Qualitative assessment of the cliff instability susceptibility at a given scale with a new multidirectional method

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Abstract—This paper aims to present a new predictive method for the assessment of rocky cliff instability susceptibility at a given scale in carbonate environment. The method (CISA, Cliff Instability Susceptibility Assessment) entails in situ specific geomechanical and morphological surveys, laboratory geotechnical tests, analysis of meteo-marine data together with human-related variables controlling cliff recession potential. The first step of the method consists of the subdivision of the coastal stretch in sectors based above all on morphological and geological criteria. Then, according to an heuristic approach, 28 conditioning parameters were divided in four categories (geomechanical, morphological, meteo-marine and anthropogenic) and weighted on the basis of a multifactor spatial GIS analysis using physical geographically-based measures. For each parameter 5 classes of rating were proposed; the cliff classification, in terms of cliff instability susceptibility, was obtain from the total rating which represents the summation of the single rating of the individual parameter.

An application of the CISA method was here presented through a case study along the Murgia coastline South of Bari (Apulia, SE Italy). The stretch of coastline considered in this study is entirely in the territory of the municipality of Polignano a Mare, between the localities of *San Vito* and *Largo Ardito*; it is made up of cliffs, up to 20 m high, and shore platforms interrupted by small pocket beaches. The coastal outcrops consist of Mesozoic carbonate rocks, mainly white-greyish calcilutites well stratified and, moderately to highly fractured and karstified, which are overlain by massive Plio-Pleistocene calcarenites.

***Keywords*—**Cliff, Carbonate, Instability, Method.

I. Introduction

Although rocky coasts extend along about 80% of the world shorelines, most studies on coastal processes have been focused on beaches and sandy coasts [1]-[2]. One of the main motives of this board is due to the complexity of the morphodynamic evolution of the rocky costs resulting from the interaction of marine, sub-aerial and anthropogenic processes [3]-[4]. It follows the difficulty to estimate recession rates and predict mass failure processes or phases of intense erosion [5]. Furthermore, rocky coasts usually recede at very slow rates but sporadic high-energy events can cause sudden erosion of much higher magnitude than average retreat, in the form of different types of slope mass movement [6]-and references therein. It is not for nothing that mass movements have been recognized as critical processes within coastal cliff evolution [1]-[7].

In many sites of Apulia (SE Italy), the coastline is gradually receding inland as a result of natural and human processes. It deals with densely populated and, in some places, significant historic and tourist sites. The loss and damage to the public or private property and the natural hazards for the local population associated with coastal recession mechanisms is expected to increase over time, due to increase in frequency and magnitude of extreme storm events. Improving on this situation represents an important problem for local governments, considering its political and economic impact, although the vast majority of the public tends to underestimate the level of risk associated with coastal erosion, especially in rocky coast environment [8]-[9].

Present engineering and regulatory attempts to mitigate the problems associated with rocky coastal recession are clearly inadequate, because often these are not based on solid scientific approaches but rather on empirical practices.

Actually, many are the basic factors which play an important role in the assessment of the retreat mechanisms of the Apulian rocky cliffs and the mapping of the coastal stretches most susceptible to erosion is not a simple matter. In particular, the Apulian coastal morphology is closely linked to the tectonic setting and is strongly conditioned by complex mechanisms involving sea waves action against the cliffs, carbonation, weathering and urbanization pressure [3]-[10]-[11]. The dominant and more visible retreat process of the cliffs consists of slope mass movements of different types and sizes, which include rockfalls, topples and slides controlling by discontinuity pattern and density, and mechanical properties of the carbonate outcrops.

Different methods are adopted for determining potentially instable areas or landslide hazard assessments; these techniques can be divided into three groups: expert evaluation, statistical methods, and mechanical approach [12]-[13]-[14]-[15]-and references therein.

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Thus, considering advantages and disadvantages of these approaches and the complexity of this problem as well as its economical aspect, a new multidirectional method is proposed in this paper for assessing cliff instability susceptibility at a given scale (CISA, Cliff Instability Susceptibility Assessment). In order to highlight the role and relationships of factors and eroding processes affecting the morphodynamic evolution of rocky coasts in a typical Mediterranean coastal carbonate environment, a case study along a stretch of coastline of approximately 4.5 km, in the territory of the municipality of Polignano a Mare, about 20 km SE of Bari, is carried out (Fig. 1). The suggested method is based on the expert evaluation approach and is calibrated by morphological analysis, morphoevolutive models, geomechanical surveys, geotechnical laboratory tests, deterministic analysis (the estimate of the critical height for vertical cliffs using the lower bound theorem of limit analysis) and completed by GIS-based stability assessment and mapping.

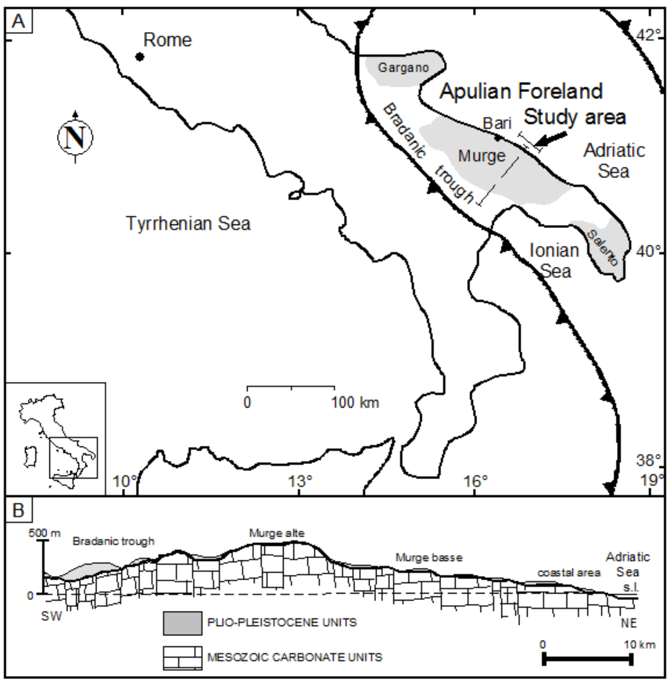

Fig.1. geographic location of the study area

II. STUDY AREA

The study site belongs to the Adriatic coastal area of the Murge plateau, an emerged part of the Apulian foreland, and is located about 30 km SE of Bari in the territory of the Municipality of Polignano a Mare, between the localities of *San Vito* and *Largo Ardito*. The Murge area consists of a carbonate region, slightly deformed by brittle structures, whose outcropping sedimentary succession is formed by 3000 m-thick Cretaceous shallow-water lagoonal and peritidal carbonates mostly deposited in low-energy inner-platform environments [16]-[17]. Only few stratigraphic intervals contain more open- and deeper-marine lithofacies in which abundant and diversified associations of rudists and benthic foraminifera can be found [18].

The prevailing morphologic characteristic of the Apulian coastal area is the presence of a series of marine terraces linked by small scarps subparallel to the coastline. These are carved by short erosive incisions (locally named “lame” and “gravine”) in simple catchments and watersheds that are difficult to recognise, as often occurs in karst areas [19]. The marine terraces develop on wide plains from about 150 m a.s.l. to the present sea level, maintaining a gentle slope to the NE, and give the southeastern side of the Murge a typical terraced profile. Sixteen levels of marine terraces have been distinguished in the Murgia area between sea level and 360 m a.s.l. These terraces were formed from the middle Pleistocene onwards, due to the superimposition of regional uplift and glacio-eustatic sea level changes [20].

The studied coastal stretch is characterised by the outcropping of two main formations: well stratified micritic limestones of the Calcare di Bari Fm. (Callovian *pp.*-early Turonian) are overlain by discontinuous calcarenite deposits of the Calcarenite di Gravina Fm. (upper Pliocene–early Pleistocene). The latter, mainly constituted by biocalcarenites, is transgressive on the former through an angular erosional unconformity and thin conglomerate deposits [16]-[17]-and references therein.

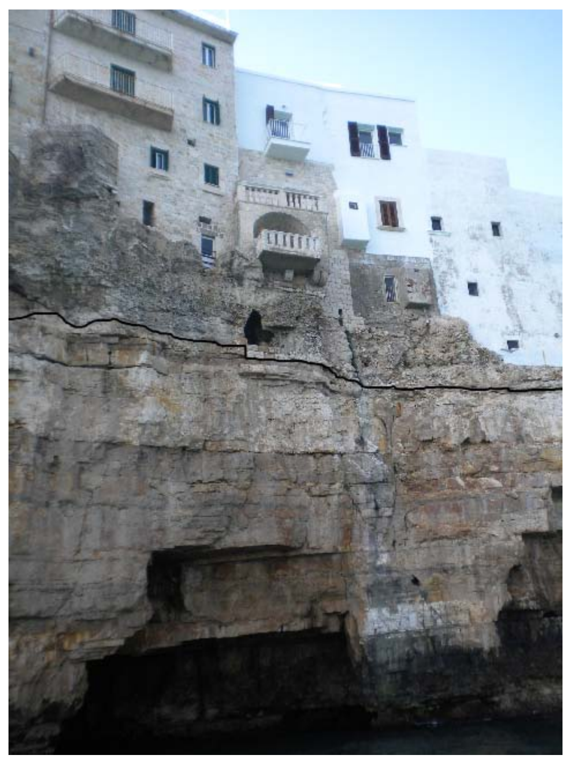
Fig. 2 appearance of the rock mass exposed along the coastal stretch of Polignano a mare. The black line indicates the stratigraphic contact between the Cretaceous micritic limestones and the overlying Plio-Pleistocene biocalcarenites

The Calcare di Bari Fm., locally, is of the Cenomanian age and consists of white-greyish micritic limestones (wackestones) and, in some places, of karstic breccias, followed at the top by Pleistocene calcarenites, wackestone–packstone in type (Fig. 2). The Mesozoic outcrops along the coast are clearly layered with bed thicknesses varying from 2 to about 100 cm; generally the limestone layers dipping gently seaward become progressively thinner upward. At places, local changes in the bedding attitude are due to folds and faults interpreted as the effects of transtentional and transpressional deformations.

The Calcarenite di Gravina Fm., here is made up of little cemented whitish or greyish coarse-grained biocalcarenites passing upward to medium-grained biocalcarenites. The bedding planes, gently dipping (5°) seaward and, locally, landward, at many places are recognizable with difficulty, so that the calcarenite outcrops assume a massive appearance [3]. The biocalcarenites contain lamellibranchs (*Pecten jacobaeus*), brachiopods, gastropods and calcareous algae, which occur in the form of shell beds rarely more than 0.2 m thick. Total thickness of the calcarenite unit varies from some mm to about 10 m; in particular, in correspondence of the historic centre of the city it is variable from 6 m to about 8 m. It deals with soft (poorly cemented) and porous calcarenites [21] [22]. The Calcarenite di Gravina Fm unconformably lies on the Calcare di Bari Fm. The lower boundary is transgressive and locally marked by reddish residual deposits (terra rossa) and/or by brackish silty deposits passing upward to shallow-water calcarenites rich in bioclasts [23].

Morphologic features along the Polignano a mare shoreline are typical of a tectonically uplifting area characterized by an indented rocky coastline where caps and inlets follow each other and steep cliffs, here from about 1.0 m (microcliffs) to 20 m in height, end in subhorizontal surfaces at the top and bottom. The study coastal area extends along 4.5 km, where pocket beaches are narrow and developed in correspondence of the inlets, and cliffs are cut in micritic limestones topped by biocalcarenites. These cliffs have notorious slope instability and evolve by different types of landslides, which are one of the main sources of risk in this coastal stretch. The area between *San Vito* and *Porto Cavallo* develops in weathered medium-grained biocalcarenites and is characterised by a uniformly sloping rocky coast with a low gradient and a slight seaward drop. In this area, it is impossible to evaluate the original width of the shore platform due to the proximity of engineering structures to the coast. A small bay cuts the whole area in two and is characterized by an eroding pocket beach formed by loose cobbles and coarse sand. Pocket beaches also form *San Vito* cove and *Santa Caterina* cove, the latter surrounded by a rocky cliff of 2.0 m in height; in both cases the pocket beaches are formed by loose medium and fine-grained sands. A gently sloping rocky coast also characterises the area between *Santa Caterina* and the tourist port. In particular, as far as *Porto Contessa*, the coastal profile is slightly concave while it is convex between *Porto Contessa* and the groyne of the tourist port. Uncontrolled urbanization also close to the shoreline and the presence of ancient quarries and artificial salt pans (man-made structures, which consist of small saline holes for the production of domestic salts on the backshore) have caused significant changes to the coastal environment and probably destroyed a microcliff of about 1 m, so that in some zones the original coastal morphology is not recognizable anymore (Fig. 3). Small ancient coastal quarries are also located along the marine cliffs where soft and porous medium-grained biocalcarenites crop out.

Fig. 3 sea level rise and human activity (ancient quarries and artificial salt pans) have favoured marine invasion and destroyed a microcliff of about 1m

After the tourist port, further to the S–SE, crossing a pocket beach with loose medium–grained sands and, in a few cases, cobbles, the rocky coast shows a steep plunging cliff, with a vertical and, in places, overhanging face. The cliff ends in subhorizontal surfaces at the top and bottom. The roof of the cliff lacks recent covering deposits due to wave splashing and weathering processes that are also responsible for rock mass decay. Cracking and breaking, due to salt crystallization and wetting/drying, and solution weathering, which dissolves pore-filling micrite matrix and sparry cement, represent the main processes that make the rock mass progressively pulverulent. Here, the cliffs range from 2.0 to 8.0 m in height and develop in medium-grained biocalcarenites of the Calcarenite di Gravina Fm. and, a little further S, in well stratified (from 0.2 to 0.5 in thickness) fractured fine-grained limestones (calcilutites) and karstic breccias, with red soil matrix, of the Calcare di Bari Fm. The lithologic contact zone is characterized by chaotic coarse-grained carbonate materials and by a surface dipping about 35° (295/35) a few metres from a large E–W right strike-slip fault in the calcarenite unit. Calcilutites dip seaward gradually from 15° to 45° towards the cliff edge suggesting a fold structure with a WNW–ESE axis.

The historical center of the city lies on a promontory overlooking the sea where the cliff reach its maximum height, about 20 m, and are well visible the stratigraphic relationships between the Calcare di Bari Fm. and the Calcarenite di Gravina Fm. The coastal sector which comprises the historic centre is not protected by retaining walls or other engineering structures. Between the historical center and *Largo Ardito* the rocky coast slopes down towards SE up to 10 m in height, in correspondence of a small promontory.

Sea caves and arches constitute the principal morphologic features of the study area (Fig. 4).

Fig. 4 sea caves and arches developed in karstic breccias (*Chiar di luna* cave)

Arches develop where the cliffs are composed of micritic limestones, while greater caves develop, favoured by a joint system, where biocalcarenites and breccias crop out. Most of the sea caves open in correspondence with coastal springs. In fact, the hydraulic base level of groundwater circulation corresponds to sea level. Several coastal springs drain groundwater along preferential pathflows where rock-mass permeability is greater [3].

Fig. 5 coastal karst morphologies: very well developed coastal karren on Cretaceous limestones on the most exposed part of the *Cala Paura* area

The study area exhibits unique karst landforms due to the influence of the marine environment, in which mechanical erosion competes with dissolution [10]-[24]. Between *Porto Contessa* and *Santa Caterina*, the shore platform shows small furrows, karst pits, potholes and coastal pans, the latter locally irregular due to the coalescence of a number of simple forms. The joint pattern, moreover, is emphasized by surface solution, which results in grooves, up to 0.30 m in depth. Between *Chiar di luna* and the historic centre of Polignano a Mare along the marine cliffs only the micritic limestones crop out; here common distinctive features of coastal karst are notches and coastal karren features. Notches that are due to the combination of grazing (molluscs) and boring (algae, sponges) organisms and mixing corrosion, are developed around mean sea level and in correspondence with fresh water outlets; karren features are dominated by large solution pans and pitted surfaces and are due to a combination of physical, biological and chemical processes (Fig. 5).

III. The CISA method

The CISA method (Cliff Instability Susceptibility Assessment) is a multidirectional method for assessing cliff instability at a given scale. The first step of the method consists of the subdivision of the coastal stretch in coastal sectors based above all on morphological and geological criteria. Cliff height, coastal landforms (caps, inlet etc.), wave and wind exposure, coastal defence structures, natural and artificial in types (wave-cut platform, beach, rock blocks, jetties etc.), were taken into account to subdivide in 6 sectors the coastal stretch under consideration. "Regional Technical Map" (CTR) of Apulia at scale 1:5000 (www.sit.puglia.it), georeferented to WGS84/UTM zone 33N system, was used as base map to generate the Coastal Stability Map of the study area (Fig. 6).

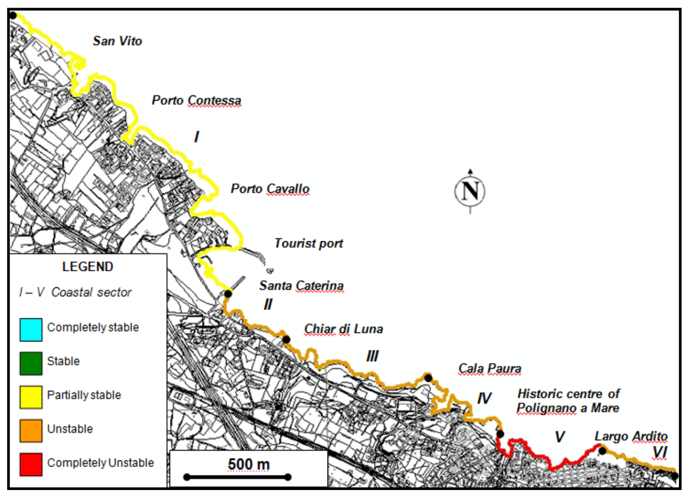

Fig. 6 costal stability map of the study area

In the second phase, a qualitative assessment of the cliff stability integrating traditional geomechanical surveys was completed by geotechnical laboratory tests, deterministic analysis (the estimate of the critical height for vertical slope using the lower bound theorem of limit analysis), multifactor spatial GIS analysis using physical geographically-based measures with the purpose of assigning the right weight to the parameters considered in this study. 28 incidence parameters were considered and regrouped in four categories: geomechanical (12), morphological (6), meteo-marine (8) and anthropogenic (2). For each parameter 5 classes of rating were proposed; the cliff classification, in terms of instability susceptibility, was obtain from the total rating which represents the summation of the single rating of the individual parameter (Table I). The stability classes with respect to coastal erosion are reported in Table II.

Discontinuities in rock masses were described according to the ISRM standards [25]. Favorability/unfavorability of discontinuities related to cliff stability was evaluated on the basis of the ratio between discontinuity orientation and persistence, and potential failure mechanism. With respect to parallelism between joints and slope face strikes, the presence of tension cracks at the cliff-top edge was considered the most hazardous condition. The RQD estimation was carried out by the the volumetric joint count (Jv) and block sizes [26]. Sea caves, arches and karst features were account as prominent natural coastal hazards.

Table I rating of 28 parameters of the CISA method

Parameters	Very bad	Bad	Normal	Good	Very good
	1	2	3	4	5
Geomechanical			JOINTS		
Number of set	Crushed rock	Three or more	Two plus random fractures	One plus random fractures	Massive, occasional random fractures
Spacing	< 0.06 m	0.06 - 0.2 m	0.2 - 0.6 m	0.6 - 2.0 m	> 2.0 m
Aperture	> 1 m	0.01 - 1 m	0.002 - 0.01 m	0.0005-0.002 m	< 0.0005 or Closed
Roughness	Smooth	Poorly rough	Rough	Very rough	Extremely rough
Weathering	Extremely weathered	Very weathered	Weathered	Slightly weathered	Unweathered
Infilling	Softening vegetation	Overconsolidated soil	Silty or sandy	Hard	Very hard impermeable
Water condition	Spring water	Wet	Very damp	Damp	Dry
Parallelism between joints and slope face strikes	0° - 20°	20° - 40°	40° - 60°	60° - 80°	80° - 90°
Joint orientation with respect to potential mass movement	Very unfavourable	Unfavourable	Fair	Favourable	Very favourable
			ENGINEERING PROPERTIES		
RQD	< 10	10 - 40	40 - 70	70 - 90	> 90
Schmidt Rebound Index	0 - 10	10 - 45	45 - 65	65 - 80	> 80
Stability index	< 0.5	0.5-1.0	1.0-1.3	1.3-1.5	>1.5
Morphological			CLIFFS		
Cliff height	> 30 m	30 - 15 m	15 - 5 m	5 - 2 m	< 2 m
Cliff slope	Overhanging	Steep 75°-90°	Strong 50°-75°	Moderate 30°-50°	Gentle < 30°
Sea-caves	Widespread	Widespread at the sea level	Widespread above the sea level	Slight	Absent
Natural breakwater	Absent	Very small	Small	Wide	Very wide
Mass movement material and evidence	Widespread	Widespread around the sea level	Only material at the foot of the cliff	Slight	Absent
Abrasive action	Very intense	Intense	Moderate	Poor	Absent
Meteo-marine			SEA-WAVES		
Effective fetch	> 250 km	250 - 200 km	200 - 150 km	150 - 100 km	< 100 km
Strong-side wind	> 160 °	160° - 120 °	120° - 80 °	80° - 40 °	< 20 °
Breaking depth	< 5.5 m	5.5 – 6.5 m	6.5 - 7.5 m	7.5 – 8.5 m	> 8.5 m
Breaking height	> 7.0 m	6.0 - 7.0 m	5.0 – 6.0 m	4.0 - 5.0 m	< 4.0 m
Distance of the breaker zone from the shoreline	< 100 m	100 – 200 m	200 – 300 m	300 – 400 m	> 400 m
Wave impact height	> 3.0 m	3.0 - 2.0 m	2.0 – 1.0 m	1.0 - 0.50 m	< 0.50 m
Wave breaker type	Plunging	Collapsing	Surging	Spilling	Absent
Exposure to storm wave fronts	80° - 90°	60° - 80°	40° - 60°	10° - 40°	< 10°
Anthropogenic			ENGINEERING STRUCTURES		
Reinforcement	Absent	Poor	Localized	Widespread	Very widespread
Artificial breakwater	Absent	Poor	Localized	Widespread	Very widespread

Table II stability classes as per CISA values

CISA Value	< 40	40-60	60-90	90-120	120 - 140
Class No.	I	II	III	IV	V
Classification	Completely unstable	Unstable	Partially stable	Stable	Completely stable

Following the standard test procedure outlined in ISRM [27]-[28], dry unit weight (γ_d), saturated unit weight (γ_{sat}), porosity (n), water absorption (w_a), degree of saturation (Sr) and uniaxial compressive strength in the natural state (σ_n) were determined on cylindrical biocalcarenite and fine-grained limestone specimens (cores from boreholes and specimens prepared from block samples fallen from the cliff face and collected along the coastline). As regards the specific gravity (G), reference was made to a value of 2.70 on the basis of the chemical composition of the rocks. In fact, these lithofacies are composed mostly of carbonate (>95%) with an often negligible insoluble residue [29]-and references therein. The determination of physical and mechanical properties was carried out on 10 samples of each lithofacies. The laboratory data are summarized in Table III. Porosity in the Plio-Pleistocene biocalcarenites is in the range 43%–50%, water absorption between 28%–36% and degree of saturation is 100% showing that pores in the rock particle systems are interconnected and continuous, so that the porosity is effective. In contrast, the Cenomanian calcilutites are characterised by lower porosity (4%–20%), water absorption (2%–10%) and degree of saturation (0.3%–3.2%). At the core scale, the low degree of saturation of these rocks demonstrates that porosity is predominantly closed.

Table III physical and mechanical properties of the lithofacies outcropping along the coastal stretch of Polignano a Mare

Physical-Mechanical Properties	Calcarenites (Calcarenite di Gravina Fm.)			Calcilutites (Calcare di Bari Fm.)		
	min	max	mean	min	max	mean
Specific gravity, G_s			2.70			2.70
Dry unit weight, γ_d (kN/m^3)	13.34	15.10	14.05	21.09	25.30	23.41
Sat. unit weight, γ_{sat} (kN/m^3)	18.20	19.32	18.66	21.11	25.32	23.42
Porosity, n (%)	42.96	49.63	46.93	4.44	20.37	11.59
Water absorption, w_a (%)	27.90	36.49	32.84	1.64	9.90	4.87
Degree of saturation, Sr (%)			100	0.32	3.22	1.28
Uniaxial compressive strength, σ_n (MPa)	1.72	3.45	2.49	18.15	24.03	21.33

Rock mass hardness of the micritic limestones and karstic breccias was also measured in situ with the Schmidt hammer (type L). Lowest hardness and density values are due to high weathering rates of the karstic breccias and disturbed limestones. It should be noted that in this paper the term weathering includes carbonation. For each coastal sector, the estimate of the critical height of the cliff was carried out with the lower bound theorem of limit analysis adopting the Mohr-Coulomb failure criterion. The shear strength of the rock masses was obtained with the envelope derived by [30]. A precautionary approach was adopted in the analysis so that for each lithofacies estimated on the cliff the lowest value of strength was utilised. Two-dimensional cliff stability analysis was performed using the weighted mean for the geotechnical parameters of the different lithotechnical units defined on the cliff face; therefore in the vertical cliff model, shear strength and unit weight were considered as uniformly constant. A correction factor equal to RQD was applied at the weighted mean of the unit weight determined in laboratory on cylindrical samples for assessing the unit weight of the rock mass. For the submerged portion of the cliff face the buoyant unit weight was taken into account. The stability index (Is) was then calculated as the ratio between cliff height and its critical height. The stability index was first proposed by [31], but the method adopted for calculating critical height of cliff face and range of values given for defining stability classes are different from those proposed in this study.

Strong side winds and fetch (effective length) were measured for each coastal sector in correspondence of caps and inlets. The effective fetch was defined along the NW, N and NE winds using the recommended procedure of the Shore Protection Manual [32] for a mid-latitude semi-enclosed basin such as the Adriatic Sea. The bottom depth and slope were calculated from the bathymetric data determined in GIS environment (Italian Nautical Charts). The maximum of the values of the offshore spectral height, Hs (m), and the offshore time peak, Tp (s), were obtained from the data collected at the Monopoli buoy (Lat 40°58’30’’N; Long 17°22’36’’ E; World Geodetic System 84) of the National Wave Measuring Network (RON) for the period July 1989-April 2008. Finally, the offshore wavelength Lo (m) was obtained from the term Linear (or Airy) Wave Theory [33] along the NW wind (315-0 °N), the N wind (315 – 45° N) and the NE wind (0 – 90 °N). For the CISA method, the breaking wave depth and the breaking wave height were determined with the Goda's nomographs [34], while the impact wave height was calculated with the empirical relationship developed by [35]; the type of breaking wave was obtained by the Okazaki & Sunamura's laboratory study [36].

IV. Results and discussion

First of all, long-term morphodynamic evolution of the coastal stretch is influenced by human activities because the study area is characterized by a heavily urbanized coastline with seafront buildings, ancient coastal quarries, saline holes and streets. Furthermore, the most part of the coastal stretch studied does not present shore protection structures such as jetties and seawalls; the only exception regards the tourist port area. At places large boulders used in the past for the protection of the cliff in the proximity of the old city of Polignano a Mare are now submerged and so not visible. In recent years, controlled removal of potentially hazardous rock blocks, anchors, rock nailing and injections with special mortars were used locally to reinforce the cliff, but the results appear to be unsatisfactory for the expected purpose. Clear signs of coastal recession are evident and include above all mass movements such as rock falls due to the undercutting action of waves at the base of the cliff or cave roof collapses (Fig. 7). Notches, erosion grooves and their increase in size cause rising shear stresses that induce the cliff to fail, but the presence of caves not only at sea level is considered a hazardous condition. Data from field observations indicate that the coastal recession appears not uniform with time and mainly governed by spatially discontinuous slope mass movements in rapid and episodic events. The basic factors controlling the sea cliff recession are the assailing forces of wave and the resisting force of the cliff-forming rock masses. The wave action consists not only of hydraulic actions (compression, tension, cavitation and wear) but also of abrasive action due to wave-moved pebbles and boulders and wedge action due to the air compressed in fissures by waves [36]. Rock mass strength is controlled by discontinuities and mechanical properties of intact rock pieces. Reduction in rock mass strength is due to weathering and fatigue caused by cyclic loading of waves at the cliff base. In particular, in the presence of an emerged wave-cut platform or rock boulders at the cliff base, weathering is the first responsible for the cliff collapses. The weathering processes include carbonation, salt weathering, water layer weathering (associated with the wetting and drying process) and biological weathering, especially by boring organisms [37]-[38]. In this case, the role of meteo-marine parameters appears to be secondary in the cliff erosion and collapses.

The assailing forces of wave depend on the wave energy, in turn depending on wind strength and duration, water depth and density, and fetch. The intensity of erosive forces controlling failure mechanisms is determined by the wave type immediately in front of the cliffs and this is determined by the relationship among offshore wave characteristics (wave height, wave angle and wave period), tidal condition and nearshore submerged morphology.

Fig. 7 mass movements: cave roof collapses (coastal sector V)

In the study area, the influence of the tidal condition was considered significant for the water layer weathering only and this because we are dealing with a typical situation in microtidal environment. Second, applying the CISA method, the weight of the meteo-marine parameters in establishing potential instability appears to be rather uniform in all the sectors with respect to that of the other groups of parameters. In situ observations spanning from 1997 to present allow to affirm that distance of the breaker zone, wave impact height, wave breaker type and exposure to storm wave fronts, expressed in terms of the angle between the coastline and prevailing storm wave fronts, seem to have a different but fundamental incidence on defining the nearshore wave energy for the studied coastal sectors. At the same time, the role of scattering processes induced by nearshore morphology is of great importance in coastal retreat mechanisms, so visual evidence of the wave approach has to be used wherever possible. It is self-evident that the shore-parallel storm waves hitting the coast involve higher hazard levels than shore-normal wave fronts. The wave breaker type is not different for all the sectors but surging waves are typical of the sector I, while plunging waves characterise only the sector V; the plunging waves break with more energy than the others. With regards to the exposure, the best condition appears in the sector II and the worst condition in the others because they are exposed to the storms approaching from the N, NE and NW. The partial rating for each category of parameters taken into account and the total ratings for each coastal sector (CISA rating) are provided in Table IV.

As a result of the analysis of the data obtained from the applications of the CISA method, it was found that the coastal stretch of Polignano a Mare is unstable, although at places retreat processes are imperceptible (sector I). Furthermore, the urbanization of the coastal area has de facto prevented the formation at the cliff toe of natural barriers against wave action and shoreline erosion.

Table IV partial rating and CISA rating obtained for the study area

Parameters	**Coastal sectors**					
	I	II	III	IV	V	VI
Geomechanical	JOINTS					
Number of set	3	2	2	2	2	2
Spacing	3	2	2	2	2	2
Aperture	3	2	3	3	2	3
Roughness	4	3	2	2	2	2
Weathering	2	2	2	2	1	2
Infilling	3	3	4	2	1	2
Water condition	2	2	2	2	2	2
Parallelism between joints and slope face strikes	3	2	2	2	1	2
Joint orientation with respect to potential mass movement	3	1	1	1	1	1
	ENGINEERING PROPERTIES					
RQD	1	1	2	2	1	2
Schmidt Rebound Index	1	1	2	2	1	2
Stability index	5	3	3	3	2	3
PARTIAL RATING	33	26	27	25	18	25
Morphological	CLIFFS					
Cliff height	5	4	4	3	2	3
Cliff slope	5	1	1	2	1	2
Sea-caves	5	1	1	1	1	2
Natural breakwater	1	1	1	1	1	2
Mass movement material and evidence	4	1	1	1	1	2
Abrasive action	4	1	2	2	1	2
PARTIAL RATING	24	9	10	10	7	13
Meteo-marine	SEA-WAVES					
Effective fetch	1	2	1	1	1	1
Strong-side wind	1	1	1	1	1	1
Breaking depth	4	1	2	2	1	1
Breaking height	4	1	1	1	1	2
Distance of the breaker zone from the shoreline	3	1	3	3	1	1
Wave impact height	4	1	1	1	1	1
Wave breaker type	3	1	1	1	1	1
Exposure to storm wave fronts	1	2	1	1	1	1
PARTIAL RATING	21	10	11	11	8	9
Anthropogenic	ENGINEERING STRUCTURES					
Reinforcement	1	1	1	1	1	1
Artificial breakwater	3	1	1	1	1	1
PARTIAL RATING	4	2	2	2	2	2
CISA RATING	**82**	**47**	**52**	**48**	**35**	**49**

V. CONCLUSION

Coastal cliff retreat is difficult to assess and model due to the episodic nature of failures and the complexity of retreat mechanisms controlled by a number of factors dependent on the properties of rock masses and meteo-marine conditions.

An ideal method for assessing cliff instability susceptibility along a coastal stretch needs for a preliminary calibration based on visual estimate, field inspections and cliff failure inventory. At same time, this method should be implemented with probabilistic and deterministic approaches. Nevertheless, it will present limitations and disadvantages in its application due to non-objective evaluations of the relative weight of the selected conditioning factors of future mass movements, difficulties of obtaining representative geotechnical data of rock masses, especially in karst areas, and because linked to a well-defined geological and environmental context.

The predictive capacity of the CISA method are not yet tested and, however, the results obtained in this study suggest that the procedure used may have a good potential for the assessment of the susceptibility of cliff failures in a typical Mediterranean coastal carbonate environment.

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REFERENCES

[1] A.S. Trenhaile, “The Geomorphology of Rock Coast”. Oxford Univ. Press, Oxford, pp. 384, 1987.

[2] L.A. Naylor, W.J. Stephenson and A.S. Trenhaile, “Rock coast geomorphology: Recent advances and future research direction”. *Geomorphology*, vol. 114, pp. 3-11, 2010.

[3] G.F. Andriani, N. Walsh, “Rocky coast geomorphology and erosional process: A case study along the Murgia coastline South of Bari, Apulia – SE Italy”. *Geomorphology*, vol. 87, pp. 224-238, 2007.

[4] M. Lim, N.J. Rosser, R. Allison and D.N. Petley, “Erosional processes in the hard rock coastal cliffs at Staithes, North Yorkshire”. *Geomorphology*, vol. 114, pp. 12-21, 2010.

[5] C.J. Hapke, “The measurement and interpretation of coastal cliff and bluff retreat”. In: 851 Formation, evolution and stability of coastal cliffs, USGS Professional Paper 1693. USGS, 852 p. 39-50, 2004.

[6] L. Del Rio, F.J. Gracia, “Erosion risk assessment of active coastal cliffs in temperate environments”. Geomorphology, vol. 112, pp. 82-95, 2009.

[7] T. Sunamura, Geomorphology of rocky coasts. Chichester (UK), John Wiley & Sons Ed, 1992.

[8] M. Reiman, Ü. Ehrlich and H. Tõnisson. “Public Demand for Shores in Natural Condition: a Contingent Valuation Study in Estonia”. *International Journal of Geology*, vol. 6, pp. 36 – 43, 2012.

[9] S. Gerasimou and A. Perdicoúlis. “Urban renaissance on Athens southern coast: the case of Palaio Faliro”. *International Journal of Energy and Environment*, vol. 3, pp. 178-185, 2009.

[10] J. De Waele, M. Mucedda and L. Montanaro. “Morphology and origin of coastal karst landforms in Miocene and Quaternary carbonate rocks along the central-western coast of Sardinia (Italy)”. *Geomorphology*, vol. 106, pp. 26–34, 2009.

[11] F. Recorbet, P. Rochette, R. Braucher, D. Bourles, L. Benedetti, D. Hantz and R.C. Finkel. “Evidence for active retreat of a coastal cliff between 35 and 12 ka in Cassis southeast France”. *Geomorphology*, vol. 115, pp. 1-2, 2010.

[12] E. Amadesi, G. Vianello, “New guidelines for mapping slope stability (Nuova guida alla realizzazione di una carta di stabilità dei versanti)”, *Mem. Soc. Geol. Ital.*, vol. 19, pp 53-60, 1997.

[13] M. Fall, R. Azzam, C. Noubactep, “A multi-method approach to study the stability of natural slopes and landslide susceptibility mapping”, *Engineering Geology*, vol. 82, pp. 241-263, 2006.

[14] F. M. S. F. Marques, R. Matildes, and P. Redweik, “Sea cliff instability susceptibility at regional scale: a statistically based assessment in the southern Algarve, Portugal”, *Nat. Hazards Earth Syst. Sci.*, vol. 13, pp. 3185–3203, 2013.

[15] P. Budetta, “Landslide Hazard Assessment of the Cilento Rocky Coasts (Southern Italy)”, *International Journal of Geology*, vol. 7, pp. 1-8, 2013.

[16] V. Festa, “Cretaceous structural features of the Murge area (Apulian Foreland, Southern Italy)”, *Eclogae Geol. Helv.*, vol. 96, pp. 11-22, 2003.

[17] L. Spalluto, “Facies evolution and sequence chronostratigraphy of a “mid”-Cretaceous shallow-water carbonate succession of the Apulia Carbonate Platform from the northern Murge area (Apulia, southern Italy)”, *Facies*, vol. 58, pp.17–36, 2012.

[18] M. Gallo Maresca, “Taxonomic and biostratigraphic aspects of the Albian «Radiolitidae» of Murge and Gargano (Apulia, Southern Italy) (Aspetti tassonomici e biostratigrafici delle «Radiolitidae» albiane delle Murge e del Gargano (Puglia, Italia meridionale))”, *Palaeopelagos*, vol. 4, pp. 223-232, 1994.

[19] M. Parise, A. Federico, M. Delle Rose and M. Sammarco, “Karst terminology in Apulia (Southern Italy)”, *Acta Carsologica*, vol. 32, pp. 65-82. 2003.

[20] N. Ciaranfi, P. Pieri and G. Ricchetti, “Note alla carta geologica delle Murge e del Salento (Puglia centromeridionale)”. Mem. Soc. Geol. Ital. Vol. 41, pp. 449–460, 1988.

[21] G.F. Andriani and N. Walsh, “Physical properties and textural parameters of calcarenitic rocks: qualitative and quantitative evaluations”. *Eng. Geol*., Vol. 67, pp. 5-15, 2002.

[22] G.F. Andriani and N. Walsh, “Petrophysical and mechanical properties of soft and porous building rocks used in Apulian monuments (south Italy)”. In: Building stone decay. Geological society, London, Special Publications, vol. 333, pp. 129-141, 2010.

[23] P. Pieri, L. Sabato, L. Spalluto and M. Tropeano, Note illustrative della carta geologica dell’area urbana di Bari in scala 1:25.000”. Rend. Online Soc. Geol. It., Vol. 14, pp. 26-36, 2011.

[24] G. F. Andriani, N. Walsh, “An example of the effects of anthropogenic changes on natural environment in the Apulian karst (southern Italy)”, *Environ. Geol.*, vol. 58, pp. 313-325, 2009.
[25] International Society for Rock Mechanics, Commission on Standardization of Laboratory and Field Tests, “Suggested Methods for the Quantitative Description of Discontinuities in Rock Masses”, Int. J. of Rock Mechanics and Mining Sciences, vol. 15, pp. 319–368, 1978.
[26] A. Palmstrom, “Measurements of and correlations between block size and rock quality designation (RQD)”. *Tunnelling and Underground Space Technology*, vol. 4, pp. 362–377, 2005.
[27] International Society for Rock Mechanics, Commission on Standardization of Laboratory and Field Tests, “Suggested methods for determining in situ deformability of rock”, Int. J. of Rock Mechanics and Mining Sciences, vol. 16, pp. 195-214, 1979.
[28] International Society for Rock Mechanics, Commission on Standardization of Laboratory and Field Tests, “Determining the Uniaxial Compressive Strength and Deformability of Rock Materials“, Int. J. Rock Mech. Min. Sci. & Geomech, Int. J. of Rock Mechanics and Mining Sciences, vol. 16, pp. 135-140, 1979.
[29] G.F. Andriani, L. Germinario, “Thermal decay of carbonate dimension stones: fabric, physical e mechanical changes”, *Environ.Earth Sci.*, DOI 10.1007/s12665-014-3160-6, 2014.
[30] G. Manev, E. Avramova-Tacheva, “On the valutation of strength and resistance condition of the Rock in Natural Rock Massif.”, in *Proceedings of the Second Congress of the International Society for Rock Mechanics*, Beograd, 1970, pp. 59-64.
[31] G. Mastronuzzi, G. Palmentola, P. Sansò, “Some theoretic aspect of rocky coast dynamics”, *Boll. di Oceanologia Teorica ed Applicata*, vol. 10, pp. 109-115, 1992.
[32] *Shore protection manual*, Coastal Engineering Research Center (U.S.), U.S. Army Coastal Engineering Research Center Ed., Washington, 1975.
[33] T. Sarpkaya, M. Isaacson, *Mechanics of Wave Forces on Offshore Structures*. Van Nostrand Reinhold, New York, New York, 651, 1981.
[34] Y. Goda, “A synthesis of breaker indices”, Trans. Japan Soc. Civil Eng., vol. 2, pp. 227-230, 1970.
[35] S. Okazaki, T. Sunamura, “Re-examination of breaker-type classification on uniformly inclined laboratory beach”, Jour. Coastal Res., vol. 7, pp. 559-564, 1991.
[36] T. Sunamura, “A relationship between wave-indiced cliff erosion and erosive force of waves”, *journal of Geology*, vol. 85, pp. 613-618, 1977.
[37] G. F. Andriani, N. Walsh, “Petrophysical and mechanical properties of soft and porous building rocks used in Apulian monuments (south Italy)”, *Geological society*, London, Special Publications, vol. 333, pp. 129-141, 2010.
[38] Stephenson, W.J. & Kirk R.M. 2000. Development of shore platforms on Kaikoura Peninsula, South Island, New Zeland, part I : the role of waves, p. 21-41, part II : the role of subaerial weathering, p. 43-56, Geomorphology, 32.