Cliffs and quarries in the eastern coast of the Favignana island (Sicily, Italy)

Favignana Island (Sicily, Italy) is a historical and environmental attraction site frequented by tourists especially during the long warm season of the year. Over several centuries the sea cliffs constituted by calcareous sandstone outcropping in the east side of the island have been exploited for the production of building stone. Currently the quarries used for the rock extraction as well as the natural cliffs are undergoing extensive erosional and gravitational processes. Besides putting at risk the safety of the people attending the area, the widespread rock falls are likely to threaten sites of great historical and anthropological value that, once destroyed, can no longer be reconstructed. The rock mass quality assessment and slope displacements monitoring of cliffs were conducted with the aim of identifying the most active areas and providing support to the local authorities in the implementation of effective and sustainable mitigation measures. If adequate measures are taken in the future, operators and users of the tourist circuit will have the opportunity to enjoy these amazing sites with a lower landslide risk

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Introduction

Sea cliffs often constitute environmental monuments of rare beauty. Notwithstanding an apparent imperturbability, these massive erosive landforms are subject to continuous evolution due to the action of gravity and aggressive exogenous agents. The geomorphologic evolution along these steep slopes, often highly fractured, mainly occurs with the detachment and movement of blocks extremely variable in size. Rock falls, topples and slides from the cliffs commonly involve single small-volume blocks and, albeit more rarely, huge rock bodies as well. Depending on several different characteristics of the cliffs and of the triggering landslide mechanism, the average coastal erosion rate can reach several decimeters per year [1]. Although these processes are not the most dangerous landslide events, their magnitude in terms of volume and velocity of the paroxysmal phase may constitute a real hazard for human beings, buildings and infrastructures in the near-shore areas [2].

A high percentage (35%) of the coastline delimiting the Italian peninsula and islands is constituted by steep sloping cliffs, plunging into the sea or separated from it by a thin strip of sandy or gravel beach, or a bank of fallen blocks [3]. In some Italian regions (e.g. Liguria, Campania, Calabria, Sicily and Sardinia) this percentage is significantly higher and the erosion processes of the cliffs constitute a serious problem. Nevertheless, the increasing thermoclastic processes and the local stress condition at the foot of the cliffs as a result of the ongoing climate change, and particularly of the variation in temperature regimes and fluctuations in

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the Mediterranean sea level, may induce an intensification of the erosion rate of the Sicilian high coastal areas [4].

Some of the most popular places of Favignana Island are bays characterised by cliffs overlooking an astonishing sea. Rock falls along the cliffs are common and involve the underlying beaches. The low human activity in these areas actually reduces the risk condition that remains concentrated during the long warm season of the year, when tourist frequentation is considerable. In addition, the quarries opened in some of these bays, locally called "pirrere", constitute a cultural heritage of great anthropological value that, once destroyed, can no longer be reconstructed.

This paper reports a brief description of the investigation on the cliffs and quarries of the eastern coast of Favignana Island (western Sicily) where a quaternary calcareous sandstone diffusely outcrops. The cliffs monitoring and the slope movements assessment carried out during the study are aimed to identify the most active areas. The study results may contribute to the mitigation of the geomorphological risk in Favignana Island and greatly support the local authorities' policies in the implementation of mitigation measures. Given the characteristics of the sites, inserted into the largest European marine protected area, the intervention measures must be characterized by a high degree of environmental sustainability. If valid, effective and sustainable measures are taken in the future, operators and users of the tourist circuit will have the opportunity to enjoy these amazing areas with a lower landslide risk.

FIGURE 1 Bivalves (left) and cross-bedded layers (right) in the calcareous sandstones

FEATURES	VALUE
Specific gravity (G_s)	2,7 g/cm^3
SiO_2 content	<1%
$MgCa(CO_3)_2$ content	1-3%
Average grain size	0,3 mm
Total porosity (n)	40-50%
Compressive strenght (σ)	20-30kg/cm^2

TABLE 1 Geotechnical characters of calcarenites

Study area

Favignana is the largest of the Egadi Islands, located off the northwest coast of Sicily, near the cities of Trapani and Marsala. It extends for approximately 19 km^2 and is surrounded by a 33 km of indented and mainly rocky coastline, marked by natural and anthropic cavities. The island is mostly flat, except for the mountain ridge that runs through it from north to south (M.te Santa Caterina, 314 m a.s.l.).

Favignana Island mainly consists of Mesozoic-Tertiary carbonates unconformably overlain by Middle-Upper Pliocene marls and shales followed by Pleistocene biocalcarenites and Tyrrhenian calcarenites [5,6,7]. The Mesozoic-Tertiary carbonates outcrop in the western and central part of the island. The lower Pleistocene biocalcarenites outcrop in the eastern part of the island, generating a wide flat plate with nearly horizontal layers. In literature, its thickness ranges between 5 and 35 m [8], though a quarry in the inner part of Cala Rossa ("Niuro vecchio" and "Niuro nuovo" caves) shows a vertical development of more than 50 m entirely in the calcarenites. The facies association suggests different depositional environments (Figure 1) from the nearshore-beach zone (close to the Mt. Santa Caterina) to the shoreface zone (in the eastern part of the Island). The Middle-Upper Pliocene marls and shale locally outcrop between the base of the calcarenite cliffs and the sea surface, partially hidden by a significant boulders deposit.

The calcarenite shows relatively high values of the porosity [9] (Table 1) related to the low diagenetic process, the low cementation (spathic calcite with meniscus structures) and to the textural characters (equi-dimensional, well sorted, loosely packed, low fine grained matrix). The value of the compressive strength offered in literature, and confirmed through some field measurements with a Schmidt hammer, indicates a weakly cemented carbonate rock.

There are three systems of faults that displace both the Mesozoic-Tertiary and Pleistocene deposits. A very recent tectonic activity involves Tyrrhenian sediments and more recent continental deposits, as revealed by kinematic indicators of NW-SE, NE-SW and W-E strike-slip fault [10] and of differential uplift [11].

The study is focused on three bays, "Cala Rossa", "Cala del Bue Marino" (Figure 2) and "Cala Azzurra", located in the eastern side of the island. In these three bays, the Pleistocenic biocalcarenites form some cliffs with height ranging from few meters (Cala Azzurra and central part of Cala Rossa) up to over 30 meters. These areas are classified as high and very high landslide hazard [12].

The cliffs of Cala Rossa and Cala del Bue Marino are separated from the sea by a narrow strip of talus deposits, whereas at Cala Azzurra a low angle slope and a beach separate the old cliff from the present shoreline, assuming respectively the shape of a seasonal sea cliffs and a coastal slope [13]. In the west side of Cala Rossa and Cala Azzurra, this wide rock slab lies on the plastic clays belonging to the Pliocene formation. The contact between the two formations can be recognised here above the sea level, while in the east side of the two bays and in Cala del Bue Marino area the surface is presumably below sea level. The overlapping of hard rock masses on a more plastic substratum leads to mechanical instability due to the diverse response of the materials to perturbations, such as seismic input, weathering, erosion or man-made excavations [14]. The resulting mass movements can be classified into two different but strictly interconnected typologies: lateral spread and rock blocks fall [15].

FIGURE 2 Rock blocks fallen at Cala del Bue Marino

The good resistance brought the biocalcarenite, improperly called "tuff", to be extracted in several hypogeal and open air quarries and used as building stone. The exploitation of the Favignana sandstone is ancient, but it reached its maximum development mainly between 1700 and 1950. Many buildings were constructed in Tunis with the "tuff" of Favignana, and Messina was rebuilt with it after the 1908 earthquake. After the World War II the "tuff" went out of the market and the mining areas were abandoned to a degradation process which increased the risk of block collapse.

Methodology

A geomechanical analysis and multi-system monitoring of the cliffs of Cala Rossa, Cala del Bue Marino and Cala Azzurra were carried out in this study between April 2012 and April 2014.

The geomechanical investigations were focused on the recognition of the rock mass joint setting and of the lithotecnical characteristics of the calcarenites in the three coves. The geomechanical characterization of the calcarenite was carried out via a traditional geomechanical field survey performed according to the ISRM standard. Twenty-five geomechanical stations were completed in the three coves (7 in the west side of Cala Rossa, 13 in the east side of Cala Rossa, 3 at Cala del Bue Marino and 2 in Cala Azzurra). Field mapping of rock discontinuities is the most common approach for the analysis of cliffs shaped on hard rock. This classical geomechanical investigation allows to characterize the main joints in terms of dip, dip direction, spacing, opening, presence of gouge material, persistency, relationship with average slope face orientation and other factors. The poles of the measured joints were plotted using the "Georient" open source software and the Schmidt equi-areal

FIGURE 3 3D joint meter installed on the giant joint of the plateaux of the west side of Cala Rossa (left) and the removable deformeter during the measurement survey

stereographic projection (lower hemisphere). Furthermore, the mechanical features of the rock mass, including the mineralogical characteristics and the rock compressive strength, were assessed with field instruments (Schmidt Hammer sclerometer) and laboratory experiments (thin sections, point load test, etc.). On the basis of the geological and geomechanical features, the values of Beniawsky/Romana (RMR/SMR) and Sicily Region classifications [16] were assigned to each station. The latter proposes a simplified approach generating an aggregate of some geomorphological, environmental and historical parameters with the mechanical characteristics typical of the traditional classification.

The monitoring activity was performed through the use of direct and indirect instruments.

A direct measurements systems was implemented with mechanical joints gauges of different kind (tell-tale, removable joint-meters, 3D joint-meters; Figure 3) in relationship with the different characteristics of the walls, discontinuities and types of movement to be recognised (one-dimensional or three-dimensional). These three mechanical join-meters systems allow to measure relative displacements between two reference pins or two anchors positioned across the joints with a resolution of a hundredth of millimeter (tenths of millimeter for the tell-tales). Overall 70 mechanical joint-meters were installed, distributed along the cliffs overlooking the sea of the three bays and also within the numerous cavities that open inside the cliffs.

The indirect measurements were carried out through Terrestrial Laser Scanner and GPS instruments. While this latter allowed to monitoring displacements of single points located at the edge of the cliff, the former acquired information about a cloud constituted by millions of points representative of the whole vertical face of the cliffs highlighted by the laser beam.

Laser scanner survey [17] were performed using a laser scanner (Riegl Z360) integrated with a high resolution digital camera (Nikon D100; Figure 4). Two Laser Scanner acquisitions (October 2012 an October 2013) were performed in all the three bays, positioning the instrument in four stations in Cala Rossa, four in Cala del Bue Marino and five in Cala Azzurra. In order to compare subsequent temporal scanning [18, 19] and re-calibrate the instrument with a precision of mm, eight fix targets and ten mobile targets around the scan points (scanpositions) were materialized as a Cartesian coordinates system.

The GPS monitoring techniques was applied only in Cala Rossa with the aim of identifying the movement of single points along the cliffs with high accuracy.

FIGURE 4 Laser scanner instruments during the acquisition survey in Cala Rossa

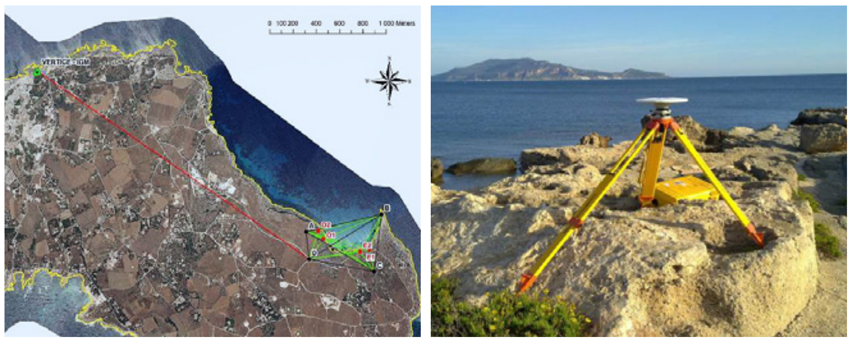

FIGURE 5 The local GPS network and one of the measurement points

The GPS network is composed by four stable vertices (A, B, C and D in Figure 5), while in proximity of the edge of the cliffs four sites were chosen, considered potentially unstable after a geomorphological survey (E1, E2, O1 and O2). The GPS network was linked with the Italian Geodetic Network (IGM95), by the geodetic point "Punta San Leonardo" located close to the Favignana's urban area. The uncertainty of these vertices was very contained, reaching a maximum of +/- 2 mm in plane and +/- 3 mm vertically.

Results

The biocalcarenitic slab shows a high degree of fracturing especially in the front portion of the cliffs and the boulder deposits at their foot constitute a clear indicator of the current activity. Several blocks of different sizes seems to be in condition of high instability and in proximity of falling. In addition to the geomorphological indicators, at least two block fall events recorded during the 24 months of the study testify the high activity of the west cliff of Cala Rossa. The first is the block of approximately 0.3m^3 collapsed on the morning of October 26, 2012 from the west cliff of Cala Rossa and recorded by the Laser Scanner monitoring. The second is the sudden collapse of a boulder on which a reference pin for the removable joint-meter measuring was installed. Its last data read in June 2013 indicated a movement of 0,72mm from the installation in October 2012 (1mm/month).

From the front slope towards the interior of the slab, the rock fracturing condition becomes less intense, with spacing ranging from less than 1m up to more than 2m or more. This may be appreciated both in the plateaux above the cliffs and within the several quarries opened inside it. Nevertheless, in the inner part of the west side of Cala Rossa cliff, upon the plateaux and approximately 25 meters from the edge, two major discontinuities have been recognized, longer than 100 meters, 50 cm open and with 40 cm of offset. These joints seem to reach the contact with the underlying clays, isolating a huge block of approximatively 30 thousand m^3 (Figure 6).

Structural analysis confirms the presence of two main joint families: NNW-SSE and NE-SW (Figure 7 and 8). The NNW-SSE joint set seems to have a significant relevance in the structural asset of the area and in the development of the instability proneness. Especially where this joint set is parallel to the slope face, it is possible to recognise an advanced lateral detensioning deformation process. Less significance seems to have the sub-horizontal stratification planes. Taking into account the attitude of the main measured joint, two failure mechanisms have been assumed for the movements in the front part of the cliffs: rock topples and rock wedge slides.

The results of the geomechanical analysis of the 25 stations, implemented in the GIS project, are showed in the rock quality maps (RMR, SMR and SR) that constitute a preliminary assessment of the rock fall susceptibility of

FIGURE 6 Giant joint of Cala Rossa

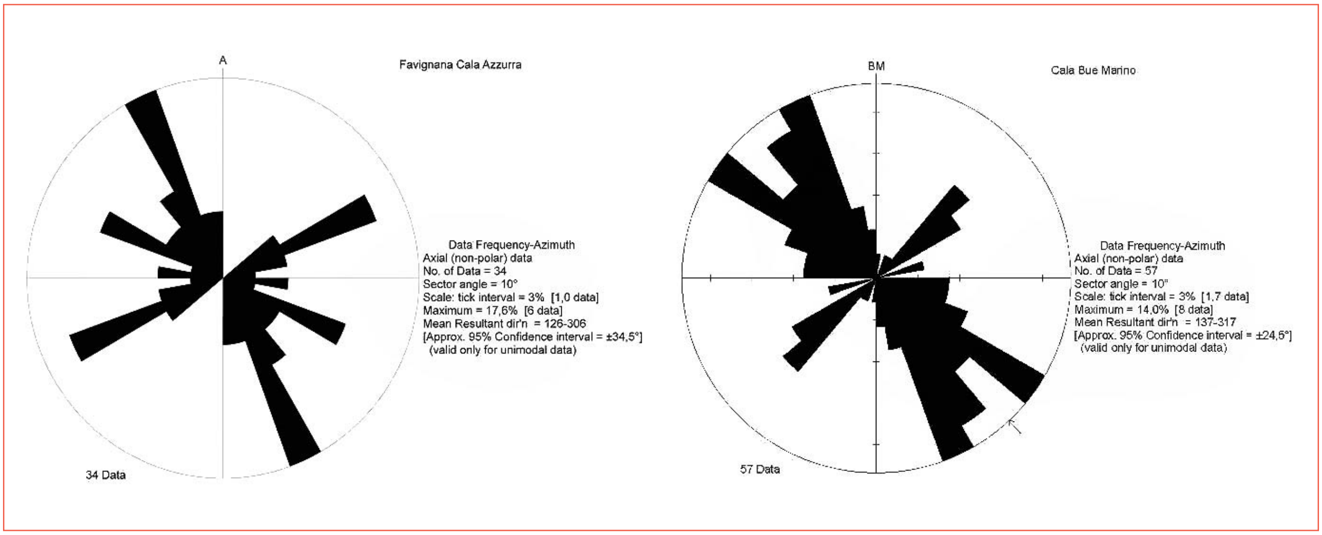

FIGURE 7 Discontinuities plot of Cala Azzurra (left) and Cala del Bue Marino (right)

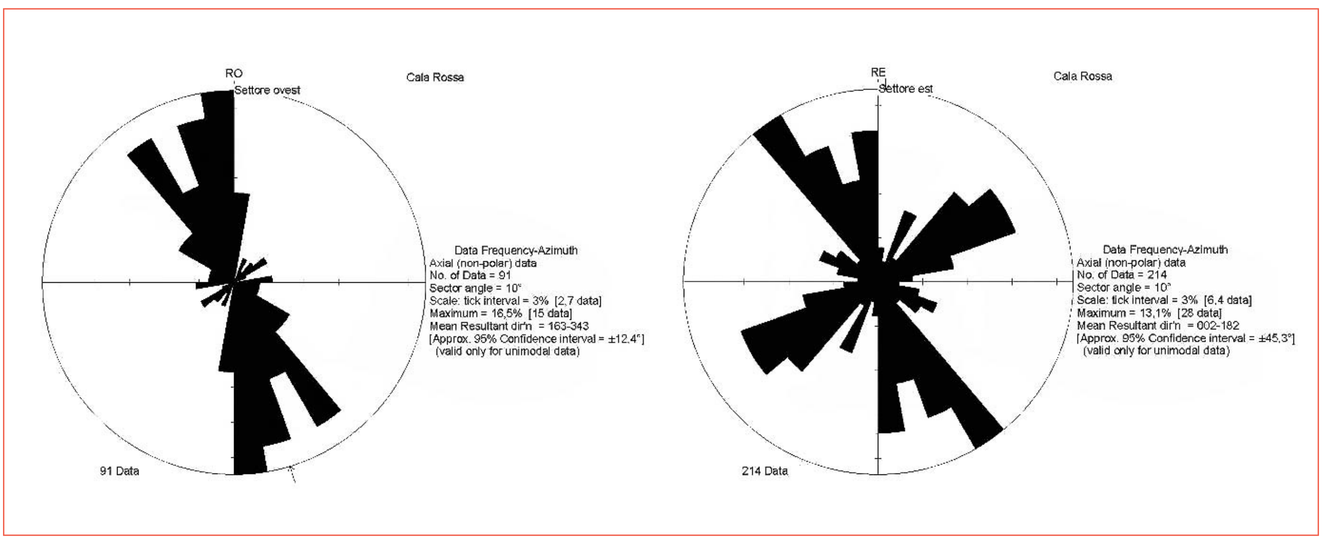

FIGURE 8 Discontinuities plot of the two side of Cala Rossa (West on the left and Est on the right)

the cliffs in the study area. The comparison between the traditional classification of Beniawsky/Romana (RMR/SMR) and the recent experimental classification of Sicily Region (SR) showed a moderate agreement in the results (Figure 9).

The movements measured by the mechanical joint-meters installed in the three bays are generally lower than 1mm (Figure 10). Only eight measurement points showed variations over the 24 months exceeding 1 mm and only 1 is greater than 5 mm (RE3M2, a joint in the central part of Cala Rossa).

From the preliminary GPS data, consisting in the first survey realised in October 2012 and the following of May 2013 and April 2014, some horizontal millimeter

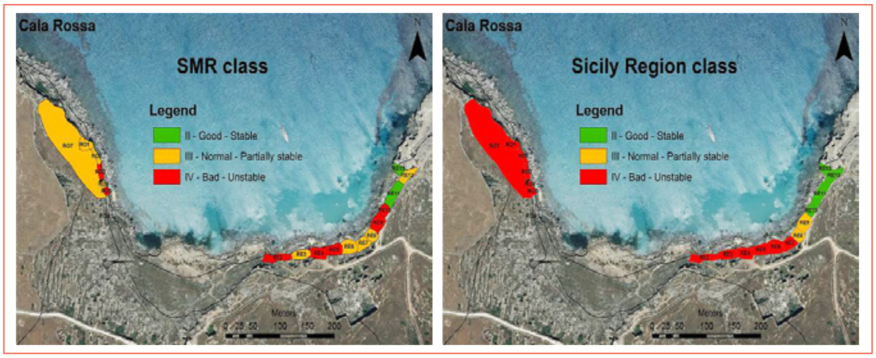

FIGURE 9 Maps of Slope Mass Rate (left) and Sicily Region classification (right)

movement of the four unstable vertices may be observed, but always inside the error ellipse and without an apparently defined trend. Only for E2 and O2 vertices it is possible to observe a vertical millimeter movement, even if inside the ellipse error, that denotes a presumable subsidence trend. The data acquired during the fourth survey, performed in June 2015 and still under processing, will allow to compare a more significant dataset and better understand the behaviour of the cliffs.

Minimal changes have been recorded in the point clouds acquired during the two Laser Scanner surveys of October 2012 and May 2013. However the comparison of the different images acquired is still being processed.

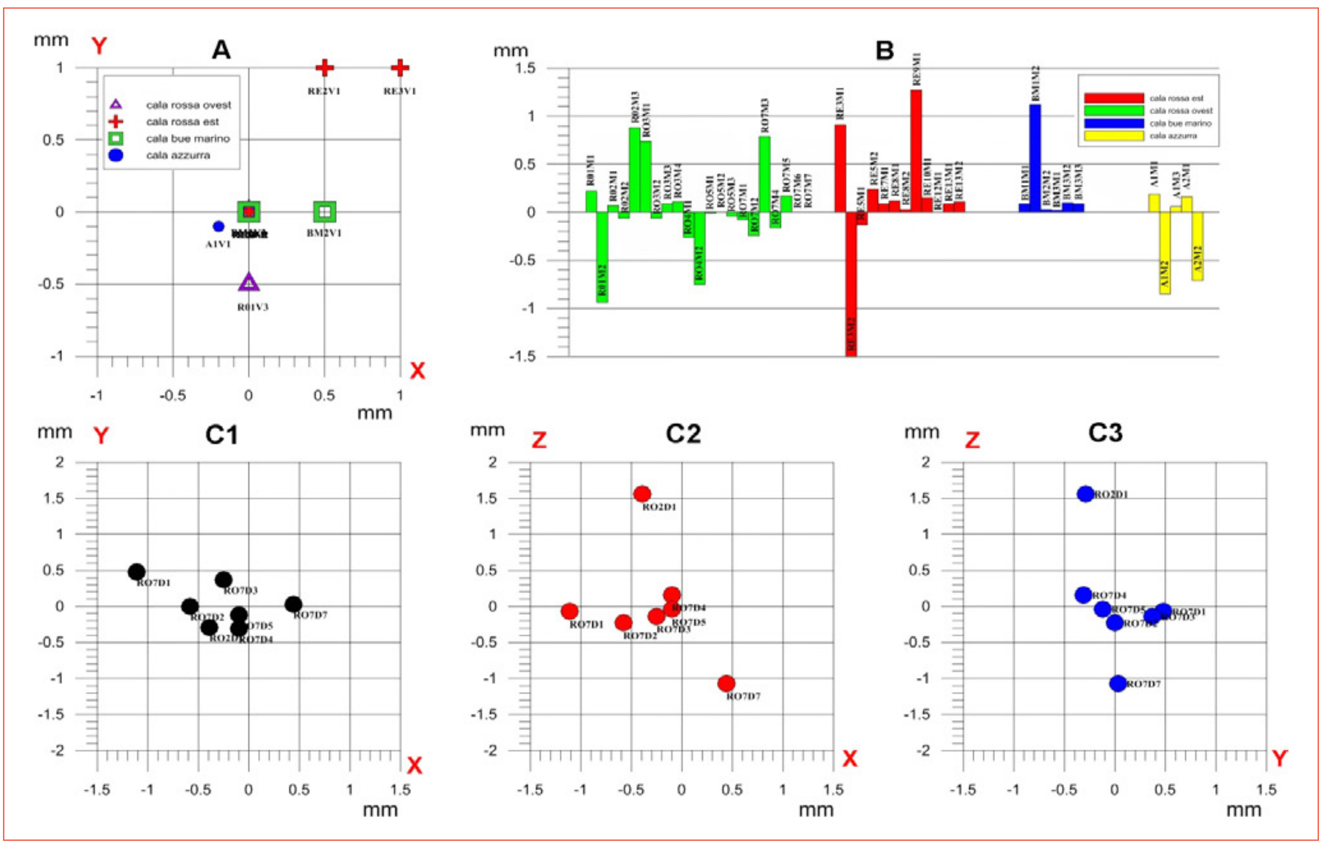

FIGURE 10 Displacements measured with the mechanical joints gauges: tell tales (A), removable joint-meters (B) and 3D joint-meters (C1, C2 and C3)

Discussion

The geological model representative of the study area is mainly characterized by the presence of the rigid body of calcarenite above the plastic clays. The clay deformations, also related with the sea waves action, induce stress condition in the overlying limestones and development of fracturing processes. The pre-existing neo-tectonic shear zones are a controlling factor for the development of the failure surfaces and of the gravitational processes. These processes develop as lateral spreading along the contact surface between the two formations and fall s.l. in the detensioned front portion of the cliffs. The position of the contact surface between the two formations above or below sea level and the consequent exposition or protection of the clays to/from the sea waves action is presumably a further controlling factor for fracturing and landslide processes.

The lack of significant movement registered by the integrated monitoring system in the periodic acquisition during the 24 months study can be easily explained with the discontinuous and impulsive behaviour of the rock collapsing processes, and does not exclude the possibility of future single or massive movements. The deepening of the deformation dynamic inevitably requires the upgrading of the current monitoring network with the installation of more sophisticated joint meters in the most critical sites, with in continuum acquisition, data logging and remote communication.

The rock mass rating of the cliffs attributed to the different measuring stations (Figure 9) shows good agreement between the SMR and SR classifications, even if the latter appears to be more conservative. It is notable that attributing the SMR and SR classes demands to take into account the geometrical relationship between the most significant joint planes and the slope orientation. Even though the analysed cliffs of three bays have strongly indented forms, due to natural and human causes, in this study only an average value of the slope orientation has been used. Consequently, the SMR and SR classes assigned to a station are affected by a certain level of approximation.

The working group plans to make few more additional field observations and deepen the elaboration of the data already acquired. An improvement of the landslide hazard assessment will be implemented on the basis of the predisposing parameters, such as the stability condition of the slopes [20, 21]. The characterization of the joint discontinuities will strengthen by the execution of the automatic and semi-automatic elaborations of the Laser Scanner images and of an innovative geophysical survey (nanoseismic monitoring) [22].

Conclusions

The geomechanical survey and analysis confirm the presence of potential instability conditions in the three bays of the study area. Consequently, a significant hazard level has been recognised in several measurement stations, mainly in Cala Rossa and Cala del Bue Marino. The monitoring systems have registered no significant displacements in the observed areas. Nevertheless, several cliff areas show evidence of impulsive dynamics. On this basis, identifying appropriate actions is absolutely crucial to prevent accidents to the users of these beautiful natural places and to avoid that the most significant quarries are further abandoned to an inexorable degradation process.

Removal of the most unstable blocks, local rock nailing and protection boulder walls at the foot of the cliffs are all interventions that can reduce the general unstable conditions in the higher hazard level sectors of the cliffs. In the most critical areas, as the west side of Cala Rossa, a partial prohibition of access is strongly recommended. Furthermore, improving the current monitoring system is a necessary prerequisite for future adoption of an early warning system.

By providing information about the hazard level and the displacements along the cliffs of the three bays, the present study results are an effective contribution to the local authorities in charge of implementing mitigation measures. The enhancement of the safety level of these areas is an essential step for a sustainable and safety tourism exploitation in the island. This is the way to ensure that what was left of the quarries can become an economic resource again, while respecting the historical and the environmental context.

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