STATIC AND DYNAMIC STABILITY ANALYSES OF PESCHICI CLIFF (SOUTHERN ITALY)

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RÉSUMÉ
La fin principale de cet article a été l'évaluation numérique de la stabilité statique et dynamique d'un tronçon de côte situé á Peschici une petite ville le long du "Promontorio del Gargano", très importante au point de vue touristique. Par conséquent un effort considérable a été fait pour évaluer numériquement soit les déplacements en cours, soit ceux qui sont seulement potentiels. Le "Promontorio del Gargano", est caractérisé par une vaste variété de morphologies différents tels que falaises calcaires, conglomératiques, larges plages, baies, cales. Dans ce travail, le rocher de Peschic a été sélectionné pour l'étude, en particulier la zone de la "Rupe Castello", pour laquelle un risque élevé est associé. L'étude s'est déroulée en deux phases. Dans un premier temps, an moyen d'une recherche géo-mécanique globale sur le promontoire en entier, plusieurs familles de discontinuité ont été déterminées (avec l'aide de stéréonet) et donc le test de Markland a été appliqué afin d'identifier les cinématiques qui peuvent, éventuellement, avoir un impact sur la stabilité du rocher. Dans la seconde phase, cinq sections géologiques dans des directions différentes ont été sélectionnées. Une version 2D d'un code commercial pour élaborer des analyses de stabilité statique et dynamique a alors été appliqué à ces régions. Ils ont été discuté quelques conclusions.

ABSTRACT
The main objective of this paper has been the numerical evaluation of static and dynamic stability of a small rock sea cliff located in Peschici, a small city along the Gargano promontory (Southern Italy),very important for tourism. A considerable effort has been spent to numerically evaluate both most likely as well as potential landslide displacements.
The Gargano promontory is characterized by a widespread occurrence of different land morphologies like cliffs, coves, bays. 'Rupe Castello' zone of the Peschici Cliff has been selected for this paper, as the zone to which the highest geohazard level has been ascribed. The study has been carried out in two steps.
In the first step, by a global geo-mechanical surveys of the whole promontory, several discontinuity families have been recognized (stereonet technique) and then a commercial software using the Markland test has been applied in order to identify the kinematic mechanism which could eventually affect the stability of the whole Peschici area.
In the second step, five geological sections in five different directions crossing the "Rupe Castello" zone, have been selected. Then a commercial 2D slope stability code has been applied in order to perform both static and dynamic stability analyses. Some conclusions have been discussed.

1. INTRODUCTION

The stability analyses represent a valid tool in order either to estimate the occurrence likelihood of landslide phenomena and to obtain indications about the hazard in areas affected by to landslide events. In particular, buildings vulnerability located close to cliffs as those shown in Fig.1, will be considered.
The selected area covers some coastal strips of the territory of Peschici, for an extension of approximately 10 km, comprised in the north-eastern side of the Gargano promontory.
In particular, Peschici is located in a zone directly plumb on the sea, lying on a cliff of invaluable beauty, at 70 meters a.s.l.. It is characterized by a large variety of morphologies, like limestone and conglomerate cliffs and wide shore, suspended valleys, bays, coves.

2. GEOLOGIC AND GEOMORPHOLOGIC FEATURES

The Gargano promontory is the result of a long geologic history lasted hundred million years, characterized by a variety of different kinds of events. Sedimentation processes and successive diagenesis generated cliffs which, later on, have been dislocated and fragmented by tectonic actions and then modeled by morphologic agents operating either in surface and in the inner deep part of the area under examination.

Figure 1. View of "Rupe Castello".

In : J. Locat, D. Perret, D. Turmel, D. Demers et S. Leroueil, (2008).
Comptes rendus de la 4e Conférence canadienne sur les géorisques: des causes à la gestion.
Proceedings of the 4th Canadian Conference on Geohazards : From Causes to Management. Presse de l'Université Laval, Québec, 594 p.

The Gargano promontory is the most northern and elevated area of the Apulian foreland. Its structure is constituted by a dominant succession of dolomitic limestone sediments, of Jurassic and Cretaceous age, placed on Triassic evaporitic lands, related to Anhydrides of Burano, result of a long evolution of a reef environment (Cremonini *et al.*, 1971), replaced in the lower Cretaceous by a carbonatic platform (Masse & Luperto Sinni, 1987). On this succession, along the perimeter of the Cape, calcarenitic sediments, related to some transgression episodes occurred within Paleocene and Quaternary periods, are located. Quaternary sediments dislocated in the area south of the Lesina Lake and east of the Varano Lake cover locally the Great Plan of Vieste, the wide terrace west of Manfredonia and some coastal strips. They are constituted by shores, recent dunes and alluvial deposits, debris, eluvial and colluvial deposits and coastal terrace deposits.

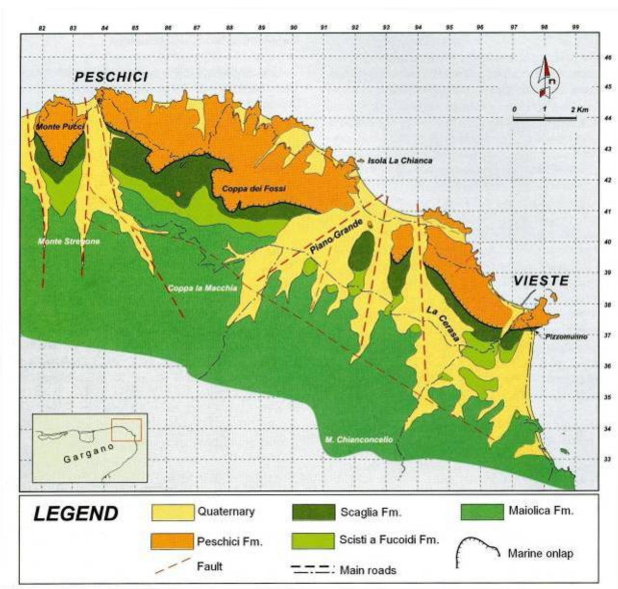

Figure 2. Simplified Gargano geologic map (Bosellini e Morsilli, 2000).

The outcropping lithologic units in the selected area (Fig. 2), from the bottom to the top, are:
Maiolica fm. (compact micritic and biomicritic limestones with cherts), Scaglia fm. (compact limestones and marly limestones alternations), 250-300 m thick layer of Nummulitic limestones of Peschici (compact organogenic limestone) (fig. 3) and then quaternary deposits. Gargano Promontory is separated from "Tavoliere delle Puglie" and Southern Apennines by means of some important tectonic joints along NE-SW direction (Fortore Volturno and Sorrento Manfredonia alignments, Ciaranfi *et al* 1983) and along NW-SE direction (Candelabro fault, Mongelli & Ricchetti, 1970). These lineaments are constituted by normal, reverse and transcurrent fault systems, discovered by geognostic surveys, Landsat satellite images, aerial photographs and high resolution seismic surveys.

3. GEOSTRUCTURAL FEATURES

The old town centre of Peschici was built on a stony reef, 70 m high on average, formed by middle and upper Eocene carbonate deposits. They are related to Nummulites limestone of Peschici and are organized in calcic turbidite banks, in Pelagic limestone, in Calcarenites and in some breccias and mega breccias levels which testify synsedimentary landslide events. At present, the outcroppings show a chaotic structure and where stratum joints are clearly localizable, the related posture is less inclined than the slope. At the base of the cliff it is possible to observe some shoreline trucks, testifying a sea erosive action due to either chemical and mechanical attack, with

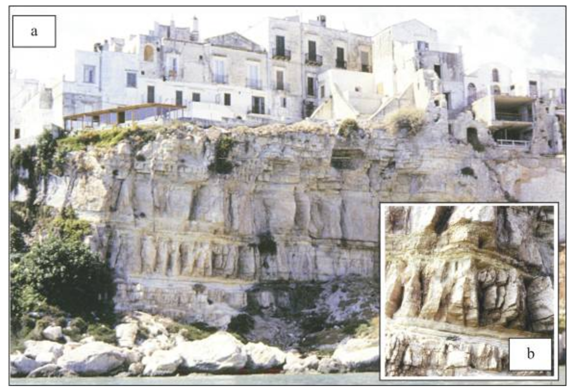

Figure 3. Particular of Peschici cliff: a) panoramic view; b) detailed erosion phenomena

phenomena of karst dissolution and removal of small fragments. This kind of erosive action is visible not only at the base but it is evident in all part of the cliff.
The dissolution action is much more discernible in correspondence of the superficial discontinuities which mark all the cliff, isolating large dimension blocks as well. Some of these blocks, in the past, fallen down and their presence at the feet of the cliff testifies this kind of events. Through a structural geomechanic survey, carried out by some rock-climbers on the walls of the cliff, it came out that its structure is crossed by different series of fractures of various entity. In the selected strip, just below the castle (Fig. 4), the prevailing system of fractures is approximately oriented along the North-South direction. The fracture plans are sub-vertical, characterized by a slight deviation towards the West. Generally the fractures are five to ten centimeters wide and they can be observed along a vertical direction of several tens of meters, before shrinking itself towards the bottom until getting lost or disappearing in sea.
Some fractures diverge remarkably from the direction of the aforementioned system. One of which, approximately 30 cm width, visible under the western side of the castle in correspondence of the panoramic garden, is of particular importance (Fig. 5). This fracture lies on a vertical plan, along an approximately direction N70E. It constitutes a potential hazard for the stability of the cliff, since it intercepts the prevailing system of fractures (North-South) with an angle that varies from 60° to 80° degrees, subdividing the whole rocks mass in a series of smaller blocks, each

separated from the others, some of which in conditions of precarious stability. Some XIV century buildings were built upon this fracture line.

4. GARGANO SEISMICITY

The map of Gargano area shows a rather intense seismic activity (Fig. 6). The earthquakes that in the centuries have interested the area are numerous. Among the most ancient earthquakes, one dated 493 A.C and another one dated 1627 should be mentioned. The last is recorded as the most dangerous one, causing a devastating tsunami and about 5000 victims. The strongest recent event of the Gargano area has taken place in 1995, with magnitude (Richter) M=4.6 (VIII - IX M.C.S. degree). Its epicentre was localized in the central part of the Cape, at about 20 km depth.

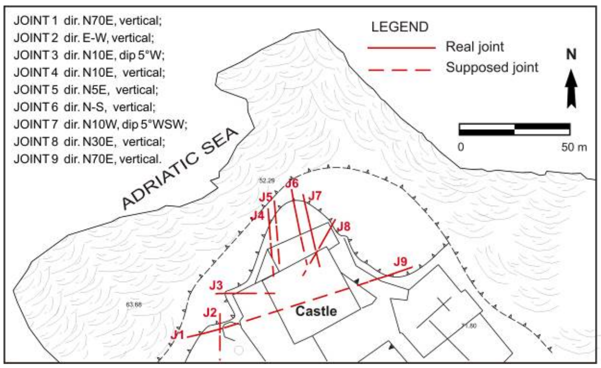

Figure 4. Outline of the fracture state of the "Rupe del Castello"

Figure 5. Fractures on the western side of the castle.

Through the comparison between historical and recent seismic occurrences, it could be inferred that the north-eastern area of the Gargano site, where Peschici is located, is concerned with a rather frequent, but not so usually high intensity seismic episodes. Such seismic activity can be interpreted as an evidence of a strong tectonic action that has determined an intense fracturing and a consequent falling down of the outcropping rocks in the territory of Peschici.

5. GEOMECHANIC SURVEYS

A geomechanic survey has been carried out in order to define a selected area within which to apply a scan line methodology. The most important collected parameters have been: the number of joints families, direction of each discontinuities, spacing between joint, roughness related to joints characterized by a small scale, compression resistance of the walls of the discontinuities, opening of the joints and type and nature of the filling material, hydraulic conditions, weathering conditions of the discontinuities walls, ending of the joints tip, persistence and height on the scansion line. In total, thirteen line mappings have been selected. Their lengths ranged between five-ten meters up to 50 meters in aerial photographic surveys.

In all these areas the geomechanical survey has been executed with line mapping according to ISRM (International Society for Rock Mechanics). In "Rupe Castello" locality, a photographic mapping has been executed because of the inaccessibility of the places. All the applied methodologies have been in agreement with the recommendations of the ISRM (International Society for Rock Mechanics).

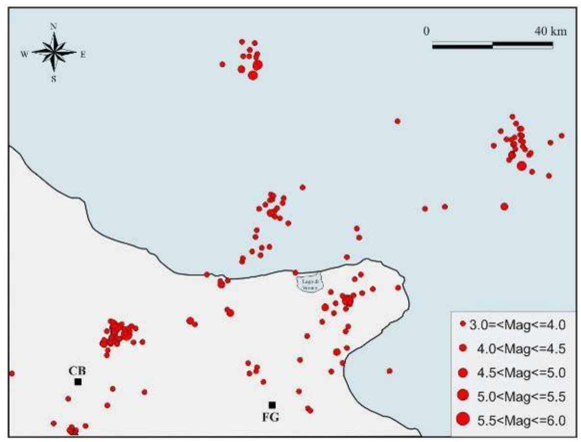

Figure 6. Earthquakes epicentres distribution

The choice of the mapping location has been carried out mostly with the attempt to interest portions of different geo-lithological and structural points of view.

6. ANALYSIS

Surveying carried out by some rock-climbers, has stressed that the ridge below the old town centre is in a fracturing condition and some portion of the related

rock mass is in unstable equilibrium. The cliff below the old town, layed on Eocenic calcarenite is characterized by a slope immersion. These lithofacies are subjected to phenomena of karst dissolution, due to metheoric and marine water. The current phenomena are characterized by the ongoing segregation of large wedges, thus subject to fall down hazard. Despite this evidence, old town buildings are not interested by important phenomena of instability. Along cliffs below the old town, a photographic survey, has been carried out in order to identify the main joints. The position of the mapping lines analyzed by photographic method is shown in figure 7. A brief description follows. Data set 1rc: the photographic survey 1rc is about 50 m long, approximately parallel to a 70 m high wall, oriented 310/89.

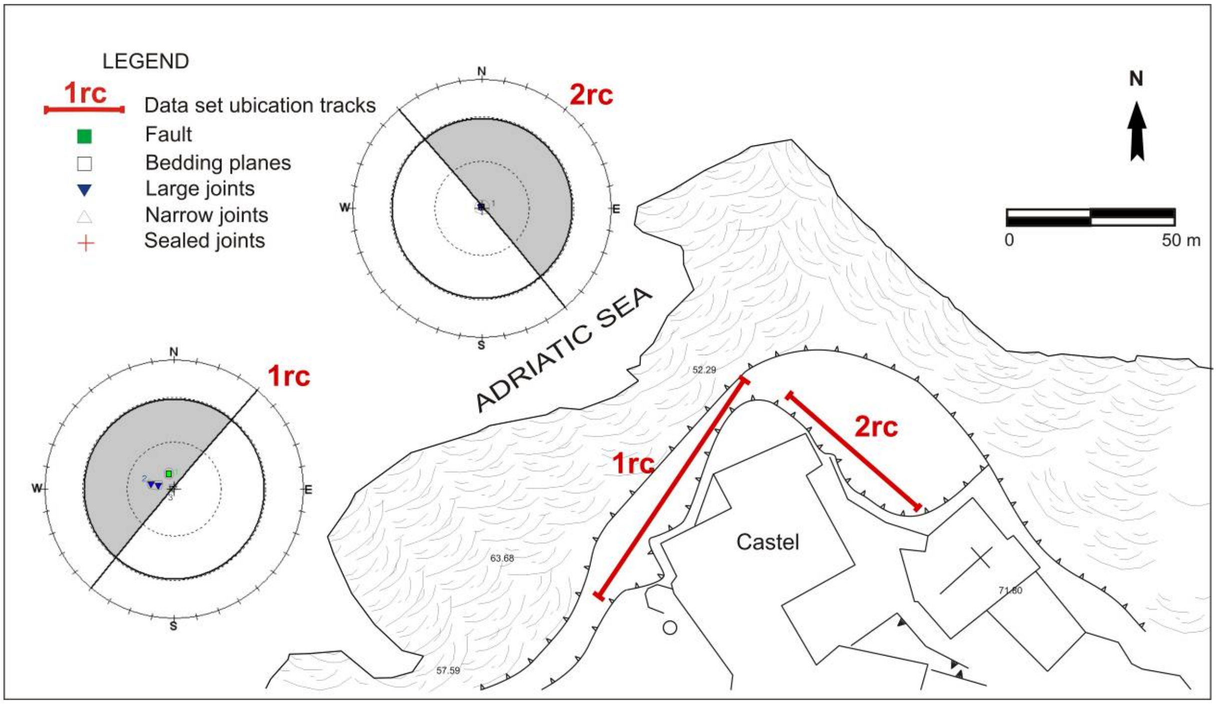

Figure 7. Location and relative distribution of the discontinuities in correspondence of the selected surveys area

From the data analysis, three families of discontinuity are emerged: family 1: constituted by one fault, with direction 340/80; family 2: constituted by important fractures, with direction 284/77; family 3: constituted by small fractures, with direction 288/89. Among these, following the indication of the Markland test, carried out by Rockpack III computer code, only the 1 and the 2 fall back in the critical zone, therefore, along the related direction, displacements could occur.

The most probable kinematic mechanism, since the verticality of the fracture, is a direct topple. In figure 8a it is possible to observe that some unstable blocks come to be isolated also by the intersection of the two families of discontinuity, in fact, their intersection point falls back in the critical zone. Fig. 8b describes the probability of kinematic mechanism occurrence for toppling. No fractures belonging to the survey area 2_{rc}, within which a photographic methodology has been applied, fall back in the critical zone related to the Markland test (not reported), therefore, the wall in examination can be considered stable

7. NUMERICAL MODELLING

The fall landslides occurrence along the coast must necessarily be due to instability factors like the seismic events and, much more frequently, the wave motion. In fact, the limit between the stable and unstable condition is closely linked. Therefore, the stability concept, should be related to the probability that an earthquake or a whichever event of elevated energy stressing the slope can occur. to the probability that the applied forces can change. In order to have a numerical idea about which the current conditions are, in the present paper an analysis of the castle's cliff stability has been carried out.

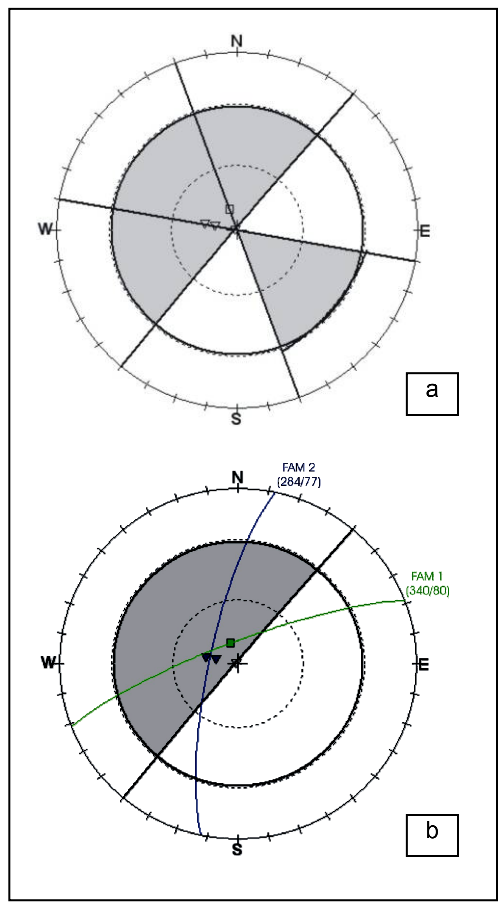

Figure 8. Markland test for wedge sliding (a), Markland test for direct topples (b).

Such analysis has been executed at first in static conditions and subsequently in dynamic conditions. The stability analysis, has been carried out through a 2D numerical modeling software, Distinct Element, UDEC 4.0. (Itasca 2004). UDEC simulates, numerically, the behavior of discontinuous media, like a fractured rock mass, subject to static or dynamic loading. It is one of the most recent 2D computer codes capable of modeling deformation of both rigid and deformable blocks.
The discontinuous media are simulated as discrete blocks; the discontinuities are considered like borders between the blocks; both large displacements and blocks rotation are allowed. Individual blocks behave as either rigid or deformable material. Deformable blocks are subdivided into mesh of finite-difference elements and each element responds according to a prescribed linear or nonlinear stress-strain law.
The strength reduction method for determining the factor has been implemented. Failure is assumed to occur when the forces cannot be balanced. This could possibly mean that just only one of the small blocks has become unstable. The user has control over specific zone and joint properties to be reduced in the calculation.
The geomechanic survey has been carried out in agreement with the Bieniawski (1978) method and it has been based on the determination of parameters such the cohesion (c), the Young's modulus (E), the angle of friction (φ), the unit weight (γ) and the uniaxial compression resistance (R'_{ck}) through Schmidt's hammer.
Every outcropping has been analyzed at least 10 times, in such a way to obtain a representative sample, which has been refined by cutting off extremely low values, related to not representative portions of weathered surface.
Then average values ,reassumed in Table 1 ,have been taken as reference parameters.

Table 1. Geomechanical parameters related to some outcropping lithotypes of the "Rupe del Castello".

Lithotypes	c (KPa)	φ (no fract.)	φ (fract.)	γ (kN/m^3)	E (GPa)
Fine grained Limestones	275	40^0	32.5^0	24.1	1.11
Calcarenites	257	38^0	30.5^0	22.3	1.04
Breccias and Megabreccias	240	37^0	29.0^0	21.7	0.94
Organogenetic Calcarenites	254	38^0	30.4^0	22.4	1.01

The following Hoek and Brown constitutive law has been assumed for static and dynamic analysis:

$$\sigma_1 = \sigma_3 + \sigma_{ci} \cdot (m_b \frac{\sigma_3}{\sigma_{ci}} + s)^a \qquad [1]$$

Where:

σ_1 = maximum main stress deformation peak;

σ_3 = minimum main stress;

m, s and a parameters whose values are related to rock mass properties;

σ_{ci} = uniaxial compression stress of intact rock.

Numerical values of these parameters, related to the four selected lithotypes, are reported in Table 2.
Then Coulomb constitutive model has been selected for Joints material. A list of some parameter values follow: normal stiffness jkn = 1.e10 Pa/m (default value), shear stiffness jks = 1.e9 Pa/m (default value), Friction angle φ = 20^o, cohesion and expansion angle equal zero.

8. DATA ANALYSES AND NUMERICAL RESULTS DISCUSSION

The analysis has been executed taking into consideration five sections (Fig. 9), oriented along various way, in order to study the stability of the Cliff in all the directions.

Table 2. Hoek and Brown geomechanical parameters related to the outcropping lithotypes selected on "Rupe del Castello" area

Lithotypes	a	s	m	σ_3	σ_c
Fine grain Limestones	0.501	0.0091	1.264	18.75	75
Calcarenites	0.503	0.0023	0.925	7.5	33
Breccias and Megabreccias	0.501	0.0091	1.580	8.75	35
Organogenetic Calcarenites	0.501	0.0091	1.580	7.5	33

The directions of the selected sections are: section A-A' (NW-SE); section B-B' (NE-SW); section C-C' (NW-SE); section D-D' (WNW-ESE); section E-E' (N-S). For each section a factor of safety has been calculated both in static and dynamic conditions. The dynamic analysis has been carried out applying a seismic loading at the numerical model base. The applied input has been a design earthquake appropriately scaled based on the Italian seismic classification (a=0.25g). Thus the selected earthquake acceleration has been introduced into the model as a scaled earthquake signal. In table 3 the values of the relative factor of safety related to all the sections, are reported. Except for the E-E' section, all the other factors of safety are rather high. For a better understanding of the identified kinematic mechanism, sections have been subdivided in two groups. In the first one A-A' and C-C' sections, while in the second one B-B', D-D', E-E' sections. Only A-A' and the E-E' sections will be discussed since the most representative of each group. In fig.10 and 11, their profiles and the related joints, bedding plans, blocks geologic characterization and numerical meshing have been reported.

Table 3 Values of the safety factors for both type of analyses.

Lithotypes	A	B	C	D	E
Static F_s	1.84	3.06	1.52	2.3	1.11
Dynamic F_s	1.63	2.10	1.36	1.63	0.90

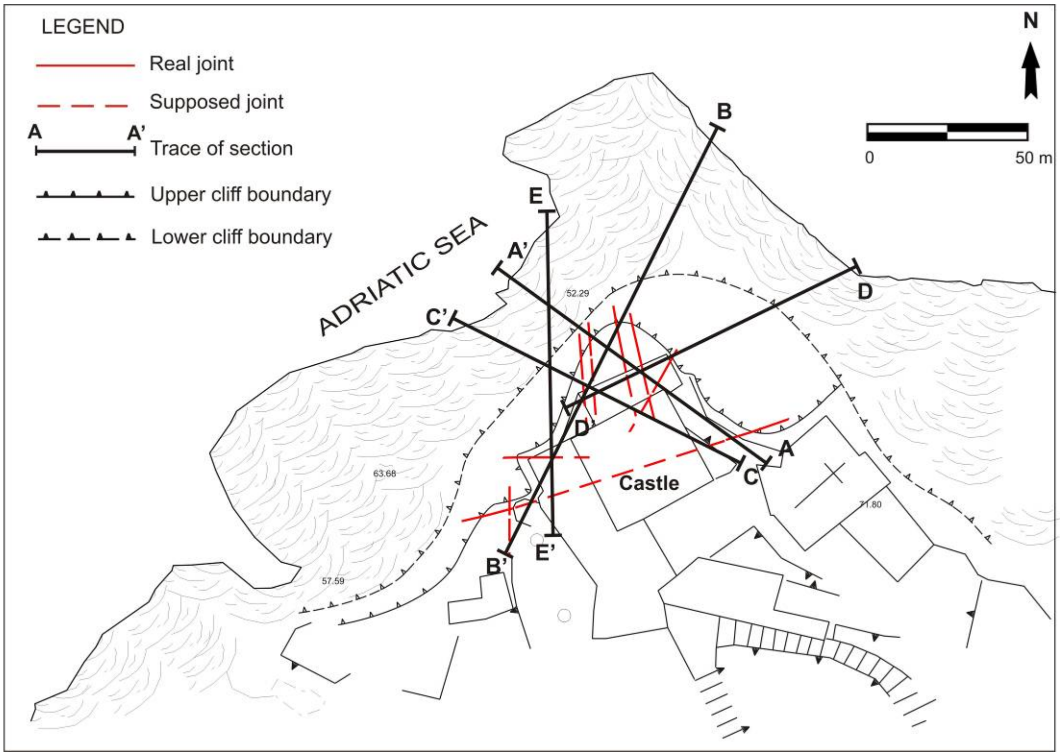

Figure 9: Location of the analyzed sections

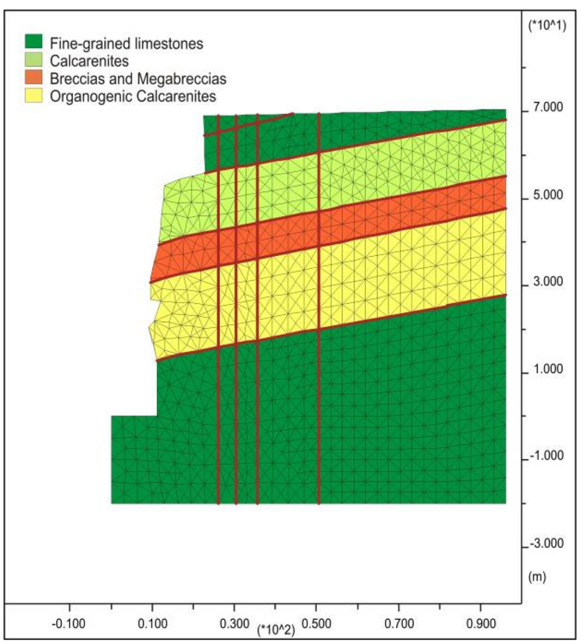

Figure 10. Discretized A-A' numerical and geologic section

8.1. Numerical static result discussion related to A-A' section

The static factor of safety related to A-A' section with direction NW-SE is equal to 1.84. From fig. 12, it is evident that the numerical displacements are concentrated in the upper portion of the section.

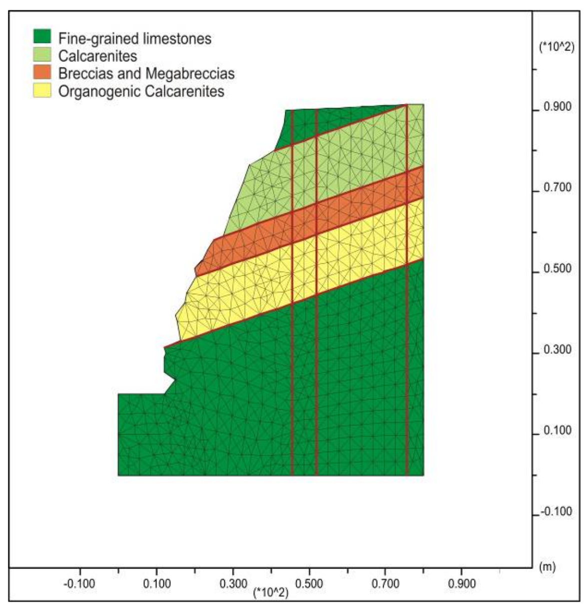

Figure 11. Discretized E-E' numerical and geologic section

The related four displacing blocks, see fig. 13, show the tendency to slip on their plan and to separate themselves along the vertical joints.

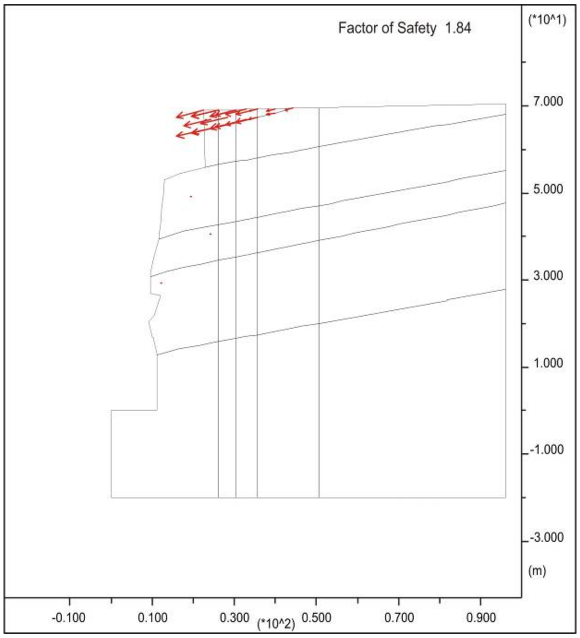

Figure 12. A-A' section, static analyses, displacement vectors plot

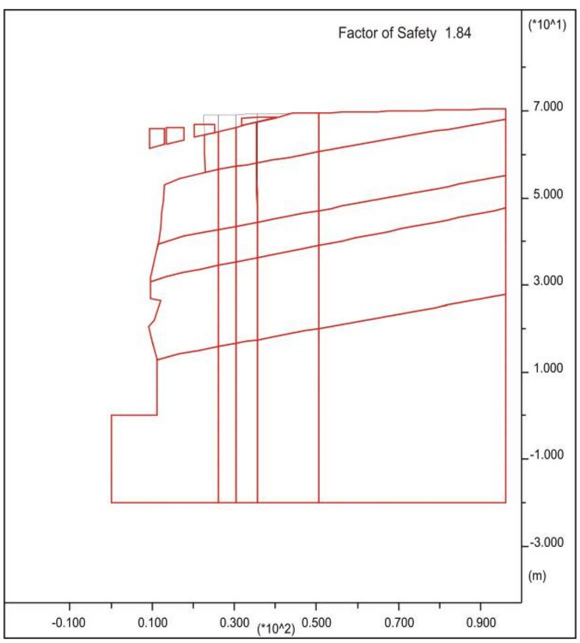

Figure 13. A-A' section, static analyses, deformed meshing

8.2. Numerical dynamic result discussion related to A-A' section

Dynamic analyses results are very similar, by displacements point of view, to the static ones, see fig. 14, but in this case the factor of safety is lower and equal to 1.63. Moreover it is possible to recognize, from figures 14 and 15, that the blocks which become unstable are only the three more external, while the quarter does not show any perceivable numerical displacements.

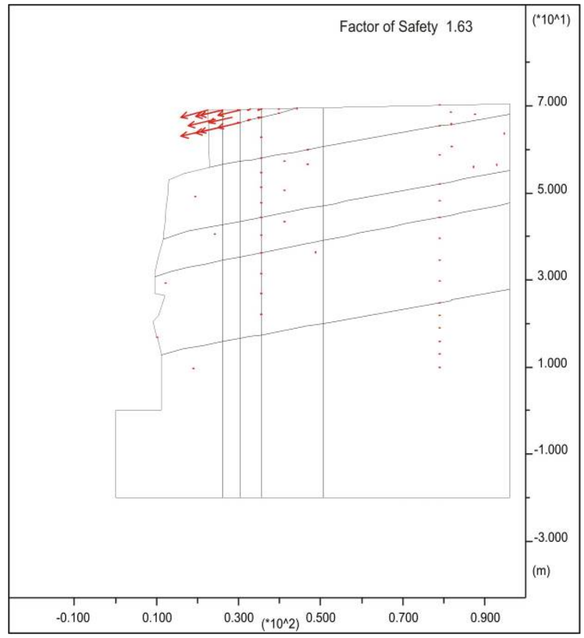

Figure 14. A-A' section, dynamic analyses, displacement vectors plot

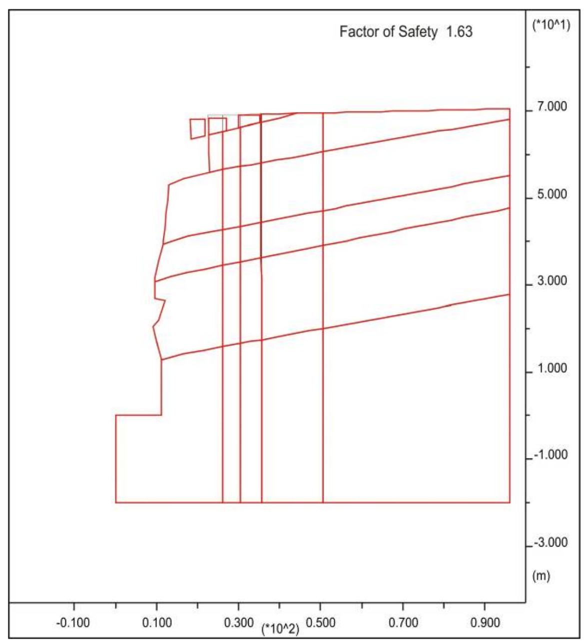

Figure 15. A-A' section, dynamic analyses, deformed meshing

8.3. Numerical static result discussion related to E-E' section

The static safety factor related to E-E' section with direction N-S is equal to 1.11. Fig. 16, shows that half section is involved in instability displacements except the lower fine grain limestone. The kinematic mechanism is better understood observing fig. 17. Blocks show tendency to slip on their plan and to spinning, while the most internal joints open themselves.

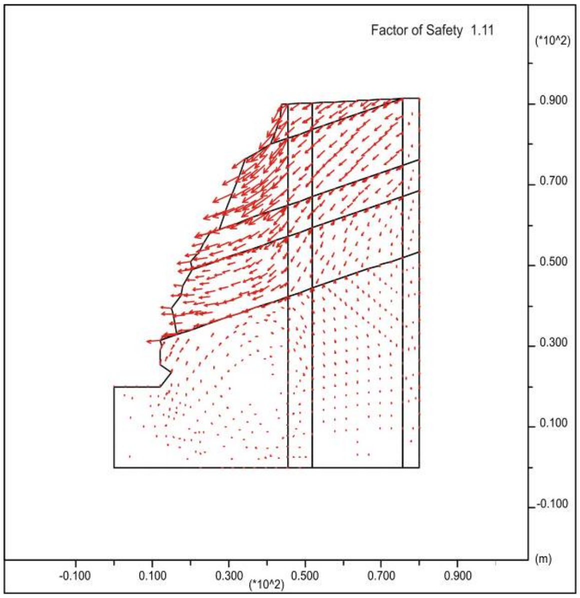

Figure 16. E-E' section, static analyses, displacement vectors plot

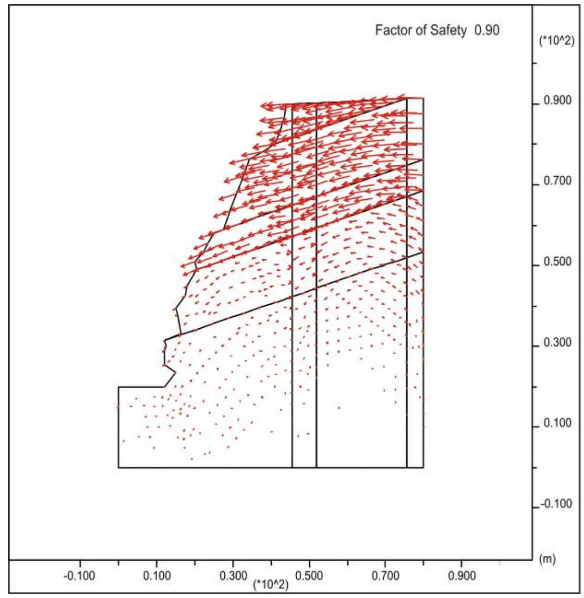

Figure 18. E-E' section, dynamic analyses, displacement vectors plot

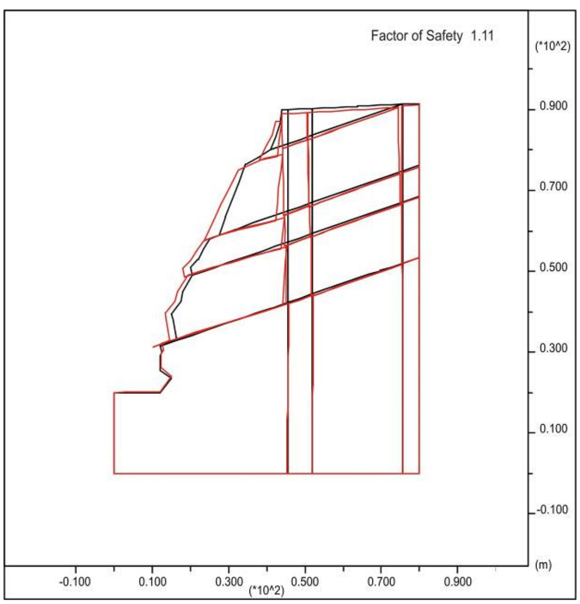

Figure 17. E-E' section, static analyses, deformed meshing

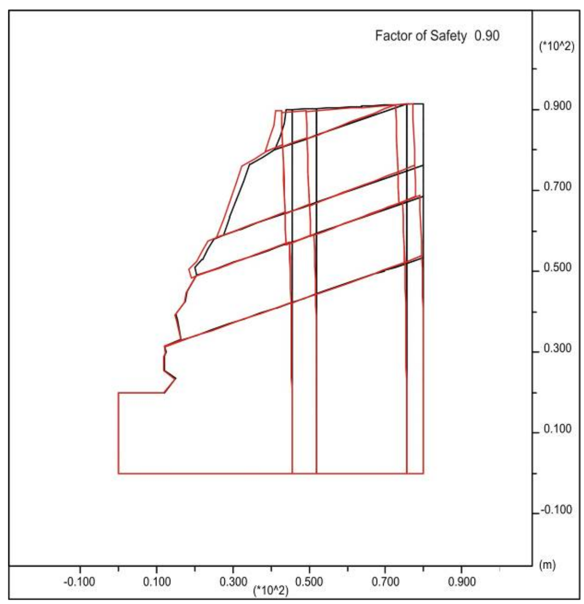

Figure 19. E-E' section, dynamic analyses, deformed meshing

8.4. Numerical dynamic result discussion related to E-E' section

For this section dynamic analyses results are different to the static ones, see fig. 18.
The factor of safety is lower than the unity. The entire three more superficial formations are involved in some displacements (Fig.19). Moreover, it is possible to notice from both diagrams that the blocks slip along the plans of layer.

9. CONCLUSION

In this study, multidisciplinary and multiscale approaches have been applied to study instability characteristic of an area, like Peschici' Cliff, very important by a touristic and environmental point of view.
It has been necessary to investigate the geo lithologic-structural characteristics of the area, in order to characterize those aspects that could trigger the landslide activation.

Moreover an accurate geo mechanical study has been carried out to identify and measure both static and dynamic parameters which can control the events evolution, through the areas in which landslides have a high occurrence probability.

The multiscale approach has been necessary in order to identify the types of possible kinematic mechanism involved in a potential instability of cliffs along the coast of Peschici. Subsequently studies have been performed to investigate, in a more detailed scale, a zone characterized by a high risk conditions (Rupe Castello) because the presence of some historical buildings over the cliff. The task has been performed in two main steps. During the first phase geo mechanic surveys of some cliff's strips have been carried out in order to graphically represent (stereonet) the identified discontinuity families and to execute the test of Markland. The test has allowed to characterize the kinematic mechanisms that potentially could interest the selected area. By the analysis of static stability, it emerged that in all the coastal strips under examination, with the exception of some cases, direct toppling landslides could occur. The main reason is that all discontinuities of the rocks mass localized in the area under study are nearly or completely vertical and oriented approximately in parallel with the slope. In the second phase of the work, the cliff of "Rupe Castello", has been analyzed. Five schematic geologic sections of the cliff have been reconstructed, oriented in various ways; these have been object of numerical analysis, using a Distinct Elements computer program, in order to carry out, for each section, static and dynamic stability analysis. Then the sections have been subdivided in 2 groups based on the kinematic mechanism found by the Markland test analyses. Finally, it followed that the western side of Rupe Castello could be interested by a type of a mixing between toppling and long slide along the bedding plains landslide.

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