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HYDRO-GEOMORPHOLOGICAL EVOLUTION ANALYSIS OF A CLIFF

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EXTENDED ABSTRACT

Il presente articolo illustra un'analisi dell'evoluzione geomorfologica a medio termine di un tratto di costa alta, denominato "Ripe Rosse", situato nel Comune di Montecorice, una delle aree costiere a maggior pregio ambientale, naturalistico e paesaggistico del Parco Nazionale del Cilento, Vallo di Diano ed Alburni, a sua volta patrimonio mondiale dell'UNESCO. L'area, inoltre, è attraversata a monte da un'importante strada provinciale (ex S.S. 267) che costituisce un ulteriore elemento di rischio in quanto rappresenta l'unica arteria di collegamento lungo la dorsale Nord-Sud in un'area ad alta densità turistica. Negli ultimi anni (dal 2010), infatti, il tratto in questione ha evidenziato un notevole incremento delle condizioni di rischio idrogeologico legate sia alle modificazioni antropiche del versante a monte della stessa strada provinciale (ex S.S. 267), sia ad un tipo particolare di evoluzione geomorfologica gravitativa a breve e medio termine comune ad altri tratti costieri del Cilento. Pertanto, risulta evidente la necessità di mettere a punto quanto prima una strategia integrata volta a salvaguardare il sito e a prevenire danni alla strada. Per prima cosa, quindi, è stato condotto uno studio preliminare finalizzato alla definizione delle principali caratteristiche geologiche e geomorfologiche delle aree in esame. Tale studio, basato sia su dettagliati rilievi di campo, sia sull'analisi della cartografia disponibile risulta indispensabile per acquisire informazioni riguardanti la predisposizione del versante oggetto di studio e sulla sua tendenza a generare frane che per il tipo di conformazione della costa risulterebbero essere di tipo rapido e quindi estremamente pericolose. Nell'esaminare una costa alta, infatti, bisogna tenere ben presente che il suo aspetto attuale è il risultato di una lunghissima evoluzione (migliaia o anche centinaia di migliaia di anni); sarebbe sbagliata quindi una semplice correlazione tra gli aspetti visibili ed i processi attualmente operanti. L'analisi ha confermato che questo tipo di costa alta è particolare, segue infatti il modello di evoluzione denominato "slope-over-wall". La genesi è in generale attribuibile alla risalita del mare olecenico, successiva all'ultima glaciazione. A causa delle oscillazioni glacio-eustatiche, la costa alta ha subito quindi un prevalente modellamento ad opera del mare durante i periodi interglaciali ed un modellamento subaereo (non marino quindi) durante i periodi glaciali. Da ciò si deduce che anche le variazioni climatiche hanno giocato un ruolo fondamentale nella genesi ed evoluzione, determinando un'alternanza di situazioni erosive ora marine, ora continentali, che si sono espletate con modalità differenti. Successivamente, sulla scorta del modello di evoluzione geomorfologico ottenuto, è stato effettuato un approfondimento di carattere ingegneristico tramite l'applicazione di un modello numerico di evoluzione della falesia. A tal fine è stato usato il software SCAPE (Soft Cliff And Platform Erosion) che, differentemente da altri software simili, offre la possibilità di poter considerare qualunque conformazione iniziale della linea di costa (presenza o meno della parete verticale così come della spiaggia) ed inoltre permette di eseguire simulazioni su lunghi periodi (anche oltre mille anni). Inoltre SCAPE consente di considerare gli effetti dell'agitazione ondosa, delle oscillazioni di marea e gli innalzamenti del livello medio mare. A livello operativo SCAPE è quello che in gergo viene definito un modello "quasi3D", nel senso che la conformazione iniziale della costa è rappresentata con una serie di sezioni trasversali (schema bidimensionale) assemblate lungo una linea di base. Le varie sezioni interagiscono tra di loro solo attraverso lo scambio di sedimenti in direzione trasversale. Il tratto di costa analizzato, della lunghezza complessiva di 525 metri, è stato suddiviso in 21 sezioni trasversali della larghezza di 25 metri ognuna. Le sezioni sono state prese ortogonalmente ad una linea di base che è inclinata di 322.21° rispetto al Nord, mentre per la falesia si è assunta un'altezza iniziale di 10 metri. L'applicazione del modello numerico ha dato risultati confortanti su come la costa si potrebbe ritirare nei prossimi 500 anni, confermando in gran parte quanto già qualitativamente scaturito dall'analisi geomorfologica. I risultati del modello di evoluzione geomorfologica, confermati anche dal modello numerico, ribadiscono come nell'analisi delle coste alte non si può prescindere dal considerare anche le superfici costiere (versanti, falesie e fondali marini) sottostanti, superfici di erosione che si sono sviluppate nel tempo come risposta ad una serie di eventi di importanza regionale e globale, riferibili a tettonica, eustatismo e clima.

ABSTRACT

The paper illustrates a mid-term geomorphological evolution analysis of the cliff called "Ripe Rosse", one of the most important rocky coast geosite in the Cilento, Vallo di Diano and Alburni UNESCO Global Geopark. Specifically, the study aims to define the main geological and geomorphological characteristics of the areas in question. High coasts are usually the result of a very long evolution (thousands or even hundreds of thousands of years). This type of high coast is particular, it follows an evolution model called "slope-over-wall". During the last decades, frequent and high-intensity landslide events have induced a significant increase in the risk especially along the unique state road connecting all touristic villages in Southern Cilento Coastland. In particular, in order to better identify integrated strategies to both preserve the geosite and prevent road damages, the geomorphological study has been supported by orientated numerical engineering modelling SCAPE (Soft Cliff And Platform Erosion). The application of the numerical model has given promising results on how the cliff will retreat in the next 500 years and therefore on how to mitigate the risk according to special value of the site.

Keywords: cliff, Ripe Rosse, geomorphological evolution, numerical model, SCAPE.

INTRODUCTION

The literature about the rocky coasts is very limited despite 23000 km of such coast borded the Mediterranean sea (Furlani *et alii*, 2014) and is less numerous than that dedicated to the low and sandy coasts. Moreover, many Mediterranean rocky coastal areas are affected by geomorphological events such as accelerated upslope cliff retreat due to the waves or cut-slope and forest fire (Valente *et alii*, 2017). The consequences of these processes are the significant increase in danger and risk to settlements, infrastructure, buildings and tourist structures (Barbarella *et alii*, 2019). To preserve the integrity of this natural heritage, studies on geomorphological evolution of a particular rocky coast have being performed, based on detailed field surveys, multi-temporal aero-photogrammetric analyses supported and validated by numerical engineering modelling. These models, which simulate the future evolution of the coastal dynamics, can allow the better managements of the rocky coasts and preserved them against the man action.

THE STUDY AREA

The study area is the coastal stretch of Montecorice, in the southern part of Campania Region, lies between the Rio Arena mouth and the Bay of Capitello. This stretch of coast, named "Ripe Rosse" (Fig. 1a), has an extension of about 2 km and an height between 2 and 10 m. "Ripe Rosse", with its steep cliff which reaches quite rapidly the sea, is one of the most representative stretches of coast in the area. An important road crosses the highest part of the slope (Fig. 1b).

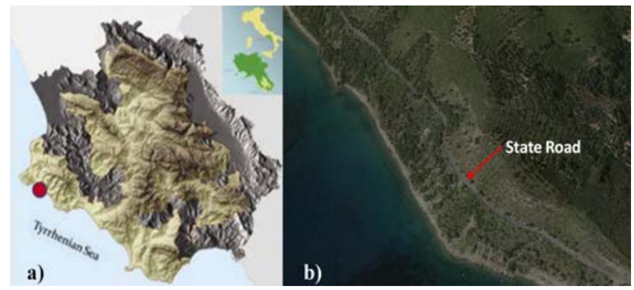

Fig. 1 - Ripe Rosse cliffed coast in Cilento, Vallo di Diano and Alburni Geopark. LEGEND: a) location of study area (red circle); b) State road crosses the highest part of cliff.

Both northward and southward, at the end of it, sandy beaches are developed where detritus of all sizes have accumulated in a rather narrow stripe. This accumulation is indicative of the numerous falls of the rocks constituting the cliff.

Ripe Rose is composed by a geologic successions originated by typically deep sea deposits (turbidities), composed by a succession of coarse and medium sandstone beds, grading upward into finer sand, silt and mud. Laterally to these successions, a thin bedded turbidities occur, intercalated by chaotic beds (Cocco *et alii*, 1986; Cavuoto *et alii* 2008; Guida & Valente, 2019). These successions outcrop below the formation of Cilento Group, at the northward base of the cliff (Cocco *et alii*, 1986; ISPRA, 2015). These geologic formations are influenced by erosion and rock falls processes along the cliff, where the loose sediment of all sizes have accumulated at the foot of the cliff as a beach, or in concavities of the slope as well as at the base of the slope. Cocco *et alii* (1986) and Aloia *et alii*, (2018) , made up the geomorphology map of the Ripe Rosse cliff where it is recognized that the beach deposits has a width from 2 to 4 m. The cliff is constituted of a moderate slope of 40° in the upper part, connected to a steep slope (80°) in the basal cliff that reach the sea with a very gentle slope of the coastal platform.

Since the periglacial times, a succession of diverse geomorphologic processes have affected the actual landscape of the cliff. The slope was generally subject to the erosive action of waves and the weathering process causing several slides (falls, topples and rotational slides). Instead, in the northern part, the coastline, degrades to the sandy beach, with an angle less than 45°. The gentle slope is due to the slope decline process occurring in this reach of the coast, because this process acting the erosion of sediments (debris and products of the alteration of the substrate up to its base) in the upper slope and the deposit of them at the base of the cliff, allowing a regularization of the slope. Studies performed by the Geopark management on the historical aerial photos highlighted the occurrence of landslides since 1943. The mass movements are still in action on the cliff for the slope evolution caused by a composed geomorphologic processes. This condition, put into the risk the stability of the unique state road (Fig. 1b) connecting all the touristic village of the southern Cilento coastland at the top of the slope as well as the value of this geological site that is a UNESCO heritage

EVOLUTION MODEL

A detailed study was developed to understand the evolution of the coastal stretch of Montecorice. The presence of a soft rocks with a lower resistance to the erosion, allowed, since the past, the action of the subaerial processes along the slope and waves erosion at the foot of the cliff. Since the past, the composite processes influenced the geomorphologic shape of the actual coast, that is composed of a convex shape in the upper part of the slope where the weathered materials appear and a vertical wall in the lower part, where there is the unweathered rock. The conformation is typical of the well know "slope-over-wall" profile (Figs. 2 and 3) and, as widely shared in the literature, this vertical cliff may correspond to an evolution of fault plane (Bird, 2000; Trenhaile, 2010).

It can be identified the time evolution of the "slope-over-wall" in the schematic evolution model shown in Fig. 3, starting by a regularized slope until to a falesia in the evolution phase. The first area represents the slope where the original "slope-over wall" model is preserved and, on the morpho-evolutionary changes knowledge, it represents the first phase of the erosional processes. The second is the intermediate sector where the original cliff is fragmented by gullies and ravines affected by erosive and flow processes triggered by shallow retrogressive landslides. The third sector, progressively affected by active, reactivated and deep seated landslides, is the spatio-temporal expression of the definitive gravity-driven evolution of the coastal slope. At the high part of the slope the ridge that was parts of the ancient surface subject to the marine abrasion is identifiable (Barbarella *et alii*, 2019).

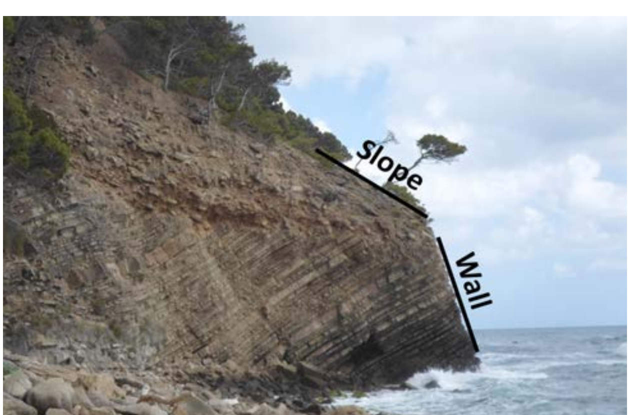

Fig. 2 - Ripe Rosse with its typical "slope-over-wall profile".

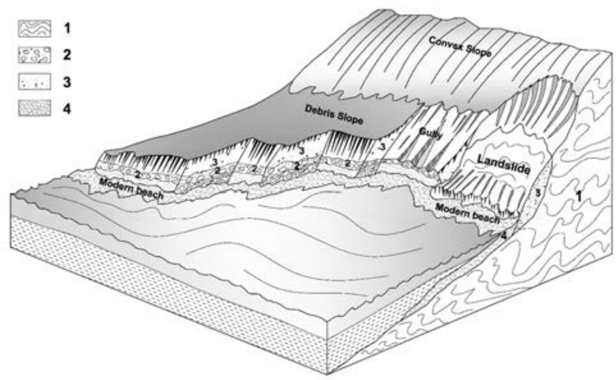

Fig. 3 - Typical evolution of "slope-over-wall" profile. LEGEND: 1. Deformed substratum; 2. Solifluction deposits; 3. Debris slope deposits. 4. Modern beach sediments.

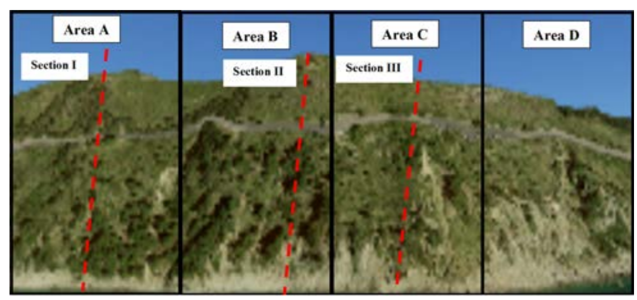

Fig. 4 - Identification of the four areas with different advanced phases of erosional processes.

Following the "slope-over- wall" evolution model, in the Ripe Rosse coast can be indentified four areas with a different advanced phases of the erosional processes (Fig. 4).

The coastal reach is divided into four morphologic areas with a different time step evolution of the geomorphologic processes acting along the coast:

A) area A is detectable as a coastal slope that sloping towards the coastal alluvial plain exhibit its basal level at the plain;

B) area B is a coastal reach in evolution sloping towards the recent beach and dune. Its evolution is affected by the action of storm waves of high intensity. The nail of the slope is composed of colluvial debris and landslides heaps;

C) area C is interested by the "slope-over-wall" process. This slope is constituted by a upper zone where the erosional debris, produced by rainy event, slipping on the basal cliff whose evolution is conditioned by undermining by storm waves.

D) area D is a time evolution of the area C. In this area the summit free face is interested by a recession process. A combined landsliding processes occurred on the slope.

Figures 5 and 6 show the representative profile respectively of the areas A and B derived by the Lidar Dem map that was acquired from an aerial platform, with a ground resolution of about 2 meters, by the Ministry of the Environment and Protection of Land and Sea within the project PON MAMPIRA (National Operational Programme 'Monitoring of marine protected areas affected by environmental offences').

The terrain profile I was related to the section line drawn on the map of the zone A. The advanced geomorphologic processes give to the profile a typical triangular shape. The same profile reveals both the presence of roto-translational landslides tracers and the detachment crown with its accumulation area since 1943. The profile II, representative of the area B, has also a triangular-trapezoidal facets because of a advanced erosion processes. The highest part of the profile shows the coastal relief ridge that was subject, in the past, to the ancient marine abrasion. On this part of the coast are highlighted roto-translational landslides traces, as for area A, with a high presence or tock landslides and free face slope replacement processes non yet regularized. The foot of profile is stabilized thanks to the dune and the beach formation.

Figure 7 shows the profile III, characteristic of the area C where the cliff is yet in evolution due to a "slope-over- wall" process.

Evolution process is still active in this area and the hatch line highlights the original cliff profile when, about eighty thousand years ago, the sea level was 130 meters below the current sea level.

At the medium and long term evolution model the cliffed

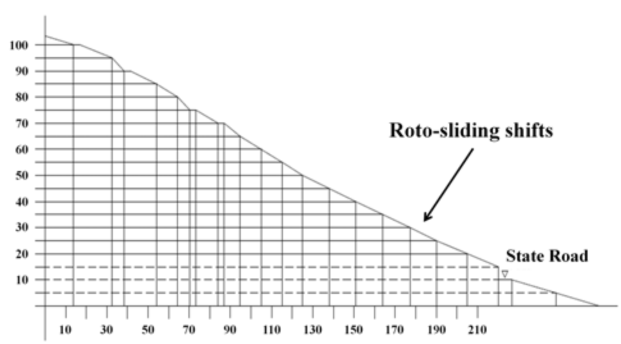

Fig. 5 - Cross profile representative of the area A.

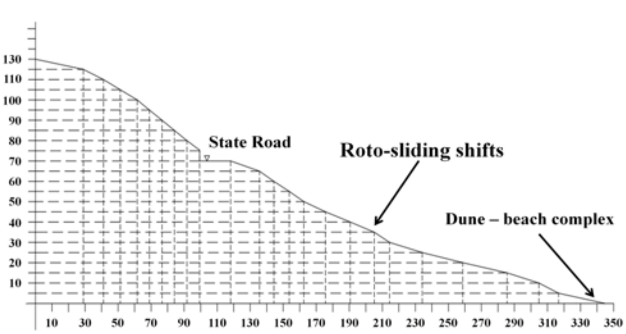

Fig. 6 - Cross profile representative of the area B.

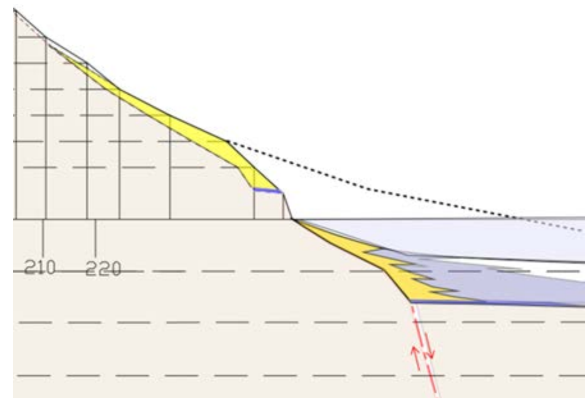

Fig. 7 - Cliff evolution profile for area C.

toe slope was progressively modelled by pure slope retreat mechanism due to the post-glacial sea level rising until present time. These processes, typical of the Pleistocene times when the sea level was lower, degrade the coast by periglacial freeze-and-thaw actions resulting in solifluction, forming coastal slopes that are then undercut by marine erosion. This process is still active on high latitude coast, where, since the past, the down-slope movement of frost-shattered rubble, generated a slopes cliff covered with angular gravel deposits extended out on the recent sea floor in a broad, diminishing apron. In the recent milder climate, these coastal slopes became vegetated and the sea waves is still undercutting the slopes.

NUMERICAL MODEL

In order to verify the qualitative reconstruction of the coastal geomorphological evolution, the numerical, physically based model SCAPE (Soft Cliff And Platform Erosion) has been used. SCAPE was developed to represent the mesoscale evolution of cliffed coasts. Its development began at Bristol University in 1999 and was first time applied to model the Naze peninsula (UK) site (Walkden & Hall, 2005). Key strength of that work included:

• good representation of shore profile emergence despite the use of quite abstract descriptions of the involve processes;
• a long term (50 years) prediction time frame;
• the representation of the effect of structures (groynes, seawalls, and hard points);
• the explicit representation of sea level rise;
• short run times and probabilistic application.

Following this success, SCAPE was used with excellent results to model the coast of North Norfolk (Walkden & Hall, 2011) and two sites (Warden Point on Isle of Sheppy and Easington) as part of the Management of Cohesive Foreshores project, (Defra/ EA, 2007, Cooper *et alii*, 2007). In 2008 SCAPE was used within the Defra/ Environment Agency R & D project Characterisation and prediction of large scale, long-term change of coastal geomorphological behaviours in a proof of concept to explore the coupled behaviour of an (hypothetical) open coast and estuary; the latter being represented by an ASMITA model (Walkden & Rossington, 2009). In recent years most applications have been largely commercial, and have included new models of the shores of Drigg (Cumbria), West Somerset, and the Wash. SCAPE simulations have also been used to inform work on coastal catch-up in the Clacton area.

The Environment Agency project Cliff and Shore Sensitivity to Accelerated Sea Level Rise used the SCAPE model in various ways, including modelling (in 2D) of the shores of Holderness

(unsuccessfully), Nash Point (Glamorgan), Birling Gap (Sussex), Happisburgh (Norfolk) and Drigg (Cumbria) (Walkden *et alii*, 2015).

Unlike other similar software, SCAPE offers the opportunity to perform simulations over long periods (even over a thousand years) and to consider any initial coastline conformation and different management scenarios (Ashton *et alii*, 2011; Walkden & Hall, 2011; Carpenter *et alii*, 2014).

SCAPE is a "quasi3D" model, in the sense that the initial conformation of the coast is represented with a series of cross sections (two-dimensional diagram) assembled along a baseline and interacting with each other through the exchange of sediments. For "Ripe Rosse" we used 21 sections, each one spaced 25 m, perpendicular to the baseline for a total length of 525 m. Baseline is oriented at 322.21° respect to North (Fig. 8).

From a strictly operational point of view, SCAPE needs a setup file, called "setup.txt", in which there are a series of keywords followed by the relative values. Some of these keywords are mandatory (such as "STARTYEAR", "ENDYEAR"), others may be omitted, in this case default values will be assigned. In addition to the "setup.txt" file, input includes other text files describing sea wave conditions (significant wave height, wave period and wave direction), tidal levels, increases in the average annual sea level (sea level rise), annual sediment flow, sediment transport and accumulated annual volume. Every model time step input data are read from input files and the system state (rock profile, beach width, beach depth and nearshore wave conditions) is recalculated, wave conditions are assumed to be constant throughout a timestep, whilst water levels are assumed to vary sinusoidally.

The alongshore transport rate is calculated by using the CERC equation (Hanson & Kraus, 1989), so the definition of the CERC constant for each transversal section must be defined. These values are read from input file "cercConstants.txt".

In output SCAPE gives a series of text files including in particular the "log.txt" file which summarizes all the information relating to the performed simulation (year of beginning and end of simulation, the different input files used, the time interval with which the output data are provided) and any error messages.

RESULTS

The simulation has been tested for 500 years starting from 1st January 2018 and considering the hypothesis of a sea level rise of 1 mm/years on a 10 m high cliff. The vertical conformation has been defined with respect to a model base line in according to the scheme shown in Fig. 9.

Section Height, Beach Height, Beach Crest Level and Mean Sea Level are defined in the "setup.txt" file, for the simulation following values have been respectively assumed: 20 m; 5 m; 17 m and 15 m.

For the beach profile, SCAPE assumes that it follows a typical Bruun/Dean curve (defined by the parameter "brunnConst") and is defined in a similar manner to the consolidate profile.

Generally a beach is not needed across the whole vertical range of the consolidated profile, and so the parameter Beach Height defines its vertical extent.

The elevation of the upper limit of the Bruun profile is defined relative to the model base level by Beach Crest Level.

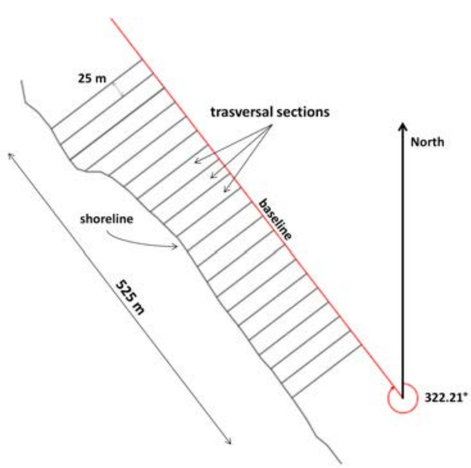

Fig. 8 - Sketch of cross sections for SCAPE model.

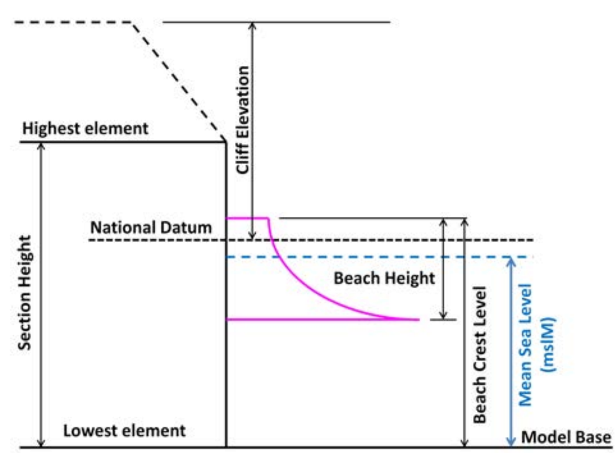

Fig. 9 - Conceptualisation of vertical conformation.

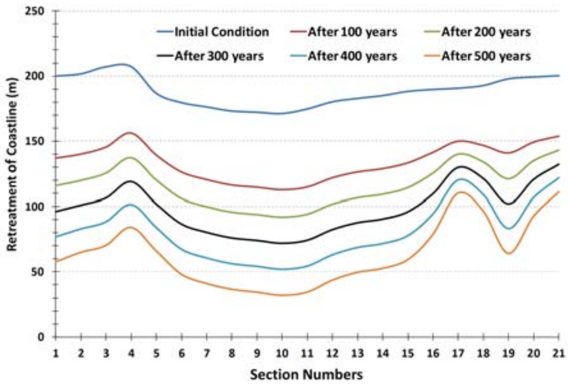

Fig. 10 - Contour retreatment (in plan) of "Ripe Rosse" cliff face at different time intervals as simulated by SCAPE software in the next 500 years in correspondence of the 21 considered sections.

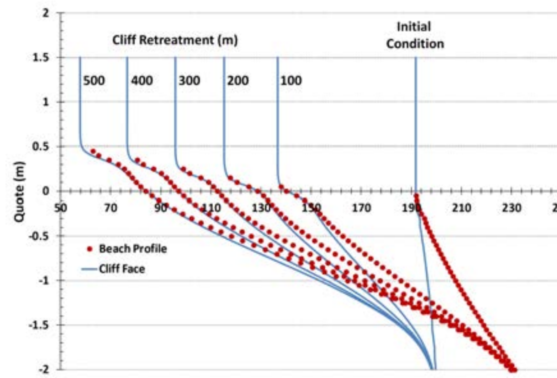

Fig. 11 - Parallel retreatment of the "wall"(blue lines) and landward shifting of the beach profile (dotted red lines) in the next 500 years simulated by SCAPE software.

The "brunnConst" is also define in the "setup.txt" file, in our simulations we fixed it at 0.2. It should be noted that no distinction is initially made between the cliff face and the shore profile; this boundary emerges through model iteration. The highest element is therefore typically set to be a small height above the expected cliff toe.

For wave and tidal conditions, values relative to year 2018, given respectively from ERA-Interim ECMWF (European Centre for Medium-Range Weather Forecasts) database and from Palinuro tide gauge, have been used. SCAPE simulations normally represent periods of time that are longer than the period for which wave data is available. When wave and tidal records are shorter than the simulation period then the code will read to the end of the "wavesAndTides.txt" file and then start reading again at the beginning. Wave transformation due to shoaling and refraction phenomena is calculated by SCAPE using classical linear wave theory.

Results along the modelled stretch are graphically represented both in plan (Fig. 10) and in representative profile (Fig. 11).

In Fig. 11 on the x-axis the retreatment of the cliff face (blue lines) are reported whereas on the y-axis are reported the emerged and submerged quote of the same coast. The vertical wall was assumed to have a height of 10 meters, but the effect was simulated only for the first meters. From the same Fig. 10 is evident how the wave erosion of cliff produces sediments that form the beach below.

The simulation shows clearly that the vertical basal part of the coastal slope recedes parallel to itself with uniform denudation intensity if the erosion processes are constant and the rock resistance is uniform. It is noted that the recession is facilitated by the progressive removal of the debris from the base of slope and the formation of a partially submerged accumulation (Cavuoto *et alii*, 2008). Unfortunately, it has not yet been possible to simulate the entire slope above the wall, however, as seen from the geomorphological reconstruction, the progressive withdrawal of the wall should intercept the threshold of the slope portion with the detrital material would accelerate the evolution of entire coastal slope. If this were to happen in hot-humid climatic conditions or under high anthropogenic pressure (slope cuts and wild fires) there would be an emphasis on the subaerial processes extended to the entire slope with a consequent evolution of the substitution of the slope shape. This evolution could entail the consumption of the top portion and therefore the shortening of the coastal slope.

The result of this evolution is the increase in risk to which the road would be subject, which is the only artery to reach the coastal resorts located southward.

CONCLUSIONS

The study carried out on "Ripe Rosse" has allowed to know in detail both the geological and the geomorphological evolution of this typical profile of rocky coast known also as "slope-over-wall". This profile was formed in rocks considered soft during the last cold phase of the Pleistocene and subsequently evolved to reach the current form. This evolution made it possible to hypothesize the conditions in which the site will be in the near future. Furthermore, a physically based modeling software (SCAPE) was applied which confirmed how qualitatively it had been imagined up to 500 years.

The estimate of the retreat of the cliff, as well as the possibility of the involvement of the convex slope with significant erosion phenomena, make possible a more sustainable choice of mitigation actions and thus be able to manage the risk without losing valuable environmental assets.

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