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ScienceDirect
Procedia Engineering 191 (2017) 263 – 269
Procedia Engineering
www.elsevier.com/locate/procedia

Symposium of the International Society for Rock Mechanics

Rock Mass Characterization Coupled with Seismic Noise Measurements to Analyze the Unstable Cliff Slope of the Selmun Promontory (Malta)

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Abstract

In the Mediterranean area, cliff slopes represent widespread high-risk landforms as they are highly frequented touristic places often interested by landslide processes. Malta represents a significant case study as several cliffs located all around the island are involved in instability processes, as evidenced by wide block-size talus distributed all along the coast line. These diffused instabilities are related to the predisponding geological setting of Malta Island, i.e. the over-position of grained limestone on plastic clay deposits, that induces lateral spreading phenomena associated to falls and topples of different-size rock blocks and is responsible for a typical landscape with stable plateau of stiff rocks bordered by unstable cliff slopes.

The ruins of Għajn Ħadid Tower, the first of the thirteen watchtowers built in 1658 by the Gran Master Martin de Redin, stand out in the Selmun area. Currently the safety of this important heritage site, already damaged by an earthquake on October 12th 1856, is threaten by a progressive moving of the landslide process towards the stable plateau area. During autumn 2015, a field-campaign was realized to characterize the jointed rock mass. A detailed engineering-geological survey was carried out to reconstruct the geological setting and to define the mechanical properties of the rock mass. Based on the surveyed joint spatial distribution, 58 single-station noise measurements were deployed to cover both the unstable zone and the stable area. The obtained 1-hour records were analyzed in the frequency domain for associating vibrational evidences to different instability levels, i.e. deriving the presence of already isolated blocks by the local seismic response.

The here presented results can be a useful contribute to begin to asses defense strategies for the Selmun Promontory, in the frame of managing the landslide risk in the study area and preserving the local historical heritage.

Peer-review under responsibility of the organizing committee of EUROCK 2017

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Peer-review under responsibility of the organizing committee of EUROCK 2017
doi:10.1016/j.proeng.2017.05.180

Keywords: unstable cliff slope; rock mass characterization; seismic measurements; local seismic response

1. Introduction

Cliff slopes are high-risk landforms in the Mediterranean area due to the diffused landslide processes that affect sites of touristic relevance as well as buildings which are part of the cultural heritage. Malta Island represents a significant case study as its geological setting, i.e. the over-position of grained limestone on plastic clay deposits, predisposes large lateral spreading processes associated to falls, slides and/or topples of different-size rock blocks. These instabilities interest countryside areas, e.g. the rock slabs where the city of Mdina and Citadel are built [1], as well as sea cliffs all along the coast line, especially in the north-west part of Malta and in Gozo island.

An important landslide process interests the Selmun Promontory, as evidenced by the large block-size talus and by the major joints on the rock plateau surface. The ruins of Għajn Ħadid Tower, the first of the thirteen watchtowers built in 1658 by the Gran Master Martin de Redin, stand out exactly in this area. Currently the safety of this important heritage site, already damaged by an earthquake on October 12th 1856, is threaten by a progressive moving of the landslide process towards the stable plateau area.

During autumn 2015, a field-campaign was realized to characterize the jointed rock mass of the Selmun Promontory cliff slope. A detailed engineering-geological survey was carried out to reconstruct the geological setting and to define the mechanical properties of the rock mass. Based on the surveyed joint spatial distribution, 58 noise measurement single-stations were deployed to cover both the unstable zone and the stable area, allowing to associate evidences of local seismic response to zones at different stability conditions, i.e. mainly related to the presence of already isolated rock blocks respect to adjacent stable zones.

The obtained results can represent an initial contribution in the frame of designing protection strategies to manage the landslide process in the Selmun Promontory as well as to preserve the heritage site of Għajn Ħadid Tower.

2. Geological and geomorphological setting

The Maltese archipelago is composed by three main islands (Malta, Gozo and Comino), located about 100 km south of southeastern Sicily. The islands represent the only currently emergent part of an extensive shallow-water shelf that extends from eastern Sicily to the Malta Graben, an important part of the threshold separating the Western and Eastern Mediterranean basins [2]. The Maltese islands are formed by limestones and clays of Oligocene and Miocene epochs that compose a sedimentary sequence of five main geological formation [1, 3, 4], from the oldest (Fig. 1a and Fig. 1b):

- Lower Coralline Limestone Formation (LCL), an hard and compact grey limestone of Oligocene (Chattian), having thickness about 140 m, which shapes the steep cliffs in the southwestern part of the Malta Island;
- Globigerina Limestone Formation (GL), a soft yellowish fine-grained limestone of Lower Miocene age (Aquitanian-Langhian) with a thickness from 20 m up to 200 m;
- Blue Clay Formation (BC), a very soft pelagic blue or greenish grey marl and limey clay of Middle Miocene age (Serravallian) with a thickness varying approximately between 20 m and 75 m;
- Greensand Formation (GS), massive, friable brown to dark green glauconite and gypsum grain-rich bioclastic limestone of Upper Miocene (Tortonian), having thickness less than 1 m in Malta and up to 10 m in central sector of Gozo;
- Upper Coralline Limestone Formation (UCL), pale grey and orange fossiliferous coarse-grained limestone, up to 160 m thick, of Upper Miocene in age (Tortonian-Messinian), composed by four different members.

The different geomechanical properties of each geological formation induces a marked difference in the values of the S-waves velocity (V_S), as evidenced by a V_S profile for the Selmun area showed in Figure 1c.

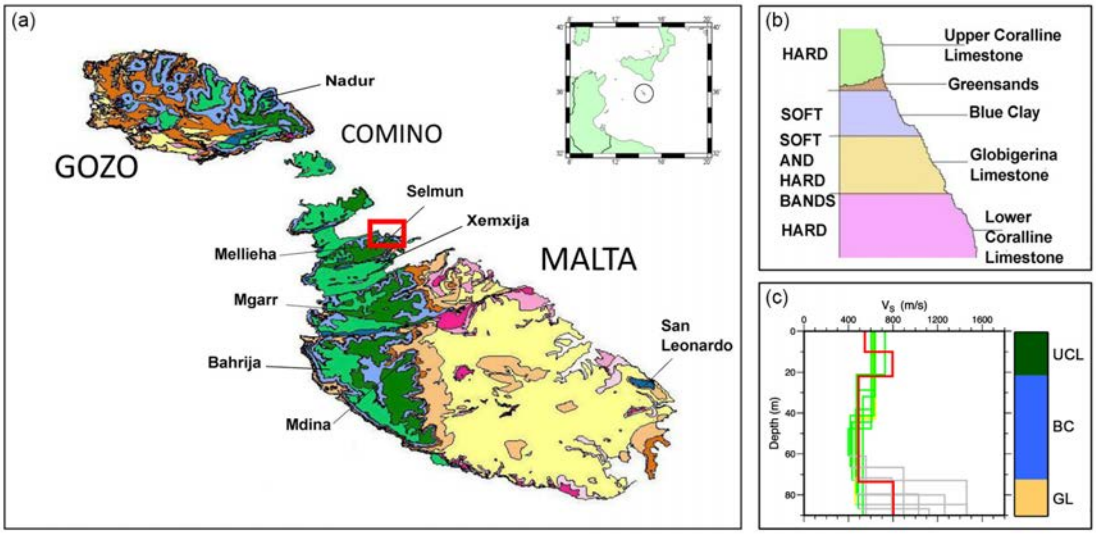

Fig. 1. Geology of the Maltese Islands: (a) the geology map (the different shades of green correspond to the four different members of the UCL), the position of the Maltese islands in the Mediterranean Sea and the location of the Selmun Promontory in Malta (in the red frame); (b) sketch of the sedimentary sequence; (c) a V_S profile for the Selmun area. (from [4]).

The stratigraphic succession in the Selmun area (Fig. 2) is composed of 20 m of the UCL, 30 m of the BC and the GL, all with almost horizontal strata. This typical geological feature, characterized by the juxtaposition of stiff rocks on a plastic deposit (i.e. the stiff UCL on the plastic BC), leads to a lateral spreading phenomenon [5]: the horizontal deformations affecting the clayey materials, with a visco-plastic behavior, induce cracks in the overlying stiff rock. Lateral spreading shapes a plateau of stiff rock bordered by jointed unstable cliffs, favoring the detachment of single rock blocks by typical rock landslide mechanisms, i.e. planar sliding, wedge sliding, toppling and falling [6]. According to [7] and [8], the resulting landslide process should be defined as a complex-type. Unstable cliff slopes cut in a summit plateau, composed of the UCL, overtopping gentle slopes of the BC are the typical landscapes of the northwestern part of the Malta Island [9].

Fig. 2. View of the Selmun Promontory with the cliff slope showing the UCL-BC contact and blocks detached from the UCL plateau.

3. Engineering-geological survey

On September 2015, a detailed engineering-geological field survey was carried out in the Selmun Promontory to reconstruct the geological setting of the cliff slope as well as to measure geomechanical properties of the jointed rock mass. A dense joint net was recognised on the plateau surface and on the cliff wall. Combing information derived by a GPS device and field observations as direction and length of joint segments, the joints of the rock mass were mapped and reported on a satellite view.

Each joint was characterized according to the ISRM standard [10] in terms of: attitude (dip direction and dip), spacing, persistence, aperture, filling, water flow, JCS coefficient (joint surface compressive strength, derived using the Schmidt rebound hammer) and JRC coefficient (joint surface roughness, obtained by the Barton comb). All the collected parameters were inventoried in an ArcGIS geo-database.

The rock mass matrix was characterized through laboratory tests performed on 18 cubic samples of the UCL. A 26.37 kN/m^3 of weight per unit volume of solid fraction γ_s was obtained by the water pycnometer method and a 21.05 kN/m^3 of natural weight per unit volume γ_n resulted by hydrostatic weighing method. The point load test estimated a uniaxial compressive strength σ_c between 63.0 MPa e 79.8 MPa. Based on the Schmidt hammer and on the laboratory tests results, an average joint surface compressive strength of 41.0 MPa was estimated for the analyzed joints.

Combining all the collected geomechanical data, it was possible to obtain an engineering-geological model of the Selmun Promontory, from which a map of the spatial distribution of the joints net (Fig. 3) and a cross-section (Fig. 4) were obtained. Additional engineering-geological cross-sections will be obtained to analyze the slope stability of the Selmun cliff slope.

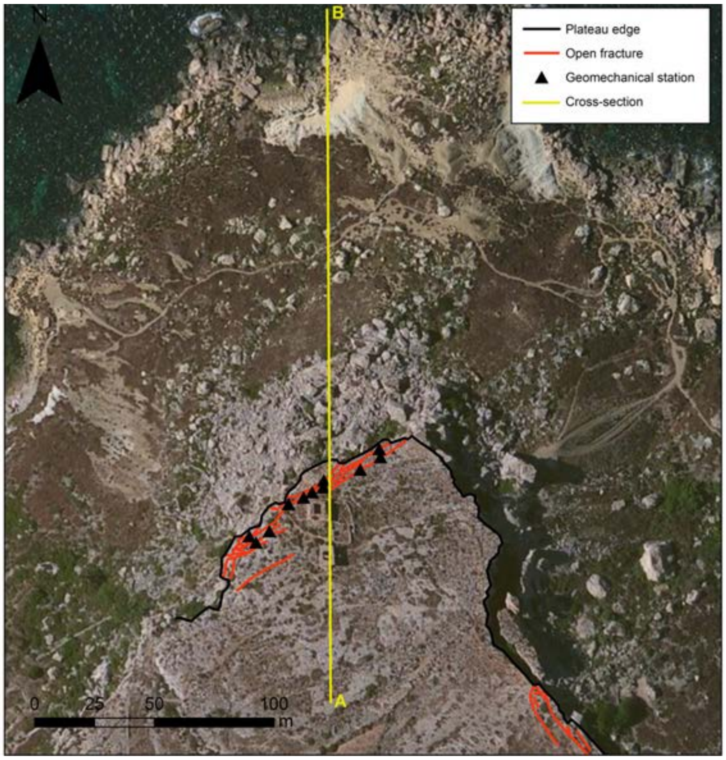

Fig. 3. Satellite view showing the engineering-geological model of the Selmun Promontory.

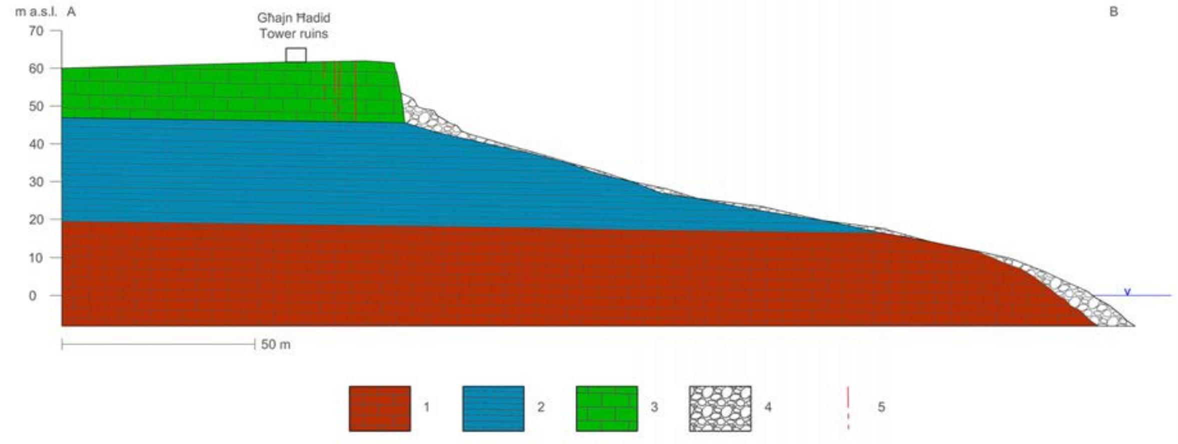

Fig. 4. Cross-section A-B (see Fig. 3) of the Selmun Promontory: 1) Globigerina Limestone; 2) Blue Clay; 3) Upper Coralline Limestone; 4) Debris slope; 5) Joint (the dashed line represents the supposed joint part).

4. Seismic noise acquisition and processing

In the period between September and October 2015, several geophysical campaigns of seismic noise measurements were carried out in the Selmun Promontory. In recent years, several studies applied ambient noise techniques to investigate landslide-involved slopes [11, 12, 13] or to characterize blocks of unstable cliffs [14, 15, 16] through different approaches, e.g. H/V spectral ratios, f-k analysis, site to reference spectral ratios, polarization analysis, base noise level variations.

Seismic noise was recorded in 58 stations over an area of approximately 0.05 km^2, to cover the unstable zones of the cliff slope as well as the stable carbonate plateau on the basis of the joint distribution (Fig. 5). A 3-component seismometer was installed in each station: 40 measurements were carried out using a LE-3D/5s seismometer by Lennartz Electronic GmbH coupled with a REFTEK 130-01 datalogger having a sampling frequency of 250 Hz; 18 measurements were carried out using a Tromino set a 256 Hz sampling frequency. In the both cases, the seismic noise was recorded for 1 hour.

Using the Geopsy software (www.geopsy.org), the time histories were divided into non-overlapping windows of 40 s and the Fast Fourier Transform (FFT) was computed for each component in the frequency range between 1.0 and 60.0 Hz. By averaging over the windows, the amplitude spectra and the H/V spectral ratio were finally achieved for each single record.

The HVSR method [17] allows to obtain the resonance frequency of a site, particularly when layers having low shear-wave velocity cause a sharp impedance contrast with the bedrock. The presence of a resonance peak in the HVSR curve has been interpreted both in terms of SH-wave resonance and in terms of the ellipticity of particle motion when the ambient noise wave train is made up predominantly of surface waves [18]. In practice, the wavefield is a combination of both types and the shape of the HVSR curve provides information about the shear wave velocity profile in shallow sediments [16].

5. Results

In the Selmun Promontory, the HVSR curves show as common feature a ubiquitous resonance peak in a narrow frequency range of 1-2 Hz and a following sharp dip of the spectral ratio. This HVSR curve feature is always present in the Maltese archipelago where the UCL outcrops and is underlain the BC [15, 19] and is related to the difference of V_S values between the three geological formations that compose the outcropping sedimentary sequence (Fig. 1c). The dip of the HVSR curve was interpreted in terms of a shallow shear-wave velocity inversion at the interface between the competent UCL and the plastic BC, while the peak can be related to Rayleigh wave ellipticity and/or trapping of SH waves in the BC low-velocity layer [16, 4].

On the other hand, the HVSR curves show marked differences in the seismic response between the unstable areas and the stable plateau zone, especially at frequency higher than 3.0 Hz (Fig. 5). In fact, in the measurements carried out within and in proximity of the unstable zones the HVSR curves show significant resonance peaks at high frequency (3.0-60.0 Hz) that are not present in the measurements carried out on the stable plateau zone. In addition, HVSR resonance peaks are much more evident in areas having higher density of fractures and blocks, as the jointed edge of the UCL plateau.

As evidenced by several papers published in the last years [14, 16], the seismic energy in the frequency higher than 3.0 Hz can be related to the vibrational behavior of the dislodged rock blocks. The seismic response of a rock block is related to its resonant frequency and depends on geometrical and mechanical properties of the rock block itself [14], but more detailed studies will be need to obtain a relationship between the vibrational modes of single rock blocks and their seismic response.

Considering the obtained preliminary results, analysis of noise measurements seems to be a useful tool to define zones having different stability levels, therefore further analysis techniques (e.g. polarization analysis [12]) will be applied at the recorded seismic data as well as at future records in order to increase the knowledge of this application field. Reliable characterization of unstable zones and rock blocks can be useful elements to design monitoring networks at the aim of providing an early warning system in order to manage the landslide risk, e.g. installing permanent sensors from which it could be possible identify an incipient failure of a cliff slope portion analyzing the noise variations over time [14].

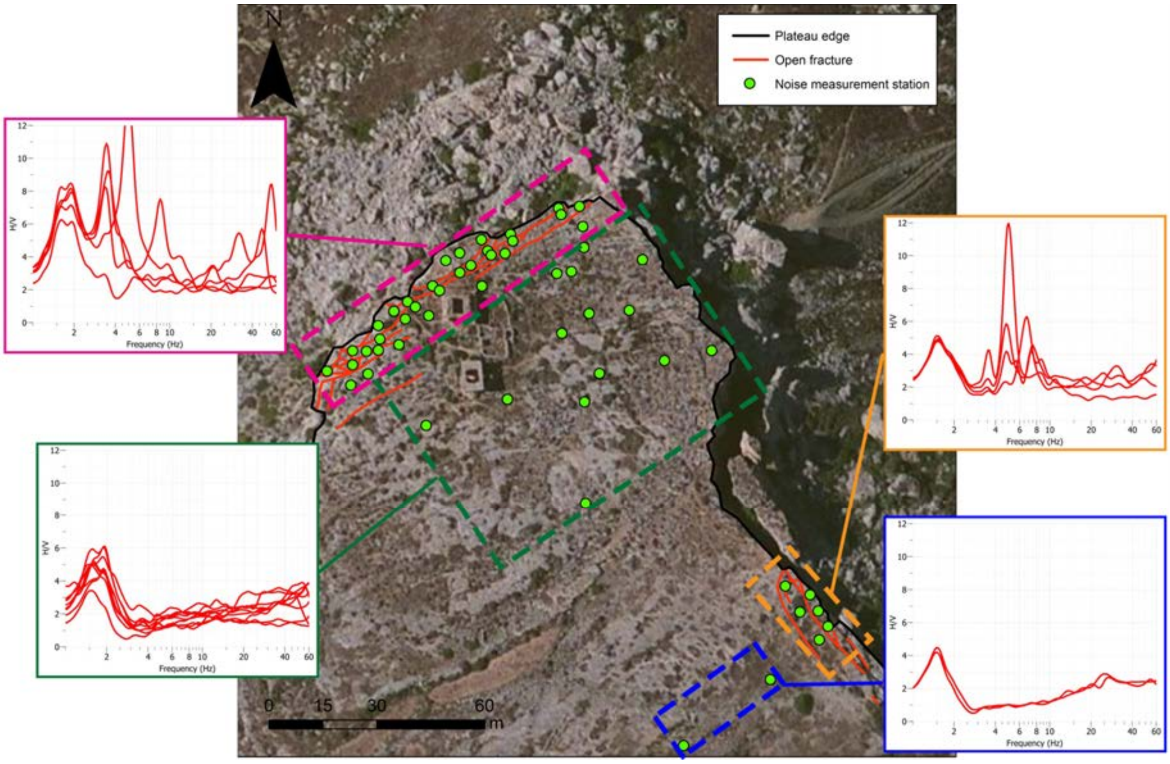

Fig. 5. Satellite view of the Selmun Promontory showing: open and estimated fractures, the 58 noise measurement stations and HVSR curves grouped by different areas; for the unstable areas (in the yellow and pink frames) only the most significant HVSR curves are shown.

6. Conclusions

In the cliff slope of the Selmun Promontory, an ongoing lateral spreading process threats the important heritage site of Għajn Ħadid Tower. On autumn 2015, a field-campaign achieved to characterize the jointed rock mass and to obtain an engineering-geological model of the Selmun Promontory. Seismic noise measurements were carried out both on the stable plateau area and on the unstable cliff. These measurements pointed out a different seismic response in the two areas, except for the first HVSR peak at 1.0-2.0 Hz related to the stratigraphic succession and observed in all measurements. At higher frequencies (3.0-60.0 Hz), a complex local seismic response made by several HVSR peaks was observed, related to the seismic response of the dislodged rock blocks.

At the light of the obtained preliminary results, analysis of noise measurements seems to be a useful tool to delimitate zones having different stability levels. More detailed studies and new investigations will be carry out to define the cliff slope stability conditions. The obtained results can be a useful contribute to begin to asses defense strategies for the Selmun Promontory, in the frame of designing protection strategies to manage the landslide process as well as to preserve the heritage site of Għajn Ħadid Tower.

Acknowledgements

The Authors wish to thank Marisa Regina for her useful support in the field geological survey and in the laboratory tests. S. D’Amico was partially support by the research project “Multidisciplinary geophysical approaches for the conservation of cultural heritage sites” funded by University of Malta (GSCRP02-16)

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