Italian Journal of Engineering Geology and Environment
www.ijege.uniroma1.it

EXAMPLES OF CLIFF INSTABILITY ALONG THE APULIAN COASTLINES

Isabella Serena LISO(*), Umberto Samuele D'ETTORRE(*), Gioacchino Francesco ANDRIANI(*), Giuseppe DIPRIZIO(*), Lidia LOIOTINE(*), Piernicola LOLLINO(*) & Mario PARISE(*)

(*)University Aldo Moro, Bari – Department of Earth and Environmental Sciences – Via Orabona 4, Bari, Italy
Corresponding author: isabella.liso@uniba.it

EXTENDED ABSTRACT

La Puglia rappresenta una delle regioni italiane a maggiore sviluppo costiero. I suoi litorali sono spesso intensamente popolati a causa di una intensa urbanizzazione, caratterizzata da strutture residenziali e turistiche; la bellezza paesaggistica e naturalistica della regione, infatti, attira ogni anno un elevato numero di turisti, soprattutto durante la stagione estiva. Nonostante tra le maggiori attrazioni turistiche siano da annoverare le falesie in roccia medio-alte ed alte, esse rappresentano anche un potenziale pericolo in termini di eventi franosi. L'instabilità delle falesie è un fenomeno che interessa molti settori delle coste pugliesi, dal Gargano a Nord sino al Salento nel settore Sud-orientale. La valutazione del grado di stabilità delle falesie costituisce, di fatto, un problema complesso di non facile risoluzione, dato il numero consistente dei fattori in gioco e delle loro interrelazioni. Ne consegue la necessità di studi approfonditi sui fattori predisponenti ad eventi franosi, basati su approcci multi-disciplinari modulabili in funzione della scala di applicazione. In questo senso, particolare attenzione deve essere posta allo sviluppo di tecniche innovative basate sull'utilizzo di modelli numerici di simulazione standardizzati ed avanzati, che possano individuare e analizzare tutti i fattori chiave determinanti il grado di stabilità/instabilità delle falesie costiere, tra i quali, ad esempio, la geometria degli ammassi rocciosi, le loro caratteristiche geotecniche e le proprietà delle discontinuità degli stessi.

Il presente contributo vuole rappresentare uno sguardo d'insieme sulle principali tipologie di falesie in roccia del territorio pugliese, con lo scopo di evidenziarne i meccanismi e il grado di instabilità in differenti contesti costieri: Gargano, Murgia centrale e Salento. I casi di studio presentati evidenziano come i meccanismi di instabilità potenziali e in atto individuati nonché la propensione al dissesto delle diverse aree siano fortemente legati ai caratteri geologici di sito e alle proprietà dei materiali coinvolti. Ne deriva che per una corretta gestione e pianificazione territoriale mirata alla prevenzione della pericolosità da frana in aree costiere risulta indispensabile elaborare modelli geologici e geotecnici di riferimento in cui assumono un ruolo fondamentale le caratteristiche geomeccaniche e geostrutturali degli ammassi rocciosi, congiuntamente agli effetti dei processi carsici e dei meccanismi di degrado dei materiali.

IJEGE, Special Issue 1 (2023): 89-97, DOI: 10.4408/IJEGE.2023-01.S-12
E-ISSN 2035-5688 | ISSN 1825-6635 / ©Author(s)

ABSTRACT

Apulia (Southern Italy) is among the most important Italian regions in terms of shoreline extension. The coastline is heavily occupied by towns and resorts hosting an increasing number of tourists, attracted by the extreme beauty of the region, especially during the summer season. Many kilometers of coasts are characterized by moderately high to high cliffs, which surely are relevant touristic attractions, but also represent hazards in terms of mass movements. The rock cliff instability processes affect the whole Apulian coastal zone, from the Gargano Promontory to the Salento Peninsula. The degree of instabilities and potential risks have to be related to the unique geological and geomorphological framework of the sites, that include intense development of karst processes, combined to the presence of nearby infrastructures and urban areas. This contribution analyses various examples of cliff instability along the Apulian coastline highlighting as the differences in geology and geomorphology lead to different degrees of hazards.

Keywords: *cliff, landslide, hazard, Apulia*

INTRODUCTION

The geological instability of high cliffs in Italy is a very challenging problem, given the geographical location and the geological setting of the peninsula. The phenomena of cliff retreat can be described as a combined action of various marine and subaerial processes working at different temporal and spatial scale (Iannucci *et alii*, 2017; Melis *et alii*, 2020; Loiotine *et alii*, 2021; Guenzi *et alii*, 2022), which have been defined and analyzed by several authors in a variety of geological and morphological settings (De Vita *et alii*, 2012; Apuzzo *et alii*, 2013; Caso *et alii*, 2014; Martino & Mazzanti, 2014; Sansò *et alii*, 2016; Fazio *et alii*, 2019; Lollino *et alii*, 2021).

Among the Italian regions, together with Liguria, Calabria and the islands of Sicily and Sardinia, Apulia (Southern Italy) is one of the most important in terms of coastal extension, with about 900 km of coast. It is characterized by a high percentage of cliffs in soft and hard rocks, where current and potential instability constitutes a serious hazard for the coastal communities, due to the possible interactions with nearby infrastructures, urban areas and tourist activities. The peculiar characters of the region (mostly consisting of carbonate rocks intensively affected by karst) need detailed studies of the rock failure processes in coastal areas, aimed at the assessment of potential hazards according to the specific site conditions. This represents one of the most effective ways to guarantee safety to tourists and local communities, that have to be protected through adequate management plans of risk mitigation.

This paper proposes an overview of the different typologies of cliff instability typically occurring along the Apulian coastlines, along with the failure mechanisms and the factors controlling the different phenomena, based on geological, geomorphological, geostructural and geomechanical evidences. In particular, in the first part of the manuscript, the issue of coastal cliff instability is discussed in general, while in the second part several examples of cliff instability phenomena along the Apulian coastlines are presented in order to show the role of the different lithologies, rock mass structural features and proneness of the outcropping rocks to weathering and karst in the activation of the failure processes.

COASTAL CLIFF INSTABILITY

Coastal cliffs mark the sector of transition between earth and sea, and represent therefore a very fragile environment, where many different factors act in creating the conditions for instability, either predisposing or triggering the phenomena (Rosen, 1980; Trenhaile, 1987; Sunamura, 1992, 2015; Stephenson and Naylor, 2010; Kennedy *et alii*, 2014). As in other settings, the main predisposing factors are intrinsic to the geological nature of outcropping materials, and to their evolution: lithology, stratigraphy, structural and morphological features, geomechanical properties of the rock mass and hydrogeology (Budetta *et alii*, 2000; Dipova, 2009). Ascertaining the main sets of discontinuity in the rock mass is one of the first actions to be deployed, aimed at the preliminary identification of the most potentially unstable sectors. When dealing with soluble rocks, and in particular with carbonates cropping out along many coastal stretches in Italy, karst has also to be taken into account as a further factor: development of karst caves and conduits, and the flow within them of constant or temporary water, may represent an additional element contributing to weakness of the rock mass, and should be properly evaluated (Andriani & Parise, 2015, 2017).

Several triggering factors are also to be accounted, even though the most important ones, in addition to meteoric events, can be generally represented by the sea waves, whose energy repeatedly impacts on the rock walls, along with the contribution of sea currents and tide cycles (Adams *et alii*, 2005; Bezerra *et alii*, 2011; Mastronuzzi *et alii*, 2014).

Weathering, as well as biological activity exerted by micro- and macro- marine organisms, may also influence the behaviour of the rock mass, especially in the case of soft rocks (Bernatchez & Dubois, 2008; Castedo *et alii*, 2012), or of highly weathered materials (Calcaterra & Parise, 2010). Weathering, beside producing a reduction in the mechanical properties of the rocks, acts through thermo-clastic and halo-clastic effects as a result of temperature variation and deposition of marine spray on discontinuities. The biological degradation is related to the metabolic activities of marine organisms, whilst, eventually, the presence of spontaneous vegetation on the cliff walls produces a mechanical degradation by means of the roots' activity, causing detachment and falls of rock blocks (Coombes, 2014).

Instability phenomena, generally expressed in the form of falls and/or topples, even involving considerable volumes of rock, produce retreat of the coast, especially where the rock mass is of poor quality or characterized by degradation of the geomechanical properties. All the aforementioned factors, combined with the extensive use of the coastlines for anthropogenic activities (tourism, harbours, etc.) are at the origin of the difficulty in approaching coastal instability studies.

Nevertheless, the coastal morphology is the main factor to take into account for the evaluation of cliff instability (Walkden & Dickson, 2008; Trenhaile, 2010, 2014): low cliffs, indeed, are more exposed to the action of the sea waves, while the presence of beaches or marine platforms at the base of rock walls reduces the mechanical wave action, preventing or decreasing the cliff retreat.

Given the complexity of the issue, a detailed analysis of all factors predisposing landslides has to be considered the scientific base for a full understanding of the coastal degradation scenario, and the best tool for adopting the most proper methodology to assess the susceptibility and hazard conditions.

Due to technology development in the last decades, the approach typically uses also digital topographic survey of the study site through LIDAR (Light Detection and Ranging) methodology, in order to obtain a small-scale geometric and morphological reconstruction. Laser Scanner and/or UAV are aimed to achieve a detailed 3D georeferenced morphological model, at large-scale case study (Rosser et al., 2005). On the basic point cloud so obtained, automatic and semi-automatic methods (Gigli & Casagli, 2011; Abellan *et alii*, 2014; Pagano *et alii*, 2020; Loiotine *et alii*, 2021a; Cardia *et alii*, 2023) may be applied to extract some structural information, to be necessarily validated with geological, structural and geo-mechanical surveys.

The approaches for assessment of the hazard conditions are different and have to be adopted as a function of the scale of application. Statistical and heuristic methods are generally chosen at the regional scale; in GIS environment thematic layers (single instability factors) are preliminary overlapped and then comprehensive coastal susceptibility and hazard maps can be realized (Dorren & Seijmonsbergen, 2003; Lollino et al. 2021). Deterministic methods, on the other hand, are adopted at the scale of the single case study (Finite Element Method – FEM, Finite Difference Method – FDM, Distinct Element Method – DEM, to mention the most important ones). Adopting specific calculation codes, they allow to develop an advanced numerical simulation of the possible failure processes and to investigate the corresponding controlling factors (Agliardi & Crosta, 2003; Fazio *et alii,* 2019; Perrotti *et alii* 2020). The implementation of such stress-strain methods requires a great accuracy of the numerical input dataset, which has to include elements as the cliff geometry, the detailed stratigraphy, the structural and hydrogeological setting and the mechanical parameters of the materials.

STUDY SITES

The coast of Apulia is characterized by a total length of about 900 km (Fig. 1), and is composed by three alternating morphological types: cliffs, beaches and slopy rocking coasts (Caldara *et alii*, 1998).

Sloping coasts (flat or convex) are the most common morphological type in the region (Mastronuzzi *et alii*, 2004). Low sloping rocky coasts are made by plain sloping cut through Plio-Pleistocene calcareous sandstone; convex rocky coasts are slopes shaped on limestones partly submerged by sea; cliffs are widespread on coastal portions, made by calcareous sandstones, clays and highly karstified limestones (Mastronuzzi & Sansò, 2006; Parise, 2008).

Fig. 1 - Study site locations. Yellow rectangles represent the three considered areas: 1. Gargano Promontory, to the north, 2. Murge Plateau, central sector, and 3. Salento Peninsula, to the south

	Gargano		Murge	Salento
Wind direction	V	M		
Mean rainfall (mm)	574,9	448,1	598,5	664,7
Rainy days	68	64	67	67
Mean temperature	16,9°C	15,4°C	16,8°C	17,5°C
Sea wave direction	NNW	E	NNW-N	NNW-SSE
Sea wave height	>2 m	<0,5m	<0,5m	>2 m
Marine storm frequency	High, H_{max} 5.4m NNW	Low, H_{max} 3.1m E	High, H_{max} 5.1m ENE	High, H_{max} 7.8m NNW

Tab. 1 - Main climatic parameters of the studied areas (data after Regione Puglia, 2007). In the Gargano column, V= Vieste, M= Mattinata

As concerns the climatic and meteo-marine conditions, these are strongly controlled at the local scale by direction of the individual bays and inlets. Nevertheless, in general terms the main parameters are shown in Table 1. It has to be noted that the frequency of marine storms is generally high at all studied areas, with the exception of the Mattinata coastlines, where it is considered low, even with lower height of sea waves (Regione Puglia, 2007).

In this section, we describe some examples of Apulian cliffs affected by instability (Fig. 1), covering the main sectors in the region, and that greatly contribute to the geo-hydrological disasters occurring in Apulia (Vennari *et alii*, 2022).

Gargano

The studied coastal sector of Gargano Promontory (Fig. 2), in northern Apulia, is highly variable in terms of geology.

Fig. 2 - Gargano, Northern Apulia: detail of the study sites

Along the Gargano coastlines, it is possible to find cliffs made of Quaternary alluvial conglomerates (Mattinata area), with different degree of cementation, with calcareous and siliceous pebbles and cobbles varying in size from a few centimeters to a few decimeters (Fig. 3). They were produced by deposition of large fans of mixed origin, where alluvial deposits intermingle with those deriving from phases of prevailing gravitational transport through debris flow activity. In such a context, the variable cementation degree of the matrix represents an important controlling factor of the cliff stability, since overhanging strata can develop due to the different susceptibility to erosion of the rock layers. Here, rock appears to be rather massive, with few structural discontinuities, apart from those generated by stress release and root excavation processes, which lead to consequent detachments along the cliff surfaces. A GSI (Hoek & Brown, 1997; Marinos *et alii*, 2005) in the range between 70 and 100 can be reasonably assumed for these rock masses, accordingly.

Further, dislocated rock volumes can be produced as an effect of the concentrated erosion of rainfall, or of the mechanical action exerted by tree roots at the top of the cliff (Fig. 3b).

Moving further north, still in the Gargano Promontory, it is possible to recognize cliffs in stratified Cretaceous limestones with flint layers and nodules (Baia di Vignanotica, Vieste, etc.) (Fig. 4). In this case, due to the high cementation degree of the rock matrix, cliff failure processes are mostly controlled by the

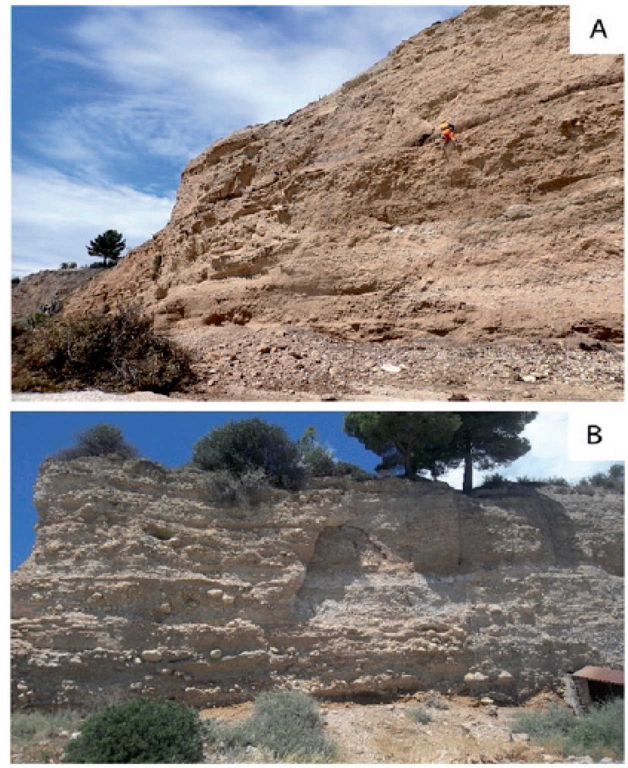

Fig. 3 - Mattinata (Gargano, Northern Apulia): a) conglomerate cliff; b) evidences of differential erosion and localized detachment of blocks

Fig. 4 - Limestone cliffs in the Gargano Promontory: A) massive limestone; B) limestones with flint layers and nodules

existing bedding planes and the structural features in the rock mass. Locally, there are also many sites where the effects of karst strongly interact in producing peculiar morphologies, such as at Grotta Sfondata (Fig. 5), with the collapse of the vault above marine and karst caves, through sinkhole processes (Gutierrez *et alii*, 2014; Parise, 2019, 2022).

Fig. 5 - Grotta Sfondata (Vieste, Gargano). Limestone cliff affected by karst processes leading to collapse sinkhole

The deriving morphology, often characterized by possibility of further detachments, are highly attractive in terms of tourism, and heavily frequented during the summer, with significant increase as concerns the presence of vulnerable elements.

Murge coastline: Polignano a Mare

In central Apulia, the cliffs in the coastal area of the Murge Plateau are characterized by Cretaceous limestones, fractured and intensively affected by karst processes (Sauro, 1991; Parise, 2011), with presence of many caves, and development of typical karst valleys, known as lame (Parise *et alii*, 2003). Most of the Murge coastal stretches are low cliffs alternating to beaches, but the case of Polignano a Mare represents an exception (Fig. 6).

There, and in the surrounding areas, many instability phenomena have occurred in the past, also with waves higher than 5 m, mostly coming from the ENE (Regione Puglia, 2007),

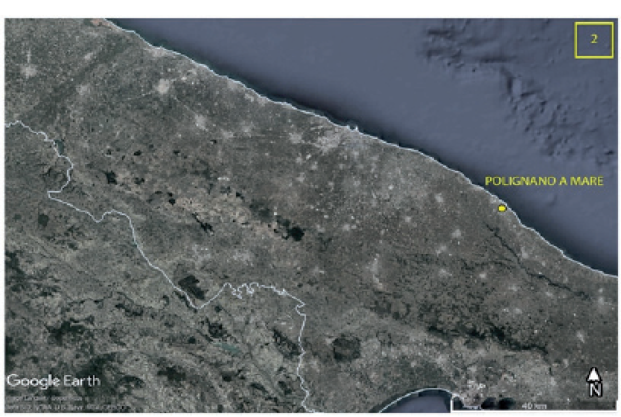

Fig. 6 - Murge, central Apulia: detail of the study site

and that have been the object of specific studies (Andriani & Walsh, 2007; Pellicani *et alii*, 2015; Loiotine *et alii*, 2021b). In particular, along the coastal stretch of Polignano a Mare well stratified limestones of the Calcare di Bari Fm. (Valanginian–late Cenomanian) overlain by discontinuous calcarenite and biocalcarenite deposits of the Calcarenite di Gravina Fm. (upper Pliocene–early Pleistocene) crop out.

The Calcare di Bari Fm. has a blocky structure related to the intersection of at least two sub-vertical joint sets, with spacing in the range 0.10-1.00 m, and the generally sub-horizontal bedding planes. The discontinuities are slightly to moderately weathered and, together with the rock mass structure, they determine GSI values ranging from 50 to 70. The Calcarenite di Gravina Fm has a massive structure but few widely spaced, moderately to highly weathered and altered discontinuities are present. This results in GSI value in the range 45-60.

Locally, the erosion mechanisms along the coast are very different and, other factors being equal, they are strictly influenced by lithology and rock strength. In fact, the coast stretches where vertical or overhanging cliffs show mainly exposures of soft and porous calcarenites are more susceptible to weathering and slope instability than those where fine-grained limestones predominate, even though the pattern and density of joints in the latter might be higher and more complex. In contrast to fine-grained limestones, the medium-grained calcarenites are more porous, loosely packed and weakly cemented; for these facies, weathering, mainly due to wetting/drying cycles and salt crystallization, is uniformly distributed in the rock mass and promote decay mechanisms and material disintegration. Three mechanisms of cliff instability can be recognised: slides, falls and topples. Planar failures along dip seaward bedding planes, which are evidence of folding, occur where the coast develops in fine-grained limestones and calcareous breccias, in correspondence of the northern coastal stretch of Polignano a Mare (Fig. 7).

On the other hand, falls of overhanging blocks due to undercutting of the cliffs and cave breakdown affect the whole coastal cliff of Polignano a Mare, involving both the limestone beds and the calcarenite succession.

Fig. 7 - Planar failures along bedding planes in the proximity of "Grotta Chiar di luna" cave (northern coastal stretch of Polignano a Mare)

In particular, most of the roof collapses involve caves formed at the contact between calcarenites and underlying limestones, and caves or notches found at sea level. Tension cracks are ubiquitous at the cliff crest and represent an important predisposing factor for toppling failures, and the detachment of unsupported rock blocks. A number of rock blocks at the foot of the cliffs, especially in the urbanized sectors and in correspondence of the historical part of the town are examples of these types of instability mechanisms.

Salento Peninsula

On the Adriatic side of Salento Peninsula, the main typical cliffs are made by soft to very soft rocks, in particular Plio-Pleistocene calcisiltites and calcarenites, leaving space to outcrops of Cretaceous-Oligocene limestones along the southernmost coastal sector, from Capo d'Otranto to Leuca (Fig. 8).

Fig. 8 - Salento, south Apulia: detail of the study site

The coastal area where soft calcisiltites and calcarenites crop out is characterized by the presence of vertical and, in places, overhanging rock faces, 12 to 18 m high, ending with sub-horizontal surfaces at the top (Fig. 9). Differential erosion and rockfall phenomena are widespread along the coastline, with episodic and localized collapses closely associated to storm waves, mostly from the NNW (Fazio *et alii*, 2019; Lollino *et alii*, 2021). Generally, failure processes occur along tension cracks controlled by stress release or tectonic joints or even faults, whereas deep erosion phenomena at the cliff toe due to wave undercutting give frequently rise to rockfalls (Fig. 9). Along these cliffs, rock mass is generally intact, with few widely spaced discontinuities, which can be characterized by unweathered to moderately weathered and altered surfaces. This results in GSI values that can range between 60 to 100.

At places, the presence of a notch, and of a tension crack close to the cliff top edge, may represent an important indicator of potential cliff failure, generally triggered by the wave loading. Moreover, intense weathering processes of these porous rocks induced by environmental factors, as rainfall infiltration or sea spray, give rise to the progressive degradation of the mechanical properties of the shallowest rock strata, thus enhancing the cliff collapse phenomena. Due to high touristic attractivity of this coastal stretch, the coastlines are frequently visited by a large number of visitors, and the risk linked to cliff instability processes is very high due to the high exposure of lives as well as structures and infrastructures. This is related to the possibility of cliff retreat, but also to the diffuse sinkholes, produced by collapses of karst caves or by suffosion (Gutierrez *at alii*, 2014; Parise, 2019, 2022). The best example for presence of both processes is located at Melendugno, in an area of tourist and archaeological importance, where the Grotta della Poesia system is present (Delle Rose & Parise, 2005; Liso &Parise, 2023).

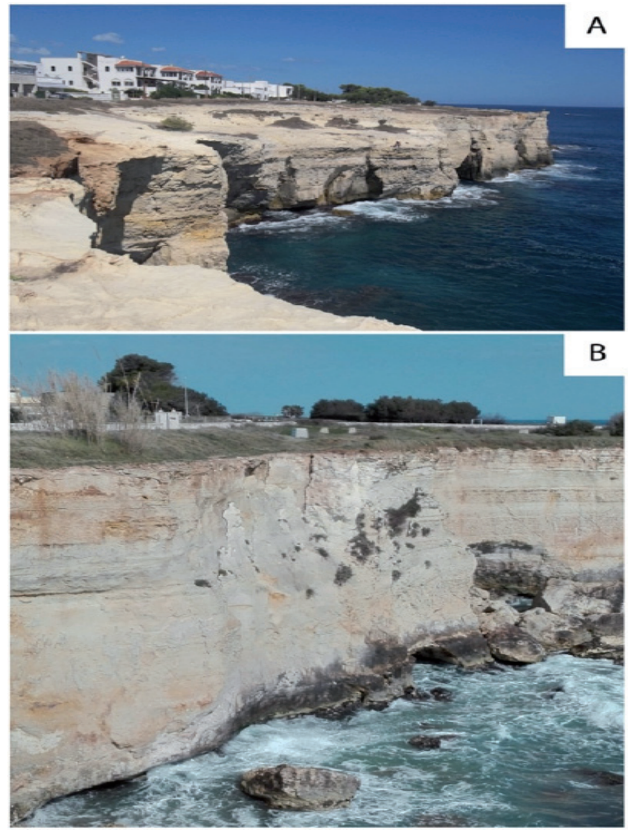

Fig. 9 - a) Typical vertical calcarenite cliff in the area of Melendugno; b) evidence of wave undercutting processes at the cliff toe

In particular, Grotta della Poesia Grande is among the best attractions for tourists, but it requires continuous control and monitoring, since several evidences of instability are visible in its surroundings, both at the surface and underground (open fractures, detachment of rock blocks from the sinkhole sides, as well as in the other flooded caves of the system).

Several detailed studies have been carried out at the Melendugno cliff case study in recent years (Delle Rose and Parise, 2004; Fazio *et alii*, 2019; Perrotti *et alii*, 2020, Lollino *et alii*, 2021), all of them being based on multi-temporal analyses, the application of numerical techniques to the simulation of the cliff behavior and the reconstruction of the corresponding failure mechanisms.

These studies have been developed by means of either finite element method or more advanced hybrid finite/discrete element techniques and highlight the different role of toe erosion and rock weathering, as well as the structural control due to joints and faults in conditioning the failure process. As an example, Fig. 10 shows the results of the application of the finite/discrete element technique (Femdem, Munjiza 2004) to an ideal cliff representative of the Melendugno coastal stretch: it clearly indicates a brittle failure mechanism of the cliff as a consequence of a slightly inclined joint structural control, combined with sea erosion at the toe.

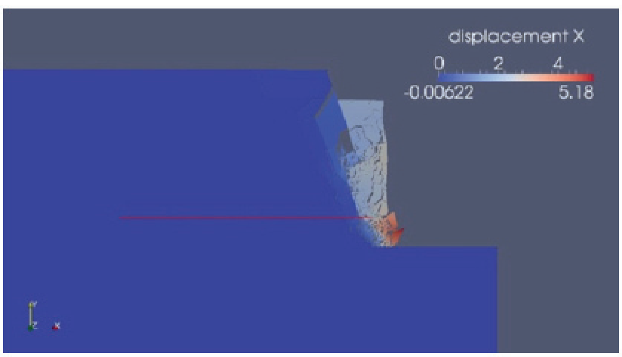

Fig. 10 - Numerical results of a FEMDEM ideal model of the Melendugno cliffs

DISCUSSION AND CONCLUSIONS

The examples described in this article illustrate some of the most frequent failure processes affecting the Apulian rocky coastlines by highlighting the most important conditioning factors, generally represented by the lithological and geostructural settings, the geomechanical properties of the rock mass, the rock susceptibility to weathering and karst, and the cliff exposure to wave storms and climatic actions. Given the importance of the coastal areas in the region, for a variety of reasons (tourism, agriculture, marine and fishing activities, transportation infrastructures, etc.), and the frequent episodes of cliff instabilities, often related to sea storms and to the most severe rainfall and wind events, the issue of cliff instability in Apulia Region certainly deserves high attention by researchers and local administrators. From this point of view, researchers should try to make increasing efforts towards different objectives, both at large and small scale. At the regional scale, reliable geographical systems highlighting the different rates of the cliff retreat over time as a function of the different conditioning factors, eventually showing also the future evolution scenarios, need to be developed for effective land planning purposes. At the same time, at the local scale, different research perspectives should be developed. Innovative techniques for detecting both the cliff geometry and the most important rock discontinuities and joint sets existing in the rock mass still need to be developed and properly applied; in particular, while the reconstruction of the cliff geometry is nowadays carried out in a straightforward manner by means of digital UAV-based or laser-scanning techniques, a strong advancement is still necessary in the field of automatic and semi-automatic identification of discontinuities from non-contact digital surveys. In addition, the monitoring activity of the cliff stability in near real-time aimed at detecting potential precursory signs of instability is still a demanding issue, due to the strong brittleness character of the cliff failure phenomena, especially when digital survey techniques based on non-contact proximal sensing are adopted. Finally, both standard and advanced numerical modelling techniques should be still deeply explored to investigate the different factors controlling the cliff failure mechanisms. In particular, these numerical simulations should be developed within the framework of the "digital-twin" model, which needs to be continuously updated and improved according to the field observations and measurements, thus pointing to a virtual truth of the rock cliff behavior. All these research activities should be coupled with the development of awareness policies toward residents and tourists, which is a fundamental element in the process of effective mitigation of the risk, in the perspective of a community more resilient towards natural hazards.

REFERENCES

Abellán A., Oppikofer T., Jaboyedoff M., Rosser N.J., Lim M. & Lato M.J. (2014) - *Terrestrial Laser Scanning of Rock Slope Instabilities*. Earth Surf. Process. Landf., **39**: 80–97.

Agliardi F. & Crosta G. (2003) – *High resolution three-dimensional numerical modelling of rockfalls*. Int. J. Rock Mech. Min. Sci., **40**: 455–471.

Adams P.N., Storlazzi C.D. & Anderson R.S. (2005) – *Nearshore wave-induced cyclical flexing of sea cliffs*. J. Geophys. Res., **110**: F02002, https://doi.org/10.1029/2004JF000217.

Andriani G.F. & Parise M. (2015) - *On the applicability of geomechanical models for carbonate rock masses interested by karst processes*. Environmental Earth Sciences, **74**: 7813-7821, DOI: 10.1007/s12665-015-4596-z.

Andriani G.F. & Parise M. (2017) - *Applying rock mass classifications to carbonate rocks for engineering purposes with a new approach using the rock engineering system*. J. Rock Mech. Geotechn. Engineering, **9**: 364-369.

Andriani G.F. & Walsh N. (2007) – *Rocky coast geomorphology and erosional processes: a case study along the Murgia coastline South of Bari, Apulia – SE Italy.* Geomorphol., **87**(3): 224–238.

Apuzzo D., De Vita P., Palma B. & Calcaterra D. (2013) - *Approaches for mapping susceptibility to rockfalls initiation in carbonate rock-masses: a case study from the Sorrento coast (southern Italy)*. Italian Journal of Geosciences, **132**(3): 380-393. Doi: 10.3301/IJG.2013.12

Bernatchez P. & Dubois J.M.M. (2008) – *Seasonal Quantification of Coastal Processes and Cliff Erosion on Fine Sediment Shorelines in a Cold Temperate Climate, North Shore of the St. Lawrence Maritime Estuary, Québec.* J. Coast. Res., **24**, 169–180.

Bezerra M.M., Moura D., Ferreira O. & Taborda R. (2011) – *Influence of wave action and lithology on sea cliff mass movements in Central Algarve Coast*. Port J Coast Res, **27**(6A): 162–171.

Budetta P., Galietta G. & Santo, A. (2000) – *A methodology for the study of the relation between coastal cliff erosion and the mechanical strength of soils and rock masses*. Eng Geol **56**: 243–256.

Calcaterra D. & Parise M. (Eds.), 2010, *Weathering as a predisposing factor to slope movements.* Geol. Soc. London, Engng. Geol. Sp. Publ. no. **23**: 233 pp.

Caldara M., Centenaro E., Mastronuzzi G., Sansò P. & Sergio A. (1998) – *Features and present evolution of Apulian Coast (Southern Italy)*. Journal of Coastal Research, Supplement Issue, **26**: 55-64.

Cardia S., Langella F., Palma B. & Parise M. (2023) – *Alternative methods for semi-automatic characterization of discontinuity sets from 3D point clouds.* Computational Geosciences, submitted.

Caso I., D’angelo R., Palma B., Parise M. & Ruocco A. (2014) – *Landslide susceptibility maps in the rock slopes of the Ventotene Island (Latium, Italy).* In: Lollino G., Giordan D., Crosta G.B., Corominas J., Azzam R., Wasowski J. & Sciarra N. (Eds.), *Engineering Geology for Society and Territory*. Landslide processes. Springer, ISBN 978-3-319-09056-6, **2**: 940-945.

Castedo R., Murphy W., Lawrence J. & Paredes C. (2012) – *A New Process-Response Coastal Recession Model of Soft Rock Cliffs*. Geomorphology, **177–178**: 128–143.

Coombes M.A. (2014) - *The rock coasts of the British Isles: weathering and biogenic processes*. In: KENNEDY D.M., STEPHENSON W.J. & NAYLOR L.A. (Eds.), *Rock Coast Geomorphology: A Global Synthesis*. Geological Society, London, Memoirs, **40:** 57–76.

Delle Rose M. & Parise M. (2004) - *Slope instability along the Adriatic coast of Salento, southern Italy.* Proceedings IX International Symposium on Landslides, Rio de Janeiro (Brasil), 28 June – 2 July 2004, **1**: 399-404.

Delle Rose M. & Parise M. (2005) - *Speleogenesi e geomorfologia del sistema carsico delle Grotte della Poesia nell’ambito dell’evoluzione quaternaria della costa Adriatica Salentina.* Atti e Memorie Commissione Grotte “E. Boegan”, **40**: 153-173.

De Vita P., Cevasco A. & Cavallo C. (2012) - *Detailed rock failure susceptibility mapping in steep rocky coasts by means of non-contact geostructural surveys: the case study of the Tigullio Gulf (Eastern Liguria, Northern Italy)*. Natural Hazards and Earth System Sciences, **12**(4): 867-880. Doi:10.5194/nhess-12-867-2012.

Dipova N. (2009) – *Preliminary assessment on the modes of instability of the Antalya (SW-Turkey) coastal cliff*. Environ Earth Sci, **59**: 547–560.

Dorren L.K.A. & Seijmonsbergen A.C. (2003) – *Comparison of three GIS-based models for predicting rockfall runout zones at a regional scale.* Geomorphology, **56**: 49–64.

Fazio N. L., Perrotti M., Andriani G.F., Mancini F., Rossi P., Castagnetti C. & Lollino P. (2019) – *A new methodological approach to assess the stability of discontinuous rocky cliffs using in-situ survey supported by UAV-based techniques and 3-D finite element model: a case study*. Eng. Geol., **260**: 105205, https://doi.org/10.1016/j.enggeo.2019.105205.

Gigli G. & Casagli N. (2011) - *Semi-Automatic Extraction of Rock Mass Structural Data from High Resolution LIDAR Point Clouds*. Int. J. Rock Mech. Min. Sc, **48**: 187–198.

Guenzi D., Godone D., Allasia P., Fazio N.L., Perrotti M. & Lollino P. (2022) – *Brief communication: Monitoring a soft-rock coastal cliff using webcams and strain sensors*. Nat. Hazards Earth Syst. Sci., **22**: 207–212, https://doi.org/10.5194/nhess-22-207-2022.

Gutierrez F., Parise M., De Waele J. & Jourde H. (2014) - *A review on natural and human-induced geohazards and impacts in karst*. Earth Science Reviews, **138**: 61-88, doi: 10.1016/j.earscirev.2014.08.002.

Hoek E. & Brown E.T. (1997) - *Practical estimates of rock mass strength*. International Journal of Rock Mechanics and Mining Sciences, **34**(8): 1165-1186.

Iannucci R., Martino S., Martorelli F., Falconi L. & Verrubbi V. (2017) - *Susceptibility to Sea Cliff Failures at Cala Rossa Bay in Favignana Island* (Italy). In: Mikoš M., Casagli N., Yin Y. & Sassa K. (eds) *Advancing Culture of Living with Landslides.* WLF 2017. Springer, Cham. https://doi.org/10.1007/978-3-319-53485-5_63.

Kennedy D.M., Stephenson W.J. & Naylor L.A. (Eds.) (2014) - *Rock Coast Geomorphology: A Global Synthesis.* Geological Society, London, Memoirs, **40**: 292 pp.

Liso I.S.& Parise M. (2023) – *Sinkhole development at the freshwater-saltwater interface in Apulia (Southern Italy)*. Proc. 17th Sinkhole Conference, Tampa (Florida, USA), 27-31 March 2023.

Loiotine L., Wolff C., Wyser E., Andriani G.F., Derron M.-H., Jaboyedoff M. & Parise M. (2021a) - *QDC-2D: a semi-automatic tool for 2D analysis of discontinuities for rock mass characterization*. Remote Sens., **13**: 5086. https://doi.org/10.3390/rs13245086.

Loiotine L., Andriani G.F., Jaboyedoff M., Parise M. & Derron M.H. (2021b) – *Comparison of Remote Sensing Techniques for Geostructural Analysis* *and Cliff Monitoring in Coastal Areas of High Tourist Attraction: The Case Study of Polignano a Mare (Southern Italy)*. Remote Sens., **13**: 5045. https://doi.org/10.3390/rs13245045.

Lollino P., Pagliarulo R., Trizzino R., Santaloia F., Pisano L., Zumpano V., Perrotti M. & Fazio N.L. (2021) - *Multiscale approach to analyse the evolution of soft rock coastal cliffs and role of controlling factors: a case study in South-Eastern Italy*. Geomatics, Natural Hazards and Risk, **12**: 1058-1081, DOI: 10.1080/19475705.2021.1910351.

Marinos V., Marinos P. & Hoek E. (2005) - *The geological strength index: applications and limitations*. Bull Eng Geol Environ, **64**: 55–65. Doi 10.1007/s10064-004-0270-5.

Martino S. & Mazzanti P. (2014) – *Integrating Geomechanical Surveys and Remote Sensing for Sea Cliff Slope Stability Analysis: The Mt. Pucci Case Study (Italy)*. Nat. Hazards Earth Syst. Sci., **14**: 831–848.

Mastronuzzi G. & Sansò P. (2006) – *Coastal geomorphology and Tsunami vulnerability. The case-study of Apulia region (Italy).* Geogr. Fis. Dinam. Quat. **29**: 83-91.

Mastronuzzi G., Pignatelli C. & Sansò P. (2004) - *Assessment of catastrophic wave impact in Apulia region (Southern Italy).* Risk Analysis **IV**, C: 681-689.

Melis M.T., Da Pelo S., Erbì I., Loche M., Deiana G., Demurtas V., Meloni M.A., Dessì F., Funedda A., Scaioni M. & ScaringI G. (2020) - *Thermal remote sensing from UAVs: A review on methods in coastal cliffs prone to landslides.* Remote Sensing, **12**(12): 1971. Doi:10.3390/rs12121971

Munjiza A. (2004). *The combined finite-discrete element method.* Wiley, Hoboken.

Pagano M., Palma B., Ruocco A. & Parise M. (2020) - *Discontinuity characterization of rock masses through Terrestrial Laser Scanner and Unmanned Aerial Vehicle techniques aimed at slope stability assessment*. Applied Sciences, **10**: 2960.

Parise M. (2008) - *Elementi di geomorfologia carsica della Puglia*. In: Parise M., Inguscio S. & Marangella A. (Eds.), Atti del 45° Corso CNSS-SSI di III livello di "Geomorfologia Carsica. Grottaglie, 2-3 febbraio 2008: 93-118.

Parise M. (2011) – *Surface and subsurface karst geomorphology in the Murge (Apulia, southern Italy).* Acta Carsologica, **40**(1): 79-93.

Parise M. (2019) - *Sinkholes*. In: White W.B., Culver D.C. & Pipan T. (Eds.), Encyclopedia of Caves. Academic Press, Elsevier, 3rd edition, ISBN ISBN 978-0-12-814124-3: 934-942.

Parise M. (2022) - *Sinkholes, Subsidence and Related Mass Movements.* In: Shroder J.J.F. (Ed.), Treatise on Geomorphology, vol. **5**. Elsevier, Academic Press: 200–220. https://dx.doi.org/10.1016/B978-0-12-818234- 5.00029-8. ISBN: 9780128182345.

Parise M., Federico A., Delle Rose M. & Sammarco M. (2003) - *Karst terminology in Apulia (southern Italy)*. Acta Carsologica, **32**(2): 65-82.

Pellicani R., Miccoli D., Spilotro G., Gallipoli M.R., Mucciarelli M. & Bianca M. (2015) - *Dynamic response of a rocky cliff under the sea wave pulse: a study along the Adriatic coast of Polignano (Apulia, Italy).* Environmental Earth Sciences, **73**(10): 6243-6257. Doi 10.1007/s12665-014-3848-7.

Perrotti M., Godone D., Allasia P., Baldo M., Fazio N.L. & Lollino P. (2020) - *Investigating the susceptibility to failure of a rock cliff by integrating Structure-from-Motion analysis and 3D geomechanical modelling.* Remote Sensing, **12**: 3994. Doi 10.3390/Rs12233994.

Rosen P.S. (1980) - *Erosion Susceptibility of the Virginia Chesapeake Bay Shoreline*. Mar. Geol., **34**: 45–59.

Rosser N.J., Petley D.N., Lim M., Dunning S.A. & Allison R.J. (2005) - *Terrestrial Laser Scanning for monitoring the process of hard rock coastal cliff erosion.* Q. J. Eng. Geol. Hydrogeol., **38**: 363–375.

Sansò P., Gianfreda F., Leucci G. & Mastronuzzi G. (2016) - *Cliff evolution and late Holocene relative sea level change along the Otranto coast (Salento peninsula, southern Apulia, Italy)*. J. Geophys. Res., **9–12**: 42–53.

Sauro U. (1991) - *A polygonal karst in Alte Murge (Puglia, southern Italy)*. Z. Geomorphol., **35**(2): 207–223.

Stephenson W. & Naylor L. (2010) - *Rock coast geomorphology.* Geomorphology, **114**: 1–100.

Sunamura T. (2015) - *Rocky Coast Processes: With Special Reference to the Recession of Soft Rock Cliffs.* Proc. Jpn. Acad. Ser. B Phys. Biol. Sci., **91**: 481–500.

Sunamura T. (1992) - *The Geomorphology of Rocky Coasts.* Wiley: Chichester, UK.

Trenhaile A.S. (1987) - *The Geomorphology of Rock Coasts*. Oxford Research Studies in Geography; Clarendon Press: Oxford, UK. ISBN 9780198232797.

Trenhaile A.S. (2010) - *Modeling Cohesive Clay Coast Evolution and Response to Climate Change*. Mar. Geol., **277**: 11–20.

Trenhaile A.S. (2014) - *Climate Change and its impact on rock coasts*. In: Kennedy D.M., Stephenson W.J. & Naylor L.A. (Eds.), *Rock Coast Geomorphology: A Global Synthesis.* Geological Society, London, Memoirs, **40**: 7–17.

Vennari C., Salvati P., Bianchi C., Casarano D., Parise M., Basso A. & Marchesini I. (2022) - *AReGeoDatHa: Apulian regional GeoDatabase for geo-hydrological hazards*. J. Environ. Management, **322**: 116051.

Walkden M. & Dickson M. (2008) - *Equilibrium Erosion of Soft Rock Shores with a Shallow or Absent Beach under Increased Sea Level Rise*. Mar. Geol., **251**: 75–84.

Received February 2023 - Accepted March 2023