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EVIDENCE OF UNSTABLE ROCK CLIFFS FROM VIBRATIONAL BEHAVIOR: CHALLENGES IN COUPLING ENGINEERING-GEOLOGICAL AND GEOPHYSICAL APPROACHES

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EXTENDED ABSTRACT

Nel corso degli ultimi decenni, la geologia applicata si è vieppiù avvalsa di approcci multidisciplinari volti a rilevare proprietà e caratteristiche fisico-meccaniche del sottosuolo prossimo alla superficie terrestre (*near surface*) al fine di comprendere e di monitorare al meglio la dinamica di processi naturali, connessi a diversificati contesti morfogenetici, quali potenziali cause di rischio naturale.

In questo ambito, la caratterizzazione delle proprietà dinamiche del *near surface* è divenuta, nel tempo, una rilevante base per la comprensione dei comportamenti vibrazionali di volumi di roccia, già dislocati da discontinuità fisiche di ammasso. Queste ultime costituiscono, di per sé, il risultato di processi di instabilità in atto in corrispondenza di sistemi rocciosi fratturati, ma ne controllano al contempo il comportamento, nella misura in cui vanno a condizionare la risposta a sollecitazioni esterne, quali quelle sismiche, regolando la fisica della propagazione di onde di superficie ad attitudine dispersiva in frequenza (quali le onde di Raleigh) e delle loro interazioni con il *near surface.* Il risultato di tali interazioni è l'evidenza di amplificazione del moto sismico a specifiche frequenze, eventualmente associata a polarizzazione e caratteristiche di marcata ellitticità sulle frequenze amplificate. È stato, oramai, ampiamente dimostrato che le frequenze del moto oscillatorio che vengono amplificate dai sistemi fisici del *near surface* sono relazionabili ai moti propri (*eigenmodes*) di elementi disgiunti e dipendono dai loro gradi di libertà, dalla loro inerzia, dalla loro rigidezza e dal coefficiente di smorzamento che rende critico, alle suddette frequenze, il loro stato di oscillatori liberi supercritici.

Questa fisica di interazione tra masse rigide, rappresentate da blocchi di roccia isolati da discontinuità, e onde sismiche, che si propagano da e verso il campo libero di superficie, è alla base della potenzialità insita in una sfidante interazione tra approcci geologico-tecnici per l'analisi geomeccanica degli ammassi fratturati e indagini geofisiche di sismica passiva, eseguibili mediante la registrazione di segnali di rumore sismico ambientale ovvero di eventi sismici di medio-bassa magnitudo.

La potenzialità diagnostica di queste tecniche di indagine geofisica accoppiate, la versatilità della strumentazione necessaria per le acquisizioni (ovvero la sua utilizzabilità per più applicazioni di natura geofisica) nonché il relativo basso costo delle campagne di registrazione, al netto del valore della strumentazione necessaria per acquisirle, le rende un efficiente strumento di analisi per la diagnosi e la perimetrazione spaziale (zonazione) del pericolo connesso a incipienti processi di instabilità per frana, quali crolli, ribaltamenti di blocchi di roccia o anche collassi generalizzati di ingenti porzioni di versante.

Questo contributo vuole esemplificare l'applicabilità delle succitate tecniche di indagine geofisica attraverso una rassegna di casistiche, grazie alle quali è stato possibile apprendere le potenzialità diagnostiche degli approcci in oggetto e, al contempo, razionalizzarne la funzionalità e la adattabilità (sotto determinati vincoli di rappresentatività) a differenti contesti morfoevolutivi. I prodotti di zonazione della pericolosità da frane in roccia, realizzati grazie a queste tecniche, appaiono del tutto integrabili in prodotti di valenza pianificatoria, quali, tra gli altri, carte tematiche sui processi di frana attivi e relativa distribuzione spaziale, carte di microzonazione sismica e relative aree di instabilità, mappe di perimetrazione del rischio residuo finalizzate alla interdizione di accesso o agibilità.

Nonostante le tecniche qui discusse siano da ritenersi ormai consolidate a livello internazionale, si continuano ad intravedere prospettive di promettente implementazione delle stesse, specie per ciò che attiene la deriva temporale dei fenomeni geomorfologici in atto, nell'ottica di individuazione e monitoraggio di processi preparatori all'innesco di frane che, a loro volta, ben si modulano sulle periodicità meteo-climatiche di corto-medio termine nonché sulle tendenze alla loro irreversibile variazione di più lungo termine. Tali prospettive di analisi, se combinate con le maggiori prestazioni fornite dalle moderne tecnologie di registrazione continua e di trasmissione e processamento in tempo (quasi) reale, nonché con le potenzialità date dall'apprendimento di sistemi di Intelligenza Artificiale, proiettano, senza dubbio, questo ambito della geofisica applicata alla geologia tecnica verso nuove e sfidanti prospettive.

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ABSTRACT

Over the last decades, engineering-geology has increasingly made use of multidisciplinary approaches aimed at detecting physical-mechanical characteristics of the subsoil in the near surface, to better understand and monitor the dynamics of natural processes as potential causes of natural risk.

Geophysical investigations by passive seismic in the near surface became over time a fundamental tool to interpretate the vibrational behaviors of rock volumes, already displaced by physical discontinuities (*i.e.* rock mass joints). The frequencies of oscillation, amplified by dislodged blocks, are polarized in specific directions, and related to eigenmodes which depend on their degrees of freedom, mass, stiffness and damping coefficient. On the other hand, the superposition of soft soil on bedrock induces stratigraphic amplification which may not be polarized if they occur in properly one-dimensional contexts.

This contribution focuses on the aforementioned investigation techniques, through a review of case studies which allowed learning their diagnostic potential and, at the same time, conceptualizing their functionality and adaptability (under certain representativeness constraints) to different morpho-evolutionary contexts. The hazard zoning for rock landslide, which have been created to date by these techniques, appear to be fully integrated into thematic maps on active landslide processes and related spatial distribution, seismic microzonation maps and related areas of instability, residual risk perimeter maps aimed at preventing access or usability of urbanized areas.

Keywords*: rock cliffs, landslides, jointed rock-masses, passive seismic, vibration.*

INTRODUCTION

Multidisciplinary approaches to the management of geohazards in the field of engineering-geology are now consolidated as particularly efficient systems for better understanding the complex relationships that lead from the physical process to its effects in the risk mitigation perspective (Hack, 2020). This understanding, more specifically, passes through the determination of the conditions that lead to the ultimate failure event and which can be theoretically distinguished into predisposing, preparatory and triggering factors (Gunzburger *et alii*, 2005; Fiorucci *et alii*, 2020). In particular, the predisposing factors involve the geo-structural features inherited by the physical system and (regardless of the duration of the time window for observing the process) they control the physical interactions between destabilizing actions and natural system. The preparatory factors express changes that the natural system undergoes as a result of context variations (*e.g.* climate changes) whether they manifest a periodic nature (*e.g.* diurnal or seasonal cycles) or whether they show trends of irreversible variation in conditions or control parameters. The trigger factors, finally, are represented by transitory actions, mostly of an impulsive nature, which cause the definitive disequilibrium of the natural system (already predisposed and prepared), leading it to collapse.

When dealing with rock landslides (Cruden & Varnes, 1996; Hungr *et alii*, 2014), the rate with which ultimate failure events occur, as well as the fragility that characterizes their occurrence (i.e. typically paroxysmal failure modes), can raise the related levels of risk both due to the relevant instantaneous energy release (or in any case very concentrated over time), and due to the absence of sufficient time for an early warning connected to precursor effects which, on the other hand, more typically characterize earth-slides. In addition, rock collapses are not necessarily triggered by transitory actions (*e.g.* earthquakes, intense precipitations, vibrational perturbations) but rather can represent the culmination of the evolution of mass rock creep processes (viscosity driven) which reach a critical condition (tertiary stage) only related to the effect of aging following an increase in the strain rate (accelerating creep), which leads irreversibly towards a generalized collapse of the slope (Delchiaro *et alii*, 2024).

As it regards the failure that causes detachments from rock slopes, the possibility of identifying and monitoring preparatory phases for the detachment process becomes crucial by concentrating observations and instrumental measurements on the generation of variations in the conditions of the physical system and/or in geomechanical factors that can be considered indications of an irreversible process of rock mass damaging (Doebling *et alii*, 1996; Zhang *et alii*, 2020; Martino *et alii*, 2020; D'angiò *et alii*, 2021).

Among these clues there is undoubtedly the increase in the kinematic freedom of blocks already separated from the rock mass, or their greater aptitude for mobilization up to detachment connected to the gradual opening of joints often combined with the weathering. This effect is recorded by the variation of physical-mechanical properties of the jointed rock mass such as its equivalent density, stiffness and strength (Moore *et alii*, 2018; Moore *et alii*, 2020). These variations in properties reflect in a consequent variation in the vibrational attitudes of the rock blocks isolated by the mass joints, or in their greater mobility which, on the one hand, increases the amplitude of the ground motion (and therefore amplifies it) and, on the other hand, increases the damping of the oscillations and therefore the inelastic percentage of strain related to not reversible deformations. Furthermore, the greater amplitude of the oscillation manifests itself with a more marked spatial orientation, i.e. with a more evident polarization of the ground motion over the block (Häusler *et alii*, 2021).

From this physically based assumption arises the integrated approach which combines the geomechanical characterization of jointed rock masses, mostly aimed at measuring and reproducing the predisposing conditions of the fractured rocks, with the analysis of the dislodged blocks vibrations and their temporal variation, to highlight preparatory processes driving toward detachment and to measure their efficiency over time through the determination of indices which express the increasing intensity of the ground motion due to effects of the vibrational behavior.

FROM DEPTH- TO VOLUME-CONTROLLED VIBRATIONAL SYSTEMS

The analysis of the seismic response related to different geo-structural contexts in the near surface has for decades represented the prerequisite for the quantification of the seismic hazard for the purposes of anti-seismic or seismically compatible design, as well as for the purposes of territorial planning aimed at implementing strategies for natural risk mitigation. This discipline has developed different approaches, both instrumentally and numerically, aimed at quantifying the effects connected to the amplification of seismic motion on the ground and therefore measuring the intensity of the geohazard in specific territorial contexts.

Among the geophysical techniques addressed to this purpose are passive seismic investigations based on the recording of environmental seismic noise and seismic events of small or medium intensity (weak motion), which provide important information on the presence of amplified motions at certain frequencies as well as on their polarization (Bensen *et alii*, 2007; D'amico *et alii*, 2019). However, when using these techniques, it is rather complicate to discriminate the stratigraphic contribution from that connected to two- or three-dimensional settings of the subsoil or of the relief (topographic effects) if they are not applied in a combined manner and in any case making more use of synchronous recordings in different measuring stations.

The theory underlying these analyses is based on the principle that surface waves, interacting with the elements of the near surface, can modify the concentration of energy at different frequencies as well as can orient the oscillations at these same frequencies towards specific directions in space (Pischiutta *et alii*, 2012); this behavior can be justified based on the frequency dispersive properties of surface waves, in particular the Raleigh waves, which make them more markedly elliptical the more they interact with highly anisotropic subsurface elements (such as dense stratigraphic intercalations, isoriented joints, morphological alignments). The physics of the interaction of surface waves, although complex in its analytical and therefore numerical reproduction, leads to objective findings such as those which allow the frequencies of the polarized motions of the Raleigh waves as well as the azimuthal orientation of their ellipticity

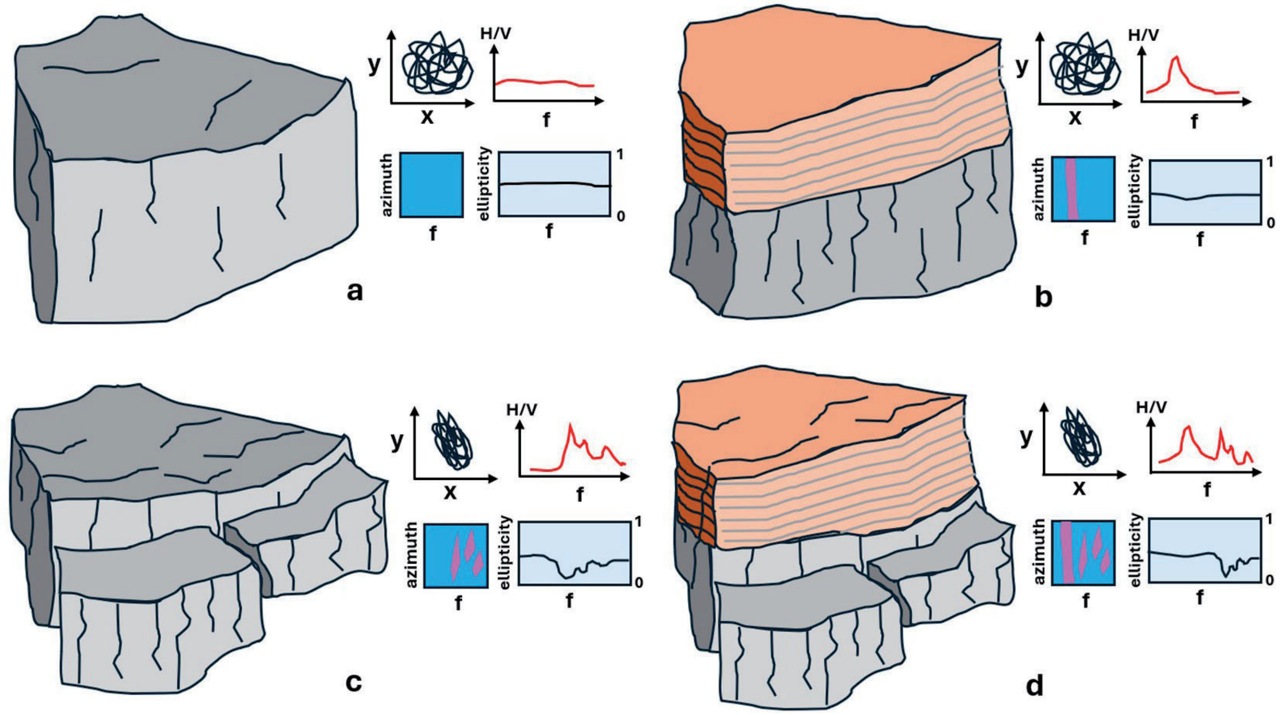

Fig. 1 - a) Sketch related to a "stable stiff rock" system; b) Sketch related to a "depth-controlled" near-surface model where the vibrational behavior depends on stratigraphic amplification due to a visco-plastic soft soil over a viscoelastic bedrock; c) sketch related to a "volume-controlled" near surface model where the vibrational behavior depends on the eigenmodes of rock blocks and it is polarized by the attitude of the joint sets; d) merge of a "depth-controlled" and a "volume-controlled" models resulting in an integrated effect of the two vibrational behaviors. In any sketch the graphs represent (clockwise from left to right): i) the ground particle motion in the y(x) direction; ii) the H/V(f) function; iii) the H/V(f) azimuthal distribution; iv) the ellipticity vs. frequency graph, where 1 corresponds to the circular particle motion and 0 to the linear one

(Burjánek *et alii*, 2012; Burjánek *et alii*, 2019). Among the most accredited techniques in this field of application can certainly be cited the Horizontal to Vertical Instantaneous Polarization (HVIP) technique (Castellano & Mulargia, 2009; Del Gaudio, 2017), based on the polarization analysis of the spectral ratios carried out at starting from environmental seismic noise (the latter implemented, among other things, in a very widespread open access software called Geopsy – www.geopsy.org), and the Time-Frequency Polarization Analysis (TFPA) technique (Burjánek *et alii*, 2010) which distinguishes the polarization analysis for the strike from that for the dip of the elliptical motion of Raileigh waves and associates the analysis of the ellipticity as a function of Raileigh wave frequencies.

Thus, over the last decade, the notion of "volume-controlled" interaction (Fig.1) has been defined (Kleinbrod *et alii*, 2019) which, in contrast to the more conventional one connected to the stratigraphic thickness of the resonant deposits (*i.e.* "depth-controlled"), opens to a perspective of use and management of passive seismic measurements to output the existence of eigenmodes of rigid dislodged systems, such as rock blocks, as well as to the monitoring of their cyclical or irreversible variations over time. The latter can be understood as indicators of ongoing damaging and, if related through environmental monitoring of weather-climatic control factors, can effectively lead to an analysis of processes preparatory to failure. Many cross-correlation techniques between environmental seismic noise signals recorded continuously for several hours and in different stations inside and outside the objects of interest lead to the identification of the natural frequencies associated with the eigenmodes of the oscillating physical system and allow their monitoring over time to highlight any variations and analyze, at the same time, their degree of reversibility.

More in particular, introducing, in theory, the expected implications for the different situations of interaction between seismic waves and elements present in the near surface the following four types of vibrational systems can be distinguished:

1. "stable system" (Fig.1a) where there is no amplification or polarization of waves and, therefore, even less ellipticity at certain frequencies;
2. "depth-controlled system" (Fig.1b), mostly regulated by stratigraphic impedance contrasts, where amplifications at non-polarized and not elliptical frequencies (*i.e.* in case of 1D multilayer resonant systems) can be evident as well as polarized but not elliptical frequencies (*i.e.* in case of 2D, basin-like resonant systems);
3. "volume-controlled systems" (Fig.1c), where amplifications at polarized and even elliptical frequencies are evident;
4. mixed "depth- and volume-controlled systems" (Fig.1d), where some frequencies fall within the type of effect referred to in point 2) above and others in that referred to in point 3) above.

EVIDENCE FROM CASE HISTORIES

Evidence of elliptical wave motions, amplified and polarized at specific frequencies can be associated with highly dislodged rock masses in which, moreover, the state of fracturing and the opening of the joints is such as to make the interaction between the physical discontinuities of the cluster and the surface waves that propagate through them.

For this reason, the efficiency of the aforementioned interaction is enhanced by the presence of deformation processes related to stiffness contrasts between overlapping lithologies, commonly known as lateral spreading (*sensu* Cruden & Varnes, 1996). In this case, the visco-plasticity of the

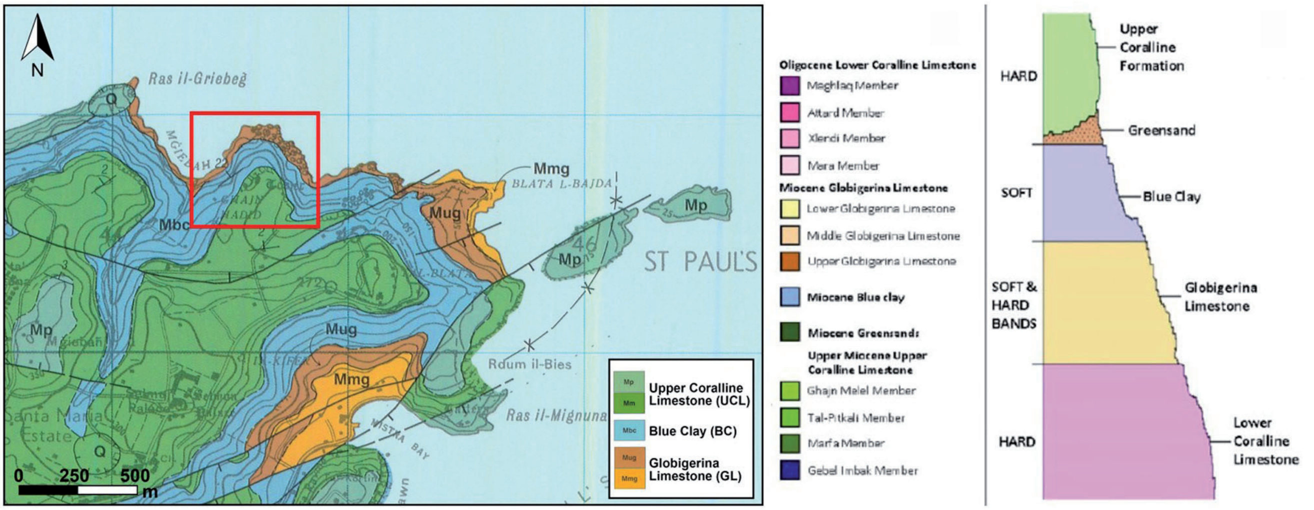

Fig. 2 - Insert of the geological map of the island of Malta (Pedley et alii, 1978) and related stratigraphic column with the outcropping stratigraphic units. The area of the Selmun promontory is shown in the red box on the map

Fig. 3 - Panoramic view of the Selmun promontory in the Island of Malta which is involved in a spectacular lateral spreading responsible for the dislodgment of the UCL over the BC formation as well as of the toppling of rock blocks all around the top-hill cliff

lithologies with more ductile behavior is responsible for dilation of pre-existing joints, if not for newly forming, that gradually enhances the geophysical "visibility" of the dislodged blocks, according to the scheme of damped oscillators ascribable to a "volume-controlled" vibrational system.

A notable "natural laboratory" for experiencing the afore mentioned geophysical approaches is represented by the Maltese archipelago where the stratigraphic overlap (Pedley *et alii*, 1978) of a calcarenitic succession attributable to the Upper Miocene, known as the "Upper Coralline Limestone (UCL)" Formation and of a consolidated clays Formation, from the Middle Miocene, known as the "Blue Clay (BC)" (Fig.2). This geological setting predisposes over a large part of the archipelago in the north-western sector of the island of Malta and in the south-eastern sector of the island of Gozo, with lateral rock spreading capable of giving rise to spectacular morphologies. The evidence of these processes are represented by wide plateaus whose edges, typically coinciding with high slopes on the coastline, are affected by tilted or overturned blocks which feed, by land sliding, imposing coastal debris layers and large cliffs below the coast (Devoto *et alii*, 2012; Mantovani *et alii*, 2013).

The UCL Formation inherits its geo-structural setting, characterized by high-angle, if not subvertical, joint sets, from a tectonic faulting, which took place since the upper Miocene and persisted throughout the Pleistocene. This tectonic had a predominantly extensional nature, connected to continental rifting (Ilies, 1981; Galve *et alii*, 2015) which generated the grabens of Pantelleria, Linosa, North Gozo and North Malta and which, in turn, is associated with a system of right transtensive faults connected to the evolution of the Malta escarpment.

On the island of Malta, the lower portion of the Miocene succession, downstream of the south-eastern boundary fault of the North Malta graben, known as the Victoria Line Fault, causes the contact between the UCL and the BC Formations to coincide approximately with the present sea level.

Several promontories located in this sector of the island, including those of Selmun and Xemjia, are conspicuously affected by lateral spreading on their edges which evolve into overturning of blocks of dimensions equal to a few tens of thousands of cubic meters (Figs. 3, 4).

In the perimeter sectors of these promontories, the effects of the interactions between the surface waves recordable in the environmental seismic noise and the mass discontinuities become visible (Panzera *et alii*, 2012; Galea *et alii*, 2014; Iannucci *et alii*, 2020). The evidence given by these interactions (Fig, 4) results

Fig. 4 - Passive seismic measurements performed at the Selmun promontory through LE-3D/5a Lennartz three-component seismometers (0.2 Hz eigenfrequency) together with REFTEK 130-01 dataloggers. The sensors were distributed astride the open joints to detect effects related to a "volume-controlled" vibrational model

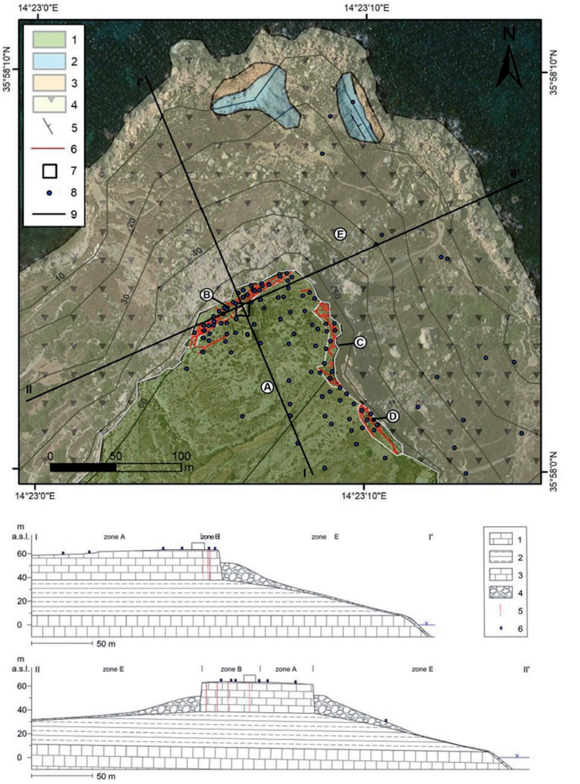

Fig. 5 - Geological sketch of the Selmun promontory and related cross-sections (modified from Iannucci et alii., 2020). (1) UCL formation; (2) BC formation; (3) GL formation; (4) slope debris; (5) attitude of strata; (6) open joint (the dashed line represents an inferred joint); (7) Għajn Ħadid Tower; (8) 1-h seismic noise measurement station; (9) traces of the reported geological cross-sections

in a clear amplification on frequency bands (Figs. 5,6,7), generally higher than 2 Hz which are well distinguished from the peak of stratigraphic amplification, located at around 1Hz, and which is associated with the seismic impedance contrast between the BC and the underlying Globigerine Limestone (GL) Formation of the Upper Oligocene– Miocene, the last one superimposed on the Lower Coralline Limestone (LCL) Formation of the Oligocene.

The GL and LCL Formations together constitute the seismic bedrock of the entire Maltese archipelago (Farrugia *et alii*, 2016), however being at different depths in the different sectors of the main islands due to the superimposition of the North Malta graben.

The geophysical evidence of the peaks in the H/V spectral ratios associated with the oscillations of the dislodged rock blocks (Iannucci *et alii*, 2017) have characteristics that allow their association to the "volume-controlled" vibrational system and in particular: *i*) they are visible exclusively in correspondence with blocks delimited by discontinuities markedly open and evolved due to the effect of lateral expansion (Fig. 6); *ii*) they are absent in areas of the plateau distant from the edges (Figs. 5, 6); *iii*) they are centered at different frequencies related to the specific dimensions of the disjoint blocks (Fig. 6); *iv*) they are associated with motions polarized orthogonally to the discontinuities as well as strongly elliptical (Fig. 6, 7) and, consequently, they are visible in complementary directions moving between border sections of the plateaus angled at approximately 90°.

If this evidence is certainly associated with the advanced state of instability of the disconnected blocks along the edges of the plateaus that characterize the north-western sector of the island of Malta, on the contrary, in the south-eastern portion of the island of Gozo (Fig. 8), the greater thicknesses of the UCL

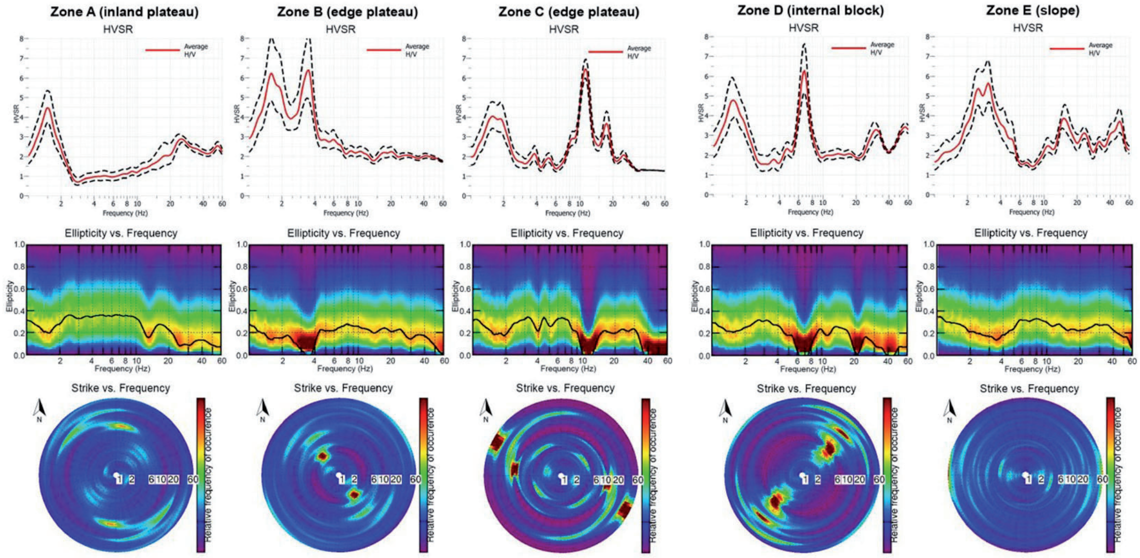

Fig. 6 - Synoptic view of HVNSR graphs, ellipticity plots and polar diagrams of strike polarization obtained for zones with different vibrational effects (see Fig. 5 for localization) at the Selmun promontory (modified from Iannucci et alii, 2020)

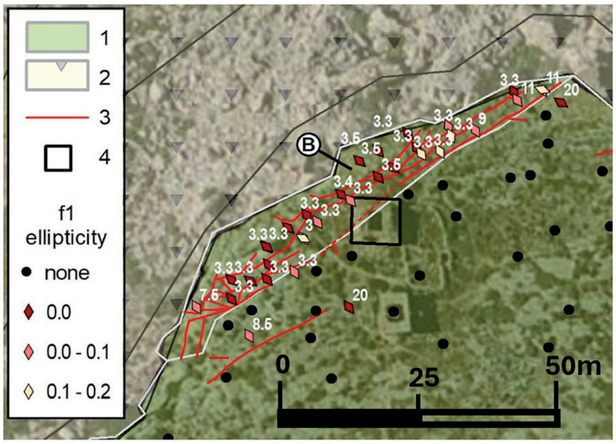

Fig. 7 - Evidence of polarization of the amplified elliptic surface waves in correspondence with dislodged blocks (zone B of Fig. 5) around the Selmun promontory top-hill (modified from Iannucci *et alii, 2020). (1) UCL formation; (2) slope debris; (3) open joints; (4) Għajn Ħadid Tower*

superimposed on the BC and lowered within the North Malta graben, lead the perimeter instability activated by the lateral spreading evolving toward a rotational sliding causing a back tilting of the involved rock blocks (Bozzano *et alii*, 2013).

As it can be observed at the Sopu promontory in the north-east sector of the Gozo island, the back tilting of rock blocks results in shear strain along joints rather than in a tensile opening (Figs. 9, 10); as a consequence, in this case the interactions of the joints with the propagating surface waves lead to less evident polarizations of the seismic ground motion at the amplified frequencies and do not reveal significant ellipticity at the same frequencies (Pistillo *et alii*, 2024). On the contrary the amplified frequencies can be related to the local stratigraphy, according more properly to a depth-controlled vibrational system.

Where rigid and jointed structures are represented by more complex physical systems than individual blocks, it is possible to identify eigenmodes linked to the geometries and the relative degrees of freedom the joints impart to the structure with the aim of highlighting variations in frequency values over time which characterize them by aiming to distinguish periodic variations and, as such, reversible from those represented by behavioral drifts (trends) and, therefore, irreversible (Bottelin *et alii*, 2013; Colombero *et alii*, 2018). Wind arches, marine arches as well as cavities are structures that particularly lend themselves to this observation since they represent objects with decidedly three-dimensional vibrational dynamics (Grechi *et alii*, 2024) but also very energized (Fig. 11) by impulsive agents (such as wind or sea waves) as well as periodic ones (such as oscillations diurnal and seasonal temperatures).

The Maltese archipelago also offers interesting scenarios for experimenting with this type of survey technique since, especially in the north-western sector of the island of Gozo, there are several marine arches carved into the formation of the LCL, among which the iconic Azur Window at the locality of Dweira then collapsed during a strong storm on the morning of 8 March 2017 (Galea *et alii*, 2018).

Among these marine arches, that of Wied Il-Mielaħ is characterized by a rather regular structure consisting of a large pillar and a beam with a shape like a parallelepiped, both in LCL and is rooted in a plateau in GL. The arch beam is visibly fractured and the presence of these joints (Fig.12), which compromise its stability in the medium-long term, cannot be ruled out as significantly influencing its vibrational response (Grechi & Martino, 2020). It is characterized by clearly visible eigenmodes, respectively at around 4.3 Hz, 5.4 Hz and 11.0Hz which, however, show evident variations over time, the more marked the higher the oscillation mode, related to the diurnal thermal cycles (Fig.12). This evidence does not

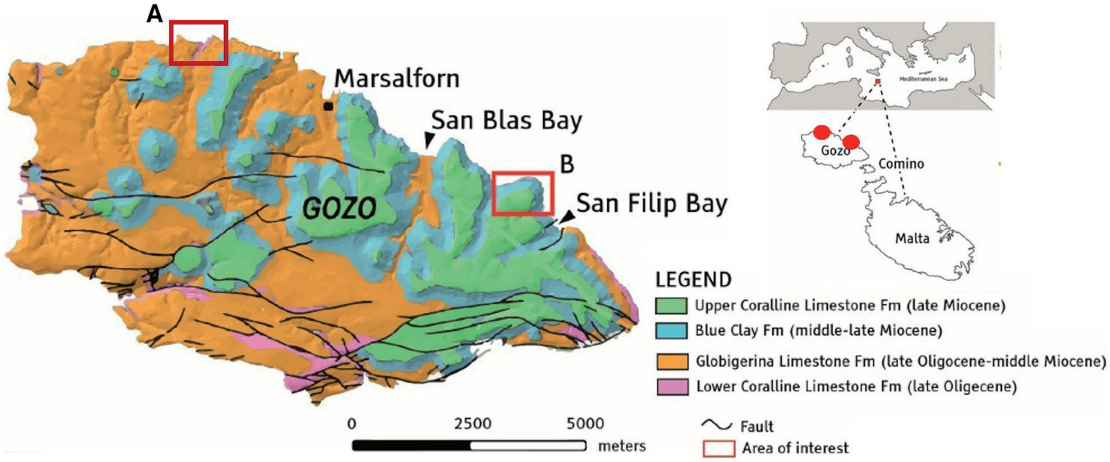

Fig. 8 - Geological map of the island of Gozo (modified from Pistillo *et alii, 2024). The area of the Wied Il-Mielaħ sea arch (A) and of the Sopu promontory (B) are shown in the red boxes on the map*

Fig. 9 - *Panoramic views of the cliff at Sopu promontory in the Island of Gozo which is involved in a lateral spreading responsible for the dislodgment of huge blocks of UCL over the BC formation causing their back tilting and toppling all along the coastal slope*

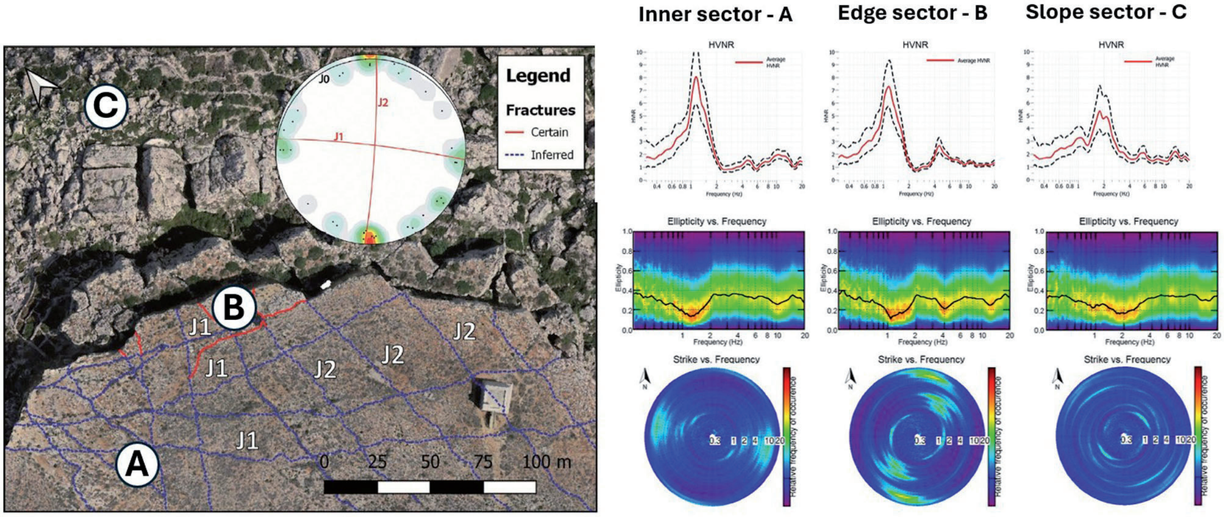

Fig. 10 - *Evidence of resonance at Sopu promontory (right) in the Island of Gozo ascribable to the local stratigraphic conditions, in different zones of the slope (left), without a marked polarization which can be justified by the different landslide mechanism affecting the rock blocks respect to the one observed at the Selmun promontory in the Island of Malta (see Fig.6 for the comparison)*

exclude the possibility of medium-long term trend of deformation, also considering the significance of the seasonal thermal gradients of the island and the temperature differences between the average value of the distribution of winter temperatures, equal to approximately 16°C (with a average thermal difference of 6°C), and the average value of the distribution of summer temperatures, equal to approximately 30°C (with an average difference of 16°C), as it was obtained from thermal photos.

FROM VIBRATIONAL MODELS TO HAZARD MAPPING

Based on the characteristics of the vibrational response of jointed rock mass systems that are predisposed to "volume-controlled" behavior, and considering the evidence of amplification, polarization and ellipticity of surface waves, it is possible to identify objective criteria for a zonation of areas differently predisposed to failure, transposing the evidence of the greater mobility of the dislodged blocks to a higher degree of their instability.

To obtain this zonation two actions may be performed: *i*) design a distribution of an environmental seismic noise measurement stations, suitable for representing the different geo-structural and morphological contexts existing on the site, with a suitable spatial resolution; *ii*) identify a stable reference site, which could be amplifying in itself but independently of instability processes. In any case, this amplification should be in relation only to stratigraphic conditions representative of the site so that any deviation in vibrational behavior due to ongoing landslide-induced deformations can be appreciated.

Fig. 11 - High intensity sea storm hitting the costal arch of Wied Il-Mielaħ on 24 February 2019. Wind map (left) and panoramic view of the sea arch (right)

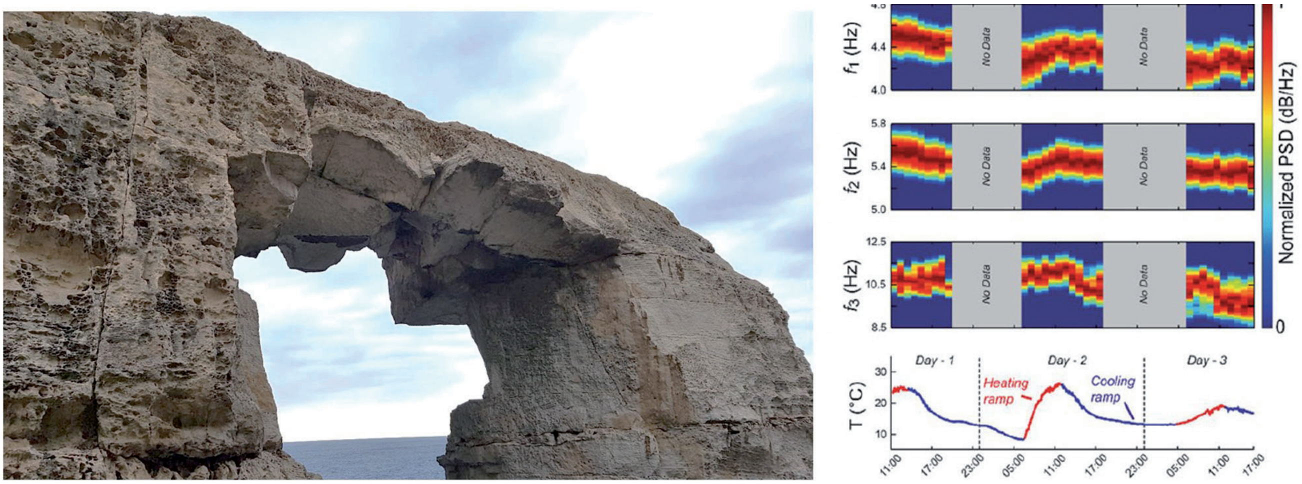

Fig. 12 - View of the Wied Il-Mielaħ sea arch where are visible the joints separating blocks from the arch beam. The graph on the right shows a detectable variation of the main eigenmode frequencies during a daily temperature change (from Grechi & Martino, 2020)

With these assumptions, zoning can lead towards a distinction based on the two "depths controlled" and "volume-controlled" models, *i.e.* "stable zones", characterized by local stratigraphic amplification, and "unstable zones" with different vibrational behavior in terms of both eigenmodes frequencies deduced from the recordings (and mostly associated with the geometries and dimensions of the rock blocks) and evidence (or not) of polarization and ellipticity at eigenmodes frequencies.

The case of the Maltese promontory of Selmun (Iannucci *et alii*, 2018) offered an excellent opportunity to experiment with such zonal approach, leading to the distinction of 5 sectors relating to an area of approximately 4 hectares (Fig. 5), based on the aforementioned criteria.

Sector A and sector E were associated with a "depth-controlled" vibrational response, *i.e.* the stable plateau in UCL and the outcrop of BC on GL, the latter differentiated by stratigraphic resonance conditions. Sectors B, C and D, on the other hand, are associated with a "mixed depth- and volume-controlled" system and with the evidence of diversified frequencies where both polarization and ellipticity are visible. This last evidence is based on the eigenmodes associated with the blocks disconnected from the UCL plateau with polarization effects on specific directions, controlled by the orientation of the joints that delimit the individual unstable blocks.

The advantage of recognizing and zoning the different types of vibrational systems, in accordance with the scheme proposed in Fig.1, consists in being able to direct the hazard study more specifically towards an analysis of the local seismic response (as in the cases of stable and "depth-controlled" models) rather than towards a stability analysis, for example in the case of rock landslides from cliffs (as in the case of "volume-controlled" and "mixed" models). In this last case the properties of dynamic inputs which could trigger the rock block failure should account for characteristic periods related to the eigenmodes of the unstable masses on the slopes (Lenti & Martino, 2013; Martino, 2015).

FINAL REMARKS

The integration of approaches for the engineering-geological characterization of jointed rock masses with geophysical investigations, based on the passive seismic technique and aimed at characterizing the vibrational behavior of natural systems, offers a promising perspective for the hazard zoning connected to landslide instabilities which involve slopes where jointed rock masses outcrop.

In particular, the diversification of vibrational models based on stratigraphic resonance ("depth-controlled") compared to those based on the oscillation of natural systems with different degrees of freedom, such as blocks disconnected from adjacent rock masses ("volume-controlled"), constitutes the theoretical prerequisite for the identification of stable zones. Local seismic amplification, which combines effects of both the local stratigraphic setting and the role of joints which infer degrees of freedom to the dislodged rock blocks (Fig. 1c), results in a polarized ground motion as well as in an accentuated ellipticity of the Raleigh waves, as proof of the significant interaction between the propagating seismic waves and the anisotropies present in the near surface.

Several case studies demonstrated the validity of these approaches suitable for greater application in mapping unstable areas as well as for the purposes of monitoring the evolution of preparatory processes as well as the time-dependent variables which can be associated to meteorological-climatic or anthropic factors.

In a future perspective, the possibility of modeling interactions between surface seismic waves and near surface elements undoubtedly represents an ambitious objective to support the interpretation of geophysical investigations, also in a view to better understanding the role of discontinuities in the determination of the eigenmodes of more complex natural systems (such as wind or marine arches but also the vaults or pillars of underground cavities).

In most cases, however, the techniques experienced so far generally use data recorded providing limited duration acquisition. The potential of the techniques discussed here must also be glimpsed from the perspective of a medium-long term monitoring, devoted to detecting variations in the physical state of the monitored system through the modification of its characteristic parameters. The final goal is to refine the predictive capacity of precursors of ultimate failure conditions. Such an application can have a strong impact on the territory and therefore implement pre-warning or safety strategies in a sustainability perspective, also in view of environment and human communities' resilience.

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