A suggested method for assessing cliff instability susceptibility at a given scale (CISA)

G.F. Andriani, V. Pellegrini

Abstract—This paper illustrates a new multidirectional method for assessing cliff instability susceptibility at a given scale (CISA, Cliff Instability Susceptibility Assessment) through a case study along the Murgia coastline North of Bari (Apulia, SE Italy). The stretch of coastline considered in this study shows an indented rocky coast with cliffs up to 12 m high, numerous small to medium-sized caps and inlets, and a well protected tourist port. The coastal outcrops are made up of Mesozoic carbonate rocks which are thickly-bedded (0.2-1.0 m) and, moderately to highly fractured and karstified. At places, clear signs of coastal erosion are evident; they consist mainly of rock falls caused by differential erosion of rock strata of varying resistance to weathering and sea wave action on the cliff face.

The CISA method is based on classifying coastal sectors using above all morphological criteria and characterising them estimating and combining 28 incidence parameters according to an heuristic approach. These parameters were divided in four categories: geomechanical (12), morphological (6), meteoro-marine (8) and anthropogenic (2). 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.

Keywords—Cliff, Carbonate, Instability, Method.

I. INTRODUCTION

In many sites of Apulia (SE Italy), the coastline is gradually receding inland as a result of natural and human processes.

In particular, morphologic features of the rocky coast, mostly produced by Quaternary tectonics, are strongly conditioned by complex mechanisms involving sea waves action against the cliffs, carbonation, weathering and urbanization pressure [1]. 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. 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. 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 [2]-[3]-[4]-[5] and references therein.

Fig.1. Geographic location of the study area.

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 2000 m in the territory of Giovinazzo, about 20 km NW of Bari, is carried out. 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.

II. SETTING

The study area is located on the Adriatic side of the Murge plateau, an emerged part of the Apulian foreland, about 20 km NW of Bari, in the territory of the Municipality of Giovinazzo (Fig. 1). The Murge plateau is characterized by a 3 km thick
Cretaceous shallow-water succession of limestones and dolostones forming a S-SW dipping monocline slightly deformed by folds and sub-vertical normal and transtensional faults [6]. This succession consists of lagoonal and peridital carbonates mostly deposited in low-energy inner-platform environments [7]. 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 [8]. The limestones and dolostones are bedded, jointed and subjected to karst processes, and represent a peculiar hydrogeological domain. 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 [1]. 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 recognize, as often occurs in karst areas [9]-[10]. 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.

The coastal stretch of Giovinazzo is characterized by the outcropping of the lower part of the Calcare di Bari Fm. (Callovian pp.-early Turonian). This part consists of an about 25-m-thick interval characterized by rudist-dominated medium- to coarse-grained deposits. Rudists form dm- to m-thick sheetlike tabular bodies with whole shells in growth position or more commonly randomly oriented [7]-[8]. The rudist beds gradually pass upward to mud-dominated fine-grained biopeloidal mudstones/wackestones and to laminated fenestral peloidal bindstone showing microbial laminations (Fig. 2).

Morphological features along the Giovinazzo shoreline are typical of an indented rocky coastline where caps and inlets follow each other and steep cliffs, here from about 1.0 m (microcliffs) to 10 m in height, end in subhorizontal surfaces at the top and bottom. Before the tourist port, further to NW, the cliff is protected by a subhorizontal or gently sloping inward wave-cut platform; the last extends from the base of the cliff for 5 m to 10 m and is submerged or emerged with rising and falling of the sea level. The most part of the coastal stretch is protected by a retaining wall made of carbonate stone masonry or unreinforced concrete (Fig. 3).

The wall is about 12 m at its highest part where there is the south side of the historical center of the city which lies on a promontory overlooking the sea. The north side of the historical center overlooks the tourist port which is bordered seaward by two jetties. Large rock or concrete boulders chaotically arranged were used in the past for the protection of the cliff and the outer walls of the old city (Fig. 4).

To the SE, a bay characterized the whole sector that at
places presents a small beach mainly formed by calcareous and concrete pebbles coming from coastal erosion processes and improvised attempts of beach nourishment (Fig. 5).

Fig. 5 – Small beach mainly formed by calcareous and concrete pebbles.

III. 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 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 5 sectors the coastal stretch under consideration. “Regional Technical Map” (CTR) of Apulia at scale 1:5000 (www.sit.puglia.it), georeferenced 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 – Coastal 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.

Table I – Rating of 28 parameters of the CISA method.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Very bad</th>
<th>Bad</th>
<th>Normal</th>
<th>Good</th>
<th>Very good</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geomechanical</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Number of discontinuity</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Intensity of joints</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Slope inclination</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Weathering</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Water depth</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Water temperature</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
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<tr>
<td>Riprap</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
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<tr>
<td>Fissures</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Tension cracks</td>
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<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Joints</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Uniaxial compressive strength</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

Table II – Stability classes as per CISA values.

<table>
<thead>
<tr>
<th>CISA Value</th>
<th>0</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class</td>
<td>I</td>
<td>II</td>
<td>III</td>
<td>IV</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Classification</td>
<td>Completely unstable</td>
<td>Unstable</td>
<td>Stable</td>
<td>Unstable</td>
<td>Stable</td>
<td></td>
</tr>
</tbody>
</table>

Discontinuities in rock masses were described according to the ISRM standards [11]. 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 volumetric joint count (Jv) and block sizes [12]. Notches and karst features were account as prominent natural coastal hazards. Following the standard test procedure outlined in ISRM [13]-[14], dry unit weight (γd), porosity (n) and uniaxial compressive strength in the dry state (σc) were determined on 10 cylindrical specimens (100 mm in diameter) prepared from little rock blocks 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. These last, in fact, are composed mostly of carbonate with an negligible insoluble residue [15]. Dry unit weight is in the range 19.0-23.2 kN/m³, porosity between 12.2-18.1% and uniaxial compressive strength between 18.3-112.5 MPa. Rock mass hardness was measured in situ with the Schmidt hammer (type L). Higher porosity and, lower strength and density values are due to high weathering rates of a coarse-grained bed at the base of the cliff cropping out in the first coastal sector. 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 [16]. A precautionary approach was adopted in the analysis so that for each lithotechnical unit 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 [17], 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.

Fig. 7 – Differential erosion of rock strata of varying resistance to weathering on the cliff face.

Strong side winds and fetch (effective length) were measured for each coastal sector in correspondence of caps, inlets and the tourist port of Giovinazzo. The effective fetch was defined along the NW, N and NE winds using the recommended procedure of the Shore Protection Manual [18] 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, $H_s$ (m), and the offshore time peak, $T_p$ (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 $L_o$ (m) was obtained from the term Linear (or Airy) Wave Theory [19] along the NW wind ($315^\circ$N), the N wind ($315^\circ - 45^\circ$N), the NE wind ($315^\circ - 90^\circ$N) and the NE wind ($0^\circ - 90^\circ$N). For the CISA method, the breaking wave depth and the breaking wave height were determined with the Goda's nomographs [20], while the impact wave height was calculated with the empirical relationship developed by [21]; the type of breaking wave was obtained by the Okazaki & Sunamura’s laboratory study [22].

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 and streets. Furthermore, the most part of the coastal stretch studied presents shore protection structures such as jetties and seawalls with natural stone facing (limestones) or unreinforced concrete. Therefore, clear signs of coastal recession are evident and include the breaking down and removal of material along the coastline by the movement of sea-water (sectors IV and V) and rock falls caused by differential erosion of rock strata of varying resistance to weathering and sea wave action on the cliff face (sector I). Data from field observations indicate that the coastal recession appears not uniform with time and mainly governed by cliff collapses. Notches and their increase in size cause rising shear stresses that induce the cliff to fail, but the presence of a highly weatherable laminated bed cropping out along the cliff face is considered a hazardous condition (Fig. 7).

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 [23]. 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 [24]-[25]. In this case, the role of meteo-marine parameters appears to be secondary in the cliff erosion and collapses (Fig. 8).

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.

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 Giovinazzo is unstable, although at places retreat processes are opposed by engineering protection structures (jetties, retaining walls etc.). Furthermore, the urbanization of the coastal area has de facto prevented the beach accretion at the cliff toe as a natural barrier against wave action and shoreline erosion.

Table III – Partial rating and CISA rating obtained for the study area.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Coastal sectors</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breaker zone</td>
<td>Number of jet</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Impact</td>
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<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
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<tr>
<td>Type</td>
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<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Roughness</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Swath width</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Stability</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Wave impact height</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Water depth</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Distance between joints and slope toe zones</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Rain infiltration with respect to surficial rock movements</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

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 1992 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 different in each sector: plunging waves are typical of the sector I and II, while collapsing and surging waves characterise the sector V and, the sectors III and IV respectively; the plunging waves break with more energy than the others. With regards to the exposure, the worst condition happens in the sectors I and II 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 III.

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


