a total of seven variables were analyzed and included in the diagonal of a matrix (*i.e.*, wave exposure, shoreline variations, cliff height, slope, quality of rock mass, surface runoff, and cliff orientations favoring the landslides; termed V1 to V7, respectively), in addition to the considered process *(i.e.*, cliff stability, V8). Next, the remaining cells of the matrix were filled according to the degree of influence between each two factors, with scores ranging from 0 to 4 depending on the influence (*i.e.*, null to critical, respectively).

The interactivity of each factor in the cliff stability was obtained as the addition of the cause (C; calculated as the sum of all the codings in the row) and effect (E; calculated as the sum of all the codings in the column) according to the Hudson's method. Therefore, this interactivity value for each factor, expressed as a percentage, corresponds to the weighted factor to obtain the susceptibility degree for the different areas of the cliff. (Table 3)

Computation of the susceptibility map

After the classification of the different factors and the definition of their respective weighted values, equation (1) was applied to obtain the landslide susceptibility values (S) as follows:

$$S=\sum fnWn/100 \qquad \text{equation (1)}$$

where f is the cliff stability factor value, defined by its influence on the cliff stability, and W the weighted value assigned to each factor f.

Land susceptibility (S) ranges from 0 to 5, allowin us to establish 5 different intervals: very low ($0<S\leq1$), low ($1<S\leq2$), moderate ($2<S\leq3$), high ($3<S\leq4$), and very high ($4<S\leq5$).

Spatial analysis tools in ArcGIS permit the multiplication of each layer of information by its corresponding weight and the addition of all the weighted maps to obtain the landslide susceptibility map. The obtained map allows the identification and classification of the different sectors of the Mont-Roig cliffs according to their landslide susceptibility value.

TABLE 2 | Potential fractures case according to cliff orientation. W=wedge failure; P=planar failure

Storm wave type		Frequency (%)	H_s (m)	T (s)	Duration (h)	Energy (kJ/m)	Return period (y)
I	Weak	50.68	2.46	5.9	14.78	$0.73\cdot10^5$	<1
II	Moderate	34.25	3.09	6.3	26.44	$1.82\cdot10^5$	1.18
III	Significant	8.22	3.83	6.8	19.17	$1.95\cdot10^5$	2.68
IV	Severe	4.11	4.47	7.1	49.67	$6.35\cdot10^5$	5.45
V	Extreme	2.74	5.73	8.15	39	$6.83\cdot10^5$	21.99

TABLE 3 | Interactivity and weight of factors favoring landslides on the Mont-Roig cliff

Potential failures	Cliff orientation							
	N	NE	E	SE	S	SW	W	NW
W 178 - 20	-	X	-	X	-	-	-	-
W 178 - 76	-	X	-	X	-	-	-	-
W 178 - 148	X	-	-	-	-	-	-	-
W 20 - 76	-	X	-	X	-	-	-	-
W 20 - 148	X	-	-	X	-	-	-	-
W 76 - 148	-	-	X	X	-	-	-	-
P-178	-	-	X	-	-	-	X	-
P-20	-	-	X	-	-	-	X	-
P-76	X	-	-	-	X	-	-	-
P-148	-	X	-	-	-	X	-	-
Total	3	4	3	5	1	1	2	0

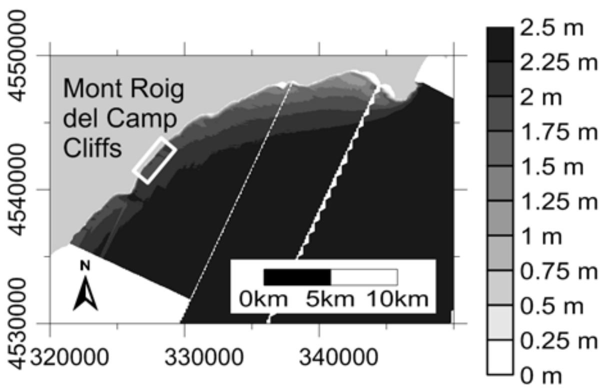


FIGURE 7 | Wave propagation for easterly storm waves (Hs=2.5m; Tp=6s).

RESULTS

Wave exposure

Easterly storm waves are clearly the most frequent, with a typical range of Hs from 2.5 to 4m and Tp from 5 to 8s, while storm events from the SSE to SSW, with similar or lower energy and Tp, are scarce (Table 1). Because of the position and shoreline orientation of the Mont Roig cliffs, the WNW to NNW storm waves recorded in the Tortosa buoy were disregarded in the following stages of this study.

Easterly storm wave characterization (Table 4) demonstrates that the most frequent storm waves are weak and moderate. As expected, all the analyzed parameters increase as the storm type increases in importance (higher wave height), except the storm duration, which does not show a clear relationship with the others.

The numerical wave propagation analysis demonstrated that easterly storm waves are also the most damaging in the study area (Fig. 7), and consequently, the calculation of the run-up was conducted for easterly storm waves, as they are the most relevant factor affecting cliff stability.

TABLE 4 | Main features of the storm waves approaching from the east. These parameters were calculated from the data available from the Catalonian Oceanographic Service

Factors	Interactivity (C+E)	Weight (%)
Wave exposure (V1)	21	15.00
Shoreline variations (V2)	17	12.14
Cliff height (V3)	12	8.57
Cliff slope (V4)	24	17.14
Quality of rock mass (V5)	25	17.86
Surface runoff (V6)	16	11.43
Cliff orientation (V7)	25	17.86
Total	140	100

Run-up values increase with slope and storm wave magnitude, ranging from 1.49 to 3.91m high. Combining these run-up values and the topography, the more active zones of the cliffs during extreme easterly storm waves are located in the headlands (Figs. 8A, 9A); however, active cliff zones also exist in the backshore of certain pocket beaches.

Shoreline variations

The Mont-Roig shoreline is in general stable; however, two sectors with a different pattern can be identified from the comparison of the 1964 and 2003 aerial photographs. The south-western sector (Fig. 10, beach profiles 1 to 45) has an average accretion rate of 0.4 m/y. In contrast, the north-eastern sector (Fig. 10, beach profiles 46 to 135) is mainly dominated by erosion in the headland, with an average rate of -0.2 m/y; however, the Mont-Roig shoreline also presents three short sectors dominated by accretion (Figs. 8B; 9B).

Thus, the map representing the influence of the shoreline variations to the cliff instability shows a positive contribution to the cliff instability in the headlands and a negative contribution in the southwest sector in addition to certain pocket beaches of the north-eastern sector (Figs. 8B; 9B).

Cliff height and slope

The cliff elevation is approximately 15m in the southwestern sector and decreases by 2m at the northeastern sector (Figs. 8C; 9C). Most of the talus slopes range from 20 to 50º (Fig. 8D; 9D). The steepest talus slopes (>50º) are located at the top of the cliff while the foot has a smooth slope. These results demonstrate the influential action of subaerial processes, as proposed by the Emery and Kuhn criterion (1982).

Quality of the rock mass

The rock mass that forms the cliffs at Mont-Roig del Camp appears notably fractured and weathered. The qual-

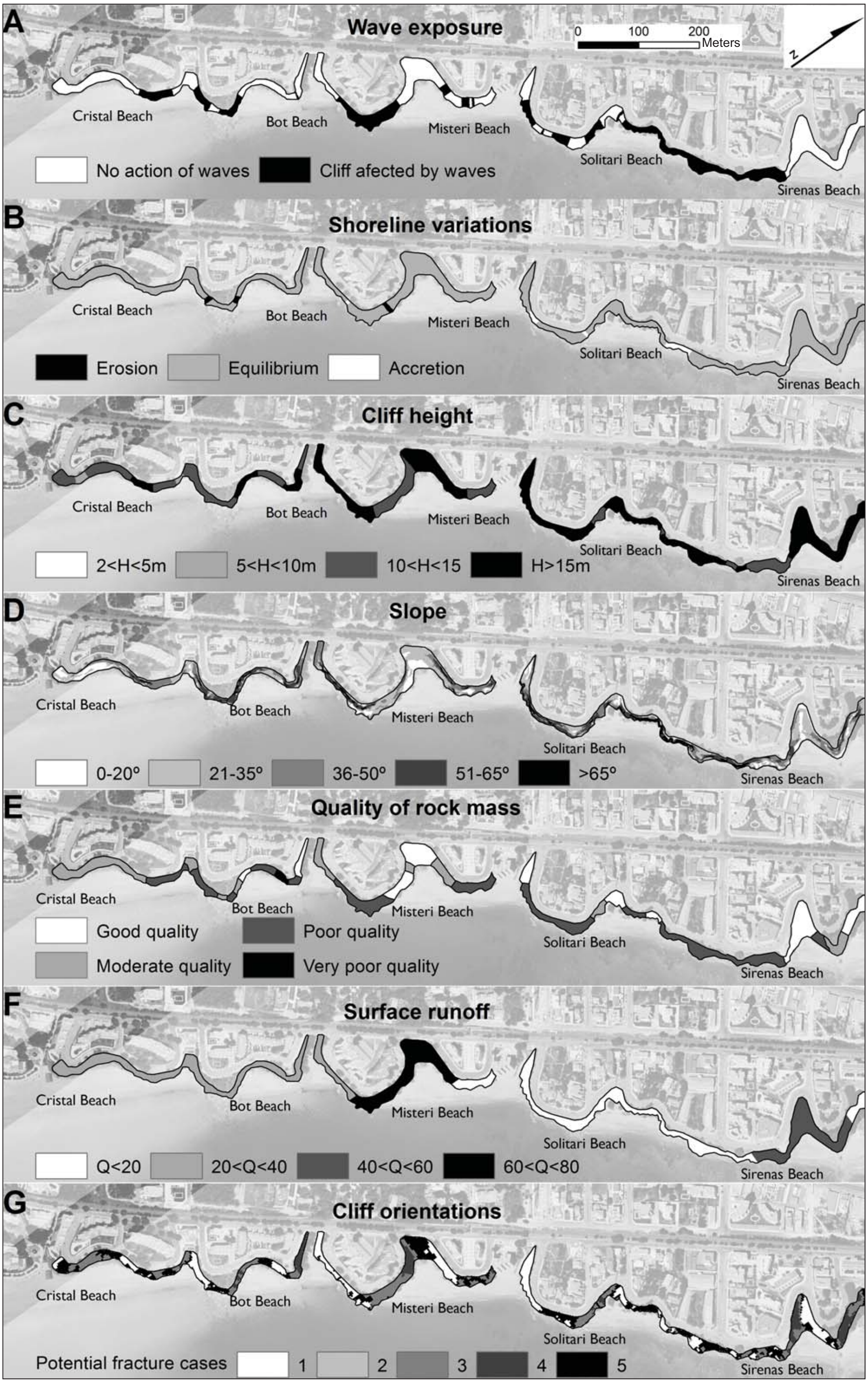


FIGURE 8 | Classified factor maps for SW coastal stretch: A) Wave exposure; B) Shoreline variations; C) Cliff height; D) Cliff slope; E) Quality of rock mass; F) Surface runoff; and G) Cliff orientations favoring the landslides. Orthophotograph base from ICC (2006).

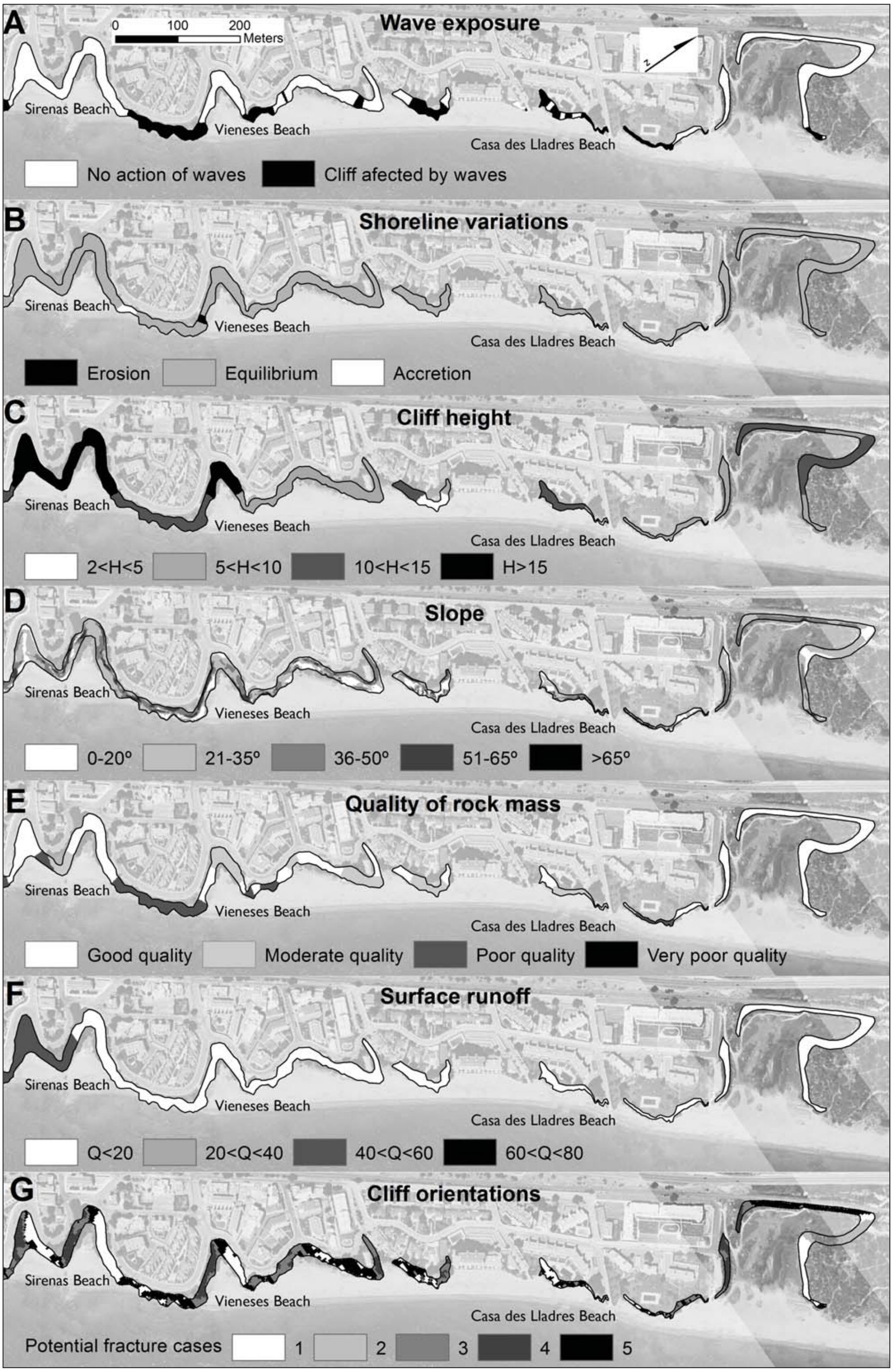


FIGURE 9 | Classified factor maps for NE coastal stretch: A) Wave exposure; B) Shoreline variations; C) Cliff height; D) Cliff slope; E) Quality of rock mass; F) Surface runoff; and G) Cliff orientations favoring the landslides. Orthophotograph base from ICC (2006).

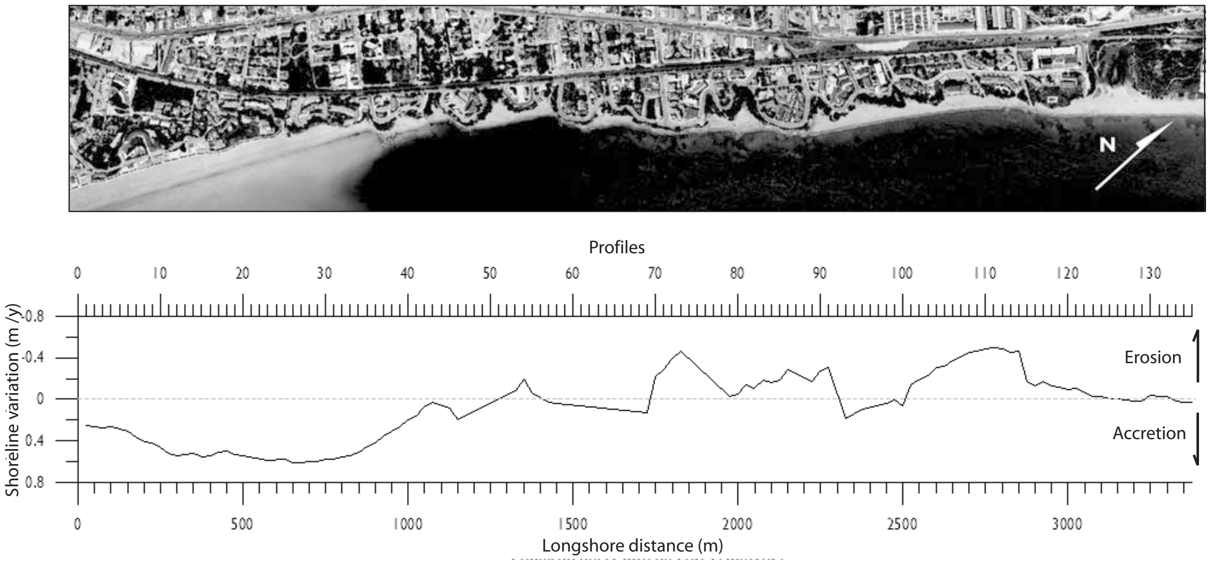


FIGURE 10 | Shoreline variations (m/y) for period 1964-2003. Orthophotograph base from ICC (2006).

ity of the rock mass in terms of geotechnical parameters (Barton *et al*., 1974) (*i.e*., strength of rock material, degree of jointing, condition of discontinuities, groundwater conditions, stress parameters) is moderate or poor in certain sections of the cliff wall, especially in the promontories, where rocky blocks of various dimensions appear (Figs. 8E; 9E).

Surface runoff

Basins 1, 2 and 4 exhibit the lowest surface runoff flow for a recurrence interval of 50 years (Figs. 6; 11). Basin 6 has moderate flow, and finally, basins 3 and 5 have the largest runoff flows. Thus, the basins were classified according to the previously established criteria: value 2 includes basins 1, 2 and 4; value 3 includes basin 6; value 4 includes basin 3; and value 5 includes basin 5 (Figs. 8F; 9F).

Cliff orientations favoring the landslides

The number and type of failure cases (*i.e*., W, wedge; P, Planar) for each talus orientation are indicated in Table 2. For example, the wedge failure between the joints trending N178 and N20 will only occur for talus oriented NE or SE. Therefore, it can be inferred that the SE and NE oriented taluses have the highest number of potential failure cases followed by the N and E oriented taluses, while the S, SW, W and NW oriented taluses are the least favorable to generate landslides. Thus different talus orientations show the same number of potential failure cases (*i.e*., SE and NE), and consequently, they have been classified and mapped with the same value of contribution to landslide failure (Figs. 8G and 9G)).

Weighting matrix

The weighting matrix designed for the study case of the Mont-Roig cliffs is shown in Figure 12. A detailed explanation of the criteria used for value assignment in this matrix can be found in Montoya (2008). According to this matrix, the quality of the rock mass (V5), the cliff orientation (V7), and the cliff slope (V4) have higher interactivity (C+E) than the other variables, and consequently, they have higher values in the weighting (Table 3).

The graphic representation of C versus E (Hudson and Harrison, 1996) indicates that the shoreline variations (V2)

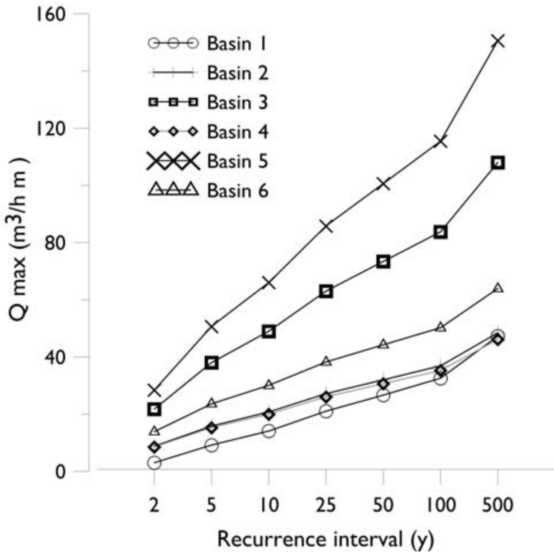


FIGURE 11 | Maximum surface runoff flow at the top of the cliff for different recurrence intervals and for each basin.

									Cause
	V1	0	1	2	3	0	3	3	12
	3	V2	1	3	3	0	2	2	14
	0	0	V3	3	0	0	0	2	5
	2	0	3	V4	0	3	3	3	14
	3	2	0	0	V5	0	4	4	13
	0	0	0	2	4	V6	3	4	13
	1	1	2	0	2	0	V7	4	10
	0	0	0	0	0	0	0	V8	0
Effect	9	3	7	10	12	3	15	22	81

FIGURE 12 | 8x8 weighting matrix with the interactions of the factors controlling the cliff stability. V1: Wave exposure; V2: Shoreline variations; V3: Cliff height; V4: Cliff slope; V5: Quality of rock mass; V6: Surface Runoff; V7: Cliff orientation; and V8: Landslides. Value 0: null influence; Value 1: Poor influence; Value 2: Moderate influence; Value 3: Strong influence; and Value 4: Critical influence.

and the surface runoff (V6) exhibit greater dominance than the other variables, followed by the slope (V4) and the wave exposure (V1) (Fig. 13). In contrast, the quality of rock mass (V5), the cliff height (V3), and, especially, the cliff orientation (V7), do not demonstrate a relevant dominance. The dominance of the factors V2 and V6 imply that they receive a lower influence of the remaining factors. This result can be explained because both V2 and V6 are related to processes that are independent from the intrinsic characteristics of the cliffs.

Susceptibility map

The landslide susceptibility map shows that, over a total of 42,700 m^2 at the Mont-Roig cliff, there is a clear prevalence of surfaces with moderate (61%) or low landslide susceptibility (33%), while areas with high (6%) landslide susceptibility are scarce (Fig. 14).

The highest landslide susceptibility is located at the top of the headlands, because they have the steepest slopes. Furthermore, most of these headlands are highly weathered because they are exposed to storm wave attacks, which are evident by the presence of many fallen blocks in the toe and basal undercutting, and the effect of surface runoff, which depends on the characteristics of each basin (Fig. 6). Finally, the effect of shoreline variations also influences the exposure or protection of these headlands to wave attack.

DISCUSSION

The landslide instability analysis usually employs a historical record of previous events to determine the hazard (Carrara *et al.*, 1991; Mateos, 2001; Gorsevski *et al.*, 2006; Budetta *et al.*, 2008,) and monitoring events that occur over the study period (Balaguer, 2005). Nevertheless, in this study, a historical record of previous events was not available, and the free access to the coastal area prevented the use of traps to determine the falling volume or similar techniques to monitor the current landslides. Therefore, the lack of data regarding the previous landslide distributions hindered the ability to apply probabilistic methods, as these methods are based on the relationships of each factor with previous and current landslides (Carrara *et al.*, 1995). Thus, it was necessary to apply the heuristic method.

The landslide and retreat cliff studies, either by probabilistic (Lee *et al.*, 2001), deterministic (Godt *et al.*, 2008) or heuristic methods (Nunes *et al.*, 2009; Budetta *et al.*, 2008) of hazard determination normally do not include a geotechnical and geomechanical characterization of the rock cliff. However, most of the studies agree that these analyses are necessary to obtain more accurate results. In cases with several lithologies, the properties of each material are commonly considered to classify the material resistance, according to tabulated values (Budetta *et al.*, 2008; Castellanos and Van Westen, 2008; Ruff and Czurda, 2008); however, the specific geomechanical properties of the outcrop and their spatial variations are not typically considered. In contrast, this study attaches the adequate importance to the classical geomechanical analysis, as a basic tool for cliff characterization.

Several limitations arose within the geomechanical study, including the difficulty to clearly distinguish joint families or to determine the resistance of notably heterogeneous materials (*i.e.*, conglomerates with a moderate to high

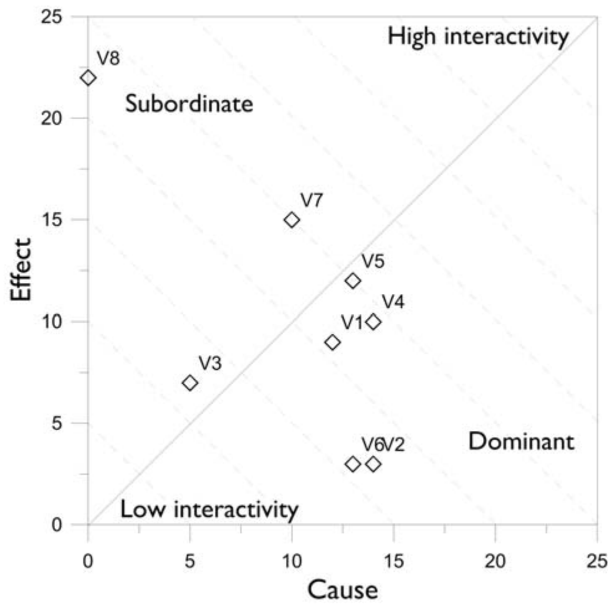


FIGURE 13 | Cause-Effect diagram. Dotted lines represent the interactivity contour lines (C+E).

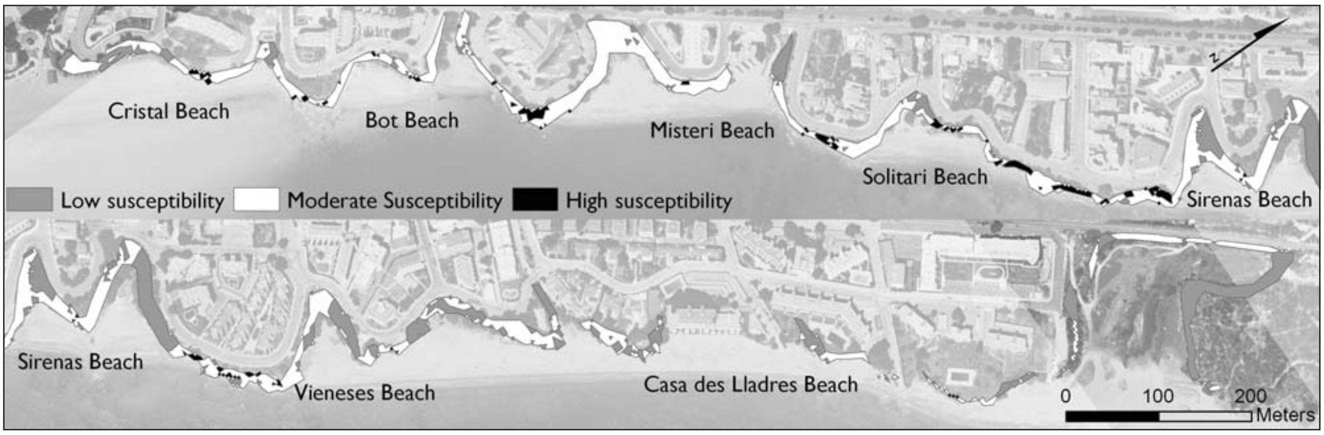


FIGURE 14 | Landslide susceptibility map. Orthophotograph base from ICC (2006).

degree of weathering, where it was necessary to validate the sclerometer fieldwork data with the PLT test in the laboratory). Despite these difficulties, the results of the rock mass characterization are essential to determine their parameters of resistance (i.e., angle of internal friction and cohesion) and consequently to delimit zones of good or poor quality according to the geomechanical classifications. Moreover, this analysis has produced geotechnical and geomechanical data of conglomerates, a scarcely documented material.

The relevance of the quality of the rock mass is also apparent in the multi-factorial analysis of the landslide susceptibility. Thus, this factor, together with cliff orientation, shows the highest influence in the cliff instability, according to their interactivity (Table 3).

This parameter is essential to determine the occurrence of planar and wedged slides, as a result of the critical parameter of the angle of internal friction along the joints, which is an intrinsic property of the rock mass. Furthermore, the quality of the rock mass also contributes to facilitating or impeding wave erosion, according to the resistance of the material. In contrast, the quality of the rock mass is also conditioned by other factors, including the presence of water due to surface runoff or the occurrence of landslides favoring the weathering process. The wave exposure and the shoreline variations also have a strong influence due to the basal cliff erosion, which modifies the rock's tensional state and consequently leads to the generation of new joints.

Following Emery and Kuhn (1982) and Trenhaile's (1987) criteria, through DEM analysis, the most important factor in reshaping the cliffs in the study area is the action of subaerial processes, while marine processes are less active.

Nevertheless, the discontinuous wave action is of great importance, and the possibility of rock falls during storms should not be disregarded (Blanco-Chao and Pérez-Alberti, 1996), because of the weathered and fractured cliff state in certain sections. The headland/beach configuration, in general, is related to the orientation of weakness planes (Blanco-Chao and Pérez-Alberti, 1996). The fallen blocks at the cliff front generate wave canals (Fig. 15) that locally increase water velocity. The combination of higher water velocity and a fractured, cracked cliff front results in the retreat of the cliff toe, which indicates that the coastal morphology is conditioned by structural factors.

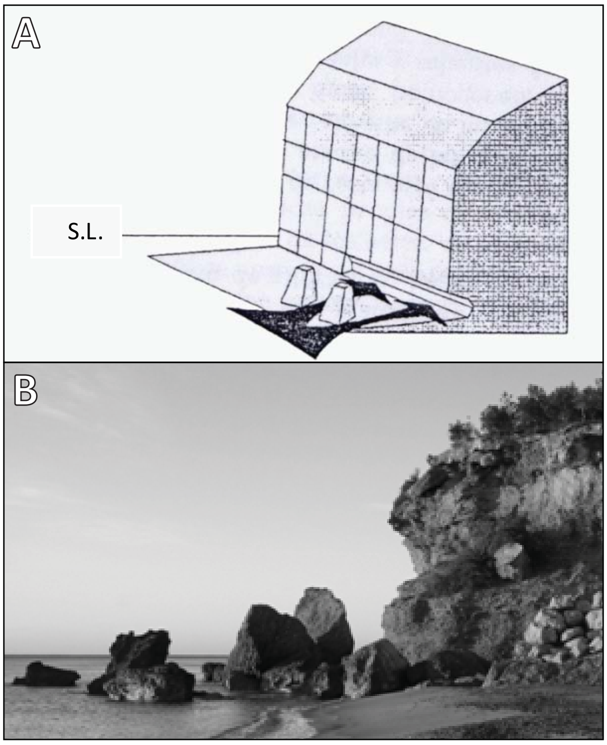


FIGURE 15 | A) Basal erosion in the sea-cliffs because of the presence of rocky blocks or rock fragments piled up in front of the cliff wall (modified from Blanco-Chao and Perez-Alberti, 1996). B) Rocky blocks at the Mont-Roig del Camp cliffs.

The promontories are affected by waves in addition to the adjacent areas and those protected by beach. This location of flooded areas can be observed in the map of areas affected by storm waves (Figs. 8A; 9A), which agrees with the storm wave flooding index proposed by Mendoza (2008) for the Catalonian coast. This author classifies the analyzed beaches at Mont-Roig del Camp as notably high-flooding grade ones, with two exceptions: Sirenas Beach, which is medium grade, and the area from Vieneses Beach to Casa des Lladres Beach, which is high grade. Our map shows that the flooded areas appear in the external zones at Sirenas Beach, reaching internal areas of the beach in the two other sectors (Figs. 8A; 9A).

Regarding the studies of rock falls, the typically applied techniques require long periods of field and laboratory work to characterize both the materials and the environmental setting (Jaboyedoff and Labiouse, 2003; Fall *et al.*, 2006; Lo *et al.*, 2010). One of the most important advantages of the proposed methodology in this study lies in its fast and easy application as a result of the availability of large amounts of geographic information accessible to all users and the development of systems such as GIS that provide the tools necessary to analyze this information. Therefore, the use of GIS in this type of study is essential and necessary to i) generate and manage the geographic database, ii) overlay information layers, iii) obtain topographic profiles at once, and iv) analyze the data spatially.

CONCLUSIONS

This work shows how, in landslide hazard areas where there is no historical record of previous events or an exhaustive monitoring cannot be performed, the application of heuristic methods is an effective alternative to evaluate the susceptibility of landslides. These methods allow the analysis of the combined influence of intrinsic and extrinsic factors to the cliffs themselves, which act as constraints and/or trigger the process. To assess the multiple interactions between different factors, it has been essential to define a weighting matrix, with specific values for this case study. Thus, according to the weighting matrix considered for the cliffs of Mont-Roig, the factors with the greatest interaction with other factors are the quality of rock mass (V5), the cliff orientation (V7), and the cliff slope (V4). However, highly dominant factors include surface runoff and shoreline variation.

The combination of the previous maps obtained for each factor by GIS tools, taking into consideration the weighting matrix, leads to the landslide susceptibility map, where it is possible to identify their spatial variations with a high resolution. Thus, the landslide susceptibility of the Mont-Roig cliff is in general moderate (61%) or low (33%); however, there are also zones with high (6%) landslide susceptibility. The highest landslide susceptibility is principally located at the top of the headlands in the central sector of the study area, as a result of their steep slopes. Moreover, most of these headlands are highly weathered by surface runoff and storm wave attacks, which are controlled by the shoreline variations.

Therefore, the surface runoff and the easterly storm wave attack are the main triggering factors. The morphology of the cliff profile indicates a predominance of subaerial agents, i.e., a significant action of surface runoff. Nevertheless, the intrinsic properties of the rock cliff are also the determining features of landslide susceptibility. The quality of the rock mass is, in general, moderate in all of the study area and consequently does not determine differences between sectors. In contrast, the cliff orientation and cliff slope variations, and the cliff height to a minor degree, are fundamental in determining the areas with high landslide susceptibility.

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