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THE ROLE OF SLOPE INSTABILTY ON DIRECTIONAL SITE EFFECTS OBSERVED AT FEKRUNA BAY, MALTA

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Introduction. The Maltese Archipelago is situated in the Mediterranean Sea, about 290 km NE of Tunisia and 90 km South of Sicily. It consists of three major islands: Malta and Gozo, the southerly and northerly islands respectively, and Comino which lies in the Comino straits separating the two largest islands. In order to better preserve the historical heritage, landscapes, and coastal areas and to promote tourism activities it has been proposed that the archipelago might be considered as an open air laboratory. In this context multidisciplinary studies integrating geology, geotechnical earthquake engineering, geomorphology as well as history and archeology were undertaken in order to develop and test methodologies for the assessment of the relationship between physical environment and cultural heritage (e.g., Soldati *et al.*, 2008).

The paper focuses on an integrated study about geomorphology and seismic site response in the Fekruna bay, in the area of Xemxija (northen-eastern part of the Malta Island, Fig. 1).

This site is very important for touristic attractions, as well as cultural and historical heritage. The area can be considered as an open laboratory since it is characterised by a geology and topography that varies over small spatial scales. Its geomorphological features are the result of the combined effect of the lithology, tectonics and coastal nature that shaped the region and such features contribute towards the degree of geological instability of the whole area and principally to the cliff sections. In particular, the combination of vulnerable geomorphologic features, intensive land use and cultural/touristic importance implies that the study area is exposed to a considerable natural risk. Buildings in Xemxija village are located in a diversity of topographical settings, such as slopes, ridges and valleys, while a variety of building types and ages can be identified. The small urban settlement is densely populated in summer, when it is used as a summer resort, with intensive recreational and commercial coastal land use. The area also provides a suitable setting for the subsequent evaluation of a number of other factors that contribute to the damage potential, and hence the holistic assessment of geo-risks.

To date, no studies combining geomorphology and site response have been carried out in the study area of Xemxija. In particular, we carried out a preliminary study of the area, focusing our attention to the risk of landsliding and rockfalls and conducting a geomorphological survey of the area in order to map and characterize the main fractures in the region. In addition we used the ambient noise Horizontal-to-Vertical Spectral Ratio (HVSR) technique in order to characterize the behavior of rock masses in the presence of fractures linked to the landslide body in the area. This type of measurement can be done quickly and with a high spatial density, providing a fast tool for setting the dynamic behavior of the rock outcropping. The HVSR method is a common tool, used for site effect investigations, based on the ratio of the horizontal to vertical components of ground motion. Generally, this spectral ratio exhibits a peak, corresponding to the fundamental frequency of the site. The ambient noise wavefield is the result of the combination of unknown fractions of both body and surface waves (Bonnefoy-Claudet *et al.* 2006). If the first are prevailing, the ratio is mainly induced by S_H resonance in the superficial layers whereas, if Rayleigh surface waves predominate, the theoretical ellipticity dictates the observed curves (Nogoshi and Igarashi 1970; Fäh *et al.,* 2001; Scherbaum *et al.,* 2003). This is especially true when a large shear-wave velocity contrast exists between the shallow layer and the bedrock, as theoretically confirmed by Malischewsky and Scherbaum (2004). Although experimental data peaks usually fit quite well the resonance frequency of the theoretical curves, they are less reliable as regards their amplitude. Nevertheless, the HVSR curve contains valuable information about the underlying structure, especially as concerns the relationship between V_S of the sediments and their thickness (Ibs-Vonseth and Wholenberg, 1999; Scherbaum *et al.,* 2003). Recordings of ambient noise and the use of the HVSR technique has recently had widespread use in studying landslides (e.g., Del Gaudio *et al.*, 2008; Burjánek *et al.*, 2010; Del Gaudio and Wasowski, 2011; Burjánek *et al.*, 2012).

The structural geology of the Fekruna and Xemxija area is dominated by the development of horst and graben blocks, bounded by ENE trending normal faults. The outcropping local geology (Pedley *et al.,* 1978, 2002) is characterised by three different lithotypes: clay from the Blue Clay (BC) formation and two different members of the Upper Coralline Limestone (UCL) formation, being one (Tal-Pitkal Member) and one softer and erodible (Mtarfa Member). Underneath the BC, a carbonatic formation, the Globigerina Limestone Formation (GL) consisting mainly of loosely aggregated planktonic foraminifers, and a Lower Coralline Limestone Formation (LCL), which consists of massive biogenic limestone beds, are present. These two lithotypes, although do not outcrop in the study area, are widely present in the Malta area. The north coast of the Malta island is characterized by lateral spreading phenomena which take place within the brittle and heavily jointed and faulted UCL formation overlying the BC formation, consisting of softer and unconsolidated material. Most of the time these processes occur in places that are not intensively built however some areas are highly frequented by both local and tourists for recreation activities.

Geomorphological analysis, experimental setup and data processing. Landslides in the northern Malta coast seem to be caused by lateral spreading and rockfall which occur within the brittle UCL formation overlying the BC. The UCL formation is characterized by a prominent plateau scarp face, whereas BC produces slopes extending from the base of the UCL scarp face to sea level. It is well known that lateral spreading usually take place in the lateral extension of cohesive rock masses lying over a deforming mass of softer material where the controlling basal shear surface is often not well defined (Pasuto and Soldati, 1996).

A detailed field survey was performed in the area to map the main coastal instability features, using a map at scale 1:2500 (MEPA, 2004). The features mapped are the result of different mechanisms, such as:

- cliff parallel fracturing due to natural cliff erosion and retreat;
- formation and detachment of blocks along the cliff edge, leading to rock collapse;
- land-sliding on sloping faces;

instability resulting from weakening of the UCL strata lying on the top of the soft BC layer that is slowly eroding and sliding.

For the HVSR analysis we recorded ambient noise at 27 sites (Fig. 1) using a 3-component seismometer (Tromino, www.tromino.eu). Time series of ambient noise, having a length of 20 minutes, were recorded with a sampling rate of 128 Hz and, following the guidelines suggested by the SESAME project (2004) they were divided in different time windows of 20 s each not overlapping each other. A 5% cosine taper was applied to each window and the Fourier spectra were calculated. The spectra of each window were smoothed using a Konno-Ohmachi window (Konno and Ohmachi, 1998) fixing the parameter *b* to 40. Finally the resulting HVSR, in the frequency range 0.5-40.0 Hz, was computed estimating the logarithmic average of the spectral ratio obtained

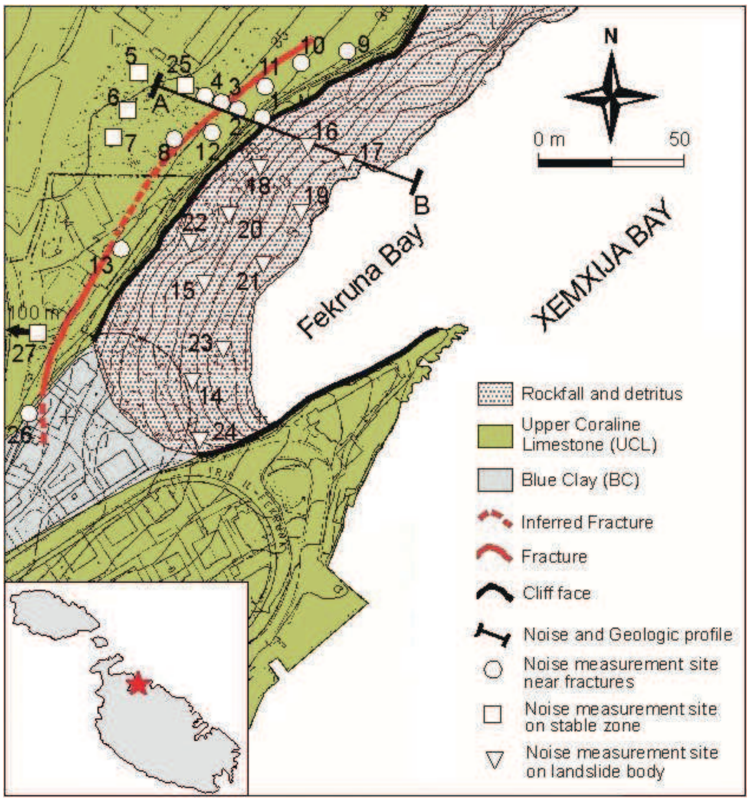

Fig. 1 - Geo-lithologic map of the north-eastern part of the Xemxija bay (modified from MEPA Various Authors, 2004). The inset shows the location of the study area (red star).

for each time window, selecting only the most stationary and excluding transients associated to very close sources.

Experimental spectral ratios were also calculated after rotating the NS and EW components of motion by steps of 10 degrees starting from 0° (north) to 180° (south). This approach, first applied to earthquake recordings in studying the directional effects due to topographic irregularities at Tarzana, California (Spudich *et al.,* 1996), has been used for ambient noise signals by several authors (Del Gaudio *et al.*, 2008; Del Gaudio and Wasowisky, 2011; Burjánek *et al.*, 2010) to identify site response directivity in the presence of an unstable slope.

A direct estimate of the polarization angle was also achieved by using the covariance matrix method (Jurkevics, 1988) to overcome the bias linked to the denominator behavior that could occur in the HVSR technique. This technique is based on the evaluation of eigenvectors and eigenvalues of the covariance matrix obtained by three-component seismograms. Signals at each site were band-pass filtered using the entire recordings and a moving window of 1 s with 20% overlap, therefore obtaining the strike of maximum polarization for each moving time window. Finally, the distribution of polarization angles of all the signals is plotted as a rose diagrams. We also applied the Time-Frequency (TF) polarization method (Burjánek *et al.*, 2010, 2012). The most important difference with the simple covariance matrix method consist in the use of a continuous wavelet transform for signal time-frequency decomposition, and later the polarization analysis on the complex wavelet amplitude for each time-frequency pair, is applied. Histograms of the polarization parameters are created over time for each frequency. Polar plots are then adopted for depicting the final results of the TF polarization method, which illustrate the combined angular and frequency dependence.

Results and discussions. We focused the present study on the part of the bay in which there is major evidence of slope instability and in which a high level of cliff fracturing is evident, as shown by the geomorphological study. A dense microtremor measurement survey was carried out in the Fekruna bay area, choosing the recording sites in order to sample the area as uniformly as possible. Moreover, several recording sites where chosen on a linear deployment for investigating the role of the fractures in the HVSR behaviour.

The HVSR measurements were performed in three different zones: indeed, we carried out one set of measurements in a stable platform and far away from the cliff edge, a set of measurement in the fractured area along the cliff, and another set on the landslide body (Fig. 1 for measurement points location and Fig. 2a for some examples of HVSR results). We were able to identify a region, away from the cliff edge, where the HVSR peaks around a stable frequency of about 1.5 Hz. These fundamental peaks may be generally associated with the interface separating the BC layer from the underlying carbonates of the Globigerina Limestone Formation (GL). Moreover, the presence of the BC layer gives rise to a velocity inversion since it has a lower shear wave velocity with respect to the overlying UCL formation. This causes the HVSR values to drop below 1 over a wide frequency range (Castellaro and Mulargia, 2009). The origin of the resonance peak as linked to the BC/GL interface was confirmed by the results obtained through a 1D modelling, performed by computing the synthetic HVSR curves (Fig. 2b). To compute the synthetic spectral ratios we considered that ambient vibrations wavefield can be represented by the superimposition of random multi modal plane waves moving in all the directions at the surface of a flat 1-D layered visco-elastic solid, as in Herrmann (2002) formulation. These waves are assumed to correspond to Rayleigh waves in the fundamental mode (Fäh *et al.*, 2001), including also the presence of Love waves (Bonnefoy-Claudet *et al.*, 2008), generated by a distribution of random independent point sources located at the surface of the Earth (Lunedei and Albarello, 2009). Although the contribution of higher modes is relatively small, we extended the modal summation up to the fifth mode. When modelling the HVSR, we applied initial constraints on the thicknesses and elastic parameters of the layers using borehole logs data to obtain approximate values of layer thicknesses and rock densities. Shear waves velocity values were also taken from a separate preliminary study carried out in the same area using the ReMi, MASW and Refraction methods (Panzera *et al.*, 2011).

The spectral ratio obtained at sites close to the cliff edge and all around the identified fractures present a behaviour similar to the one described above, but with slightly different features at the high-frequency interval. In general, in all the records we observe a clear and predominant peak at around 1.5 Hz which is associated with the interface between BC and GL. Several peaks, showing a slight increase of the amplitude on the HVSR, are also evident at higher frequency (> 9.0 Hz). The fact that these peaks are not visible in the unfractured region leads us to postulate that they may be associated with the presence of fractures and of blocks almost detached from the cliff and therefore free to oscillate. The sites on the rock-fall area show a different HVSR behaviour with respect to the measurements taken on the plateau. In this area it is possible to identify HVSRs showing bimodal dominant peaks at low frequency, in the range 1.0-3.0 Hz, as well as pronounced peaks at about 3.0 Hz and at frequency higher than 9.0 Hz. The bimodal peaks at low frequency (1.0-3.0 Hz) can, in our opinion, be associated to the contact between the rockfall and detritus unit and the BC formation, as well as to the interface between BC and the underlying GL formation.

We investigated the existence of directional effects in the site response by rotating the horizontal components of the spectral ratios obtained at each measurement site (few examples are given in Fig. 2c). In the cliff fracture zones we observed clear directional effects with an angle of about 40°-60° N in all the considered frequency range, although some variability in azimuth is observed at high frequency (>9 Hz) at site #13. On moving away from the cliff edge, the rotated HVSR show a slight change of the directional resonance angle and an amplitude decrease of the rotated spectral ratios at high frequency. Such a behavior could be linked to the increase of rock stiffness and the reduction of the amount of blocks free to oscillate. Finally, it is evident that the directionality pattern observed in the rotated HVSRs performed on the landslide body is quite complex. The general trend has a prevailing direction of about 40°-60° N at low frequency (1.0-9.0 Hz), similarly to what is observed in the fractured zone, whereas different resonant frequencies and directions that could be ascribed

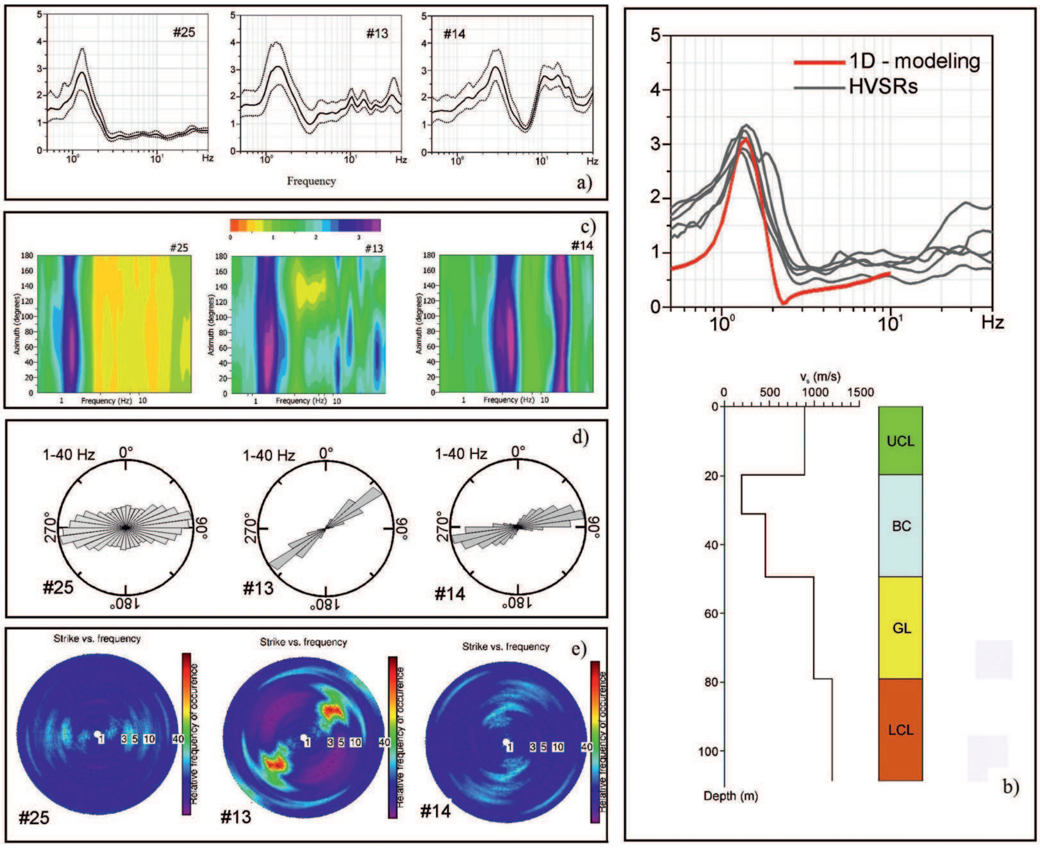

Fig. 2 - (a) Example of HVNR results obtained at some recording sites located in the not fractured zone (#25), in the cliff area (#13), and in the landslide zone (#14); (b) results obtained through a 1D modelling, performed in sites located on the non-fractured zone, by computing the synthetic HVSR curve; (c) rotate HVSR, (d) rose diagrams and (e) polar plots obtained at recording sites #25, #13 and #14.

to the vibration of smaller blocks can be observed at higher frequencies (9.0-40.0 Hz).

Furthermore, we obtained a direct estimate of the polarization angle through the full use of the three-component vector of the noise wave-field. General behavior of the noise wave-field, in this frequency range is showed through rose diagrams, whereas, in order to distinguish between properties of low and high frequency components of the signal, strike versus frequency polar plot were obtained. Some examples of the results of noise polarization analysis from recording sites on both the cliff and the landslide are shown in Fig. 2d and e. It is clear that the maxima of the horizontal polarization occur in the north-east to east-north- east direction, although in some cases the high frequency directionality is more complex. As observed by Burjánek *et al.* (2010), high-frequency ground motion can indeed be controlled by the vibration of smaller blocks that imply both different resonant frequencies and directions.

The polarization observed for the sites located away from the unstable areas (see e.g., #25 in Fig. 2) show a trend with more dispersed and variable directions. The boundaries of the landslide area therefore appear well defined by the polarization pattern and as postulated by Kolesnikov *et al.* (2003) the landslide activity is characterized by strong horizontal polarization in a broad frequency band. In our study, a tendency seems evident for the entire landslide body to generally vibrate with a north-east azimuth and, accordingly, during a strong earthquake the ground motion would be amplified in this direction. Studies of Burjánek *et al.* (2010, 2012) point out that the ambient noise

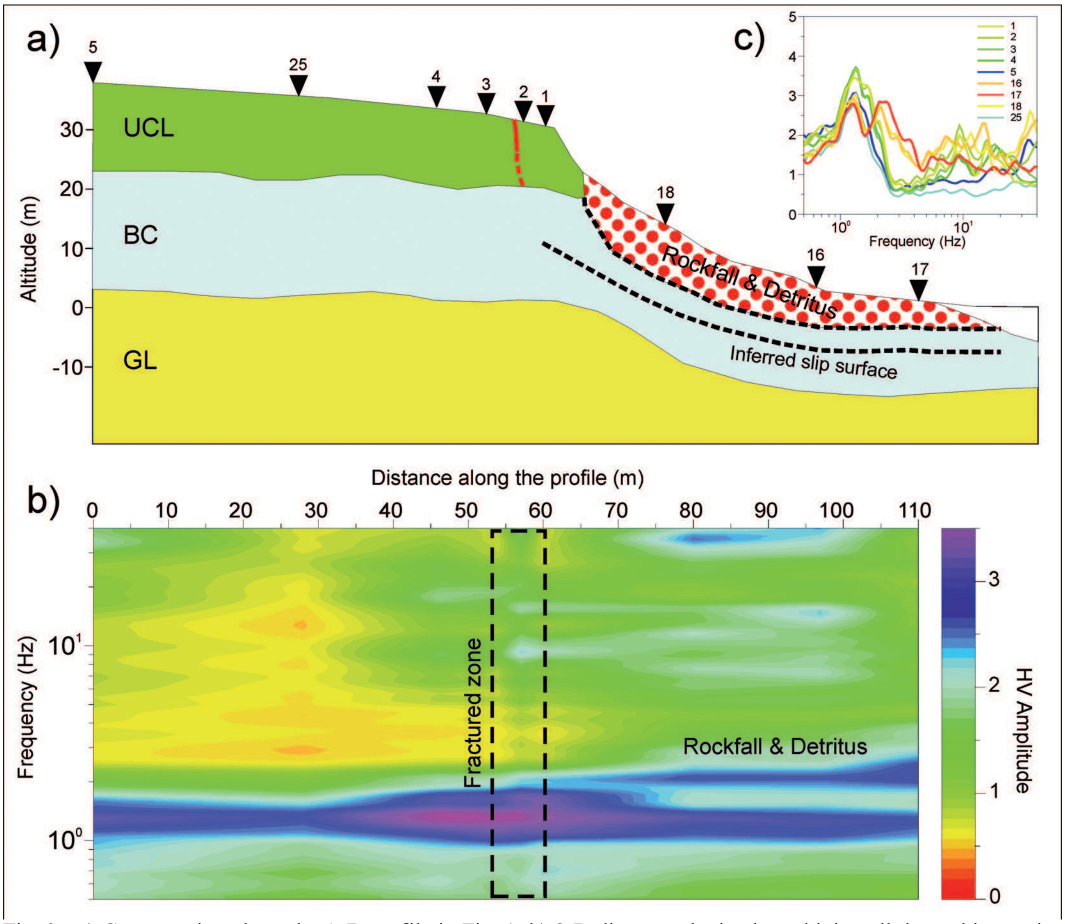

Fig. 3 - a) Cross section along the A-B profile in Fig. 1; b) 2-D diagram obtained combining all the ambient noise measurements along the profile as a function of distance (x axis) and frequency (y axis); c) HVSR results at the recording sites located across the profile.

polarization take place at about 90 degree angle to the observed fractures which are perpendicular to the sliding direction. In the present study the polarization angle is parallel to the opening cracks, which appears in contrast to the above mentioned results. A possible explanation of our findings is that there exists a prevailing north-easterly sliding direction of the landslide body which is strongly affecting the polarization direction especially in the 1-10 Hz frequency range.

Finally, in Fig. 3 we summarize the above described results into a tentative draft profile, located as shown in Fig. 1, which illustrates the main geological features and hypothesizes the shape of the landslide body. The bottom panel shows a 2-D diagram obtained by combining all the ambient noise measurements along the profile, namely the HVSR spectra. Below the sites #5 and #25 the main peaks can be associated to a sequence of layers which have different shear wave velocities and show the presence of an evident velocity inversion. Moving along the profile from measurement point #4 to #1, it is interesting to observe the increasing amplitude of the HVSR at frequencies greater than 6.0-7.0 Hz. It can also be noticed that, especially between 50 and 60 m along the profile (sites #1, #2 and #3) the influence of the fracture zone is evident (see dashed area in Fig. 3). This is associated with the presence of the mapped main fracture (marked in red in the top panel) and the vibrational mode of the almost detached blocks. Along the cross section, at distances ranging from 60 to 100 m, it is possible to note both the presence of the bimodal peak associated with the two interfaces detritus/BC and BC/GL, as well as the high frequency peaks most probably associated with the vibration of large blocks that have been detached from the cliff-face and are now partially or totally included in the BC.

Conclusions. This paper presents a preliminary field study in the Xemxjia bay area aiming to highlight the importance of evaluating the local seismic response in presence of slope instabilities related to landslide hazard. In particular, large cliff-parallel fractures that could cause cliff-edge collapse and main unstable boulders were identified, mapped and photographed in order to document the present-day situation. The most diffuse collapse mechanism is represented by rockfalls, toppling and retrogressive sliding of small to large rocks. These processes are most likely induced by the different stiffness of the clay and the overlying limestone. Recent studies have pointed out that there is no evidence of measured movements after rain or dry period (Soldati personal communication). We therefore think that the fracturing is not induced by weathering and erosion at the cliff edge. In our opinion, following the outcomes of noise measurements, the presence of the clay formation develops a sliding surface and produces tension stresses at the top of the UCL. Thus, cracks expand due to the ultimate tensile strength of the formation, defining blocks on the top of both cliff and hill which are affected by collapse mechanisms (Lollino and Pagliarulo, 2008).

It is known that seismically-induced ground acceleration can lead in some cases to land sliding and block detachment that therefore represent a considerable problem for engineering geology (Fell *et al.,* 2008). In areas prone to severe ground shaking, the effect of seismically-induced landslides on human lives and facilities can add further damage to that directly connected to the shaking (e.g., Jibson *et al.,* 2000), as experienced in several earthquakes of moderate and large magnitude such as in the recent Mw=6.3 earthquake in Christchurch (New Zealand, 22 February 2011), the Mw=6.2 L'Aquila earthquake (Italy, 6 April 2009) and the Mw=7.9 Wenchuan earthquake (China, 12 May 2008). The seismic history of the Maltese islands is adequately documented since around 1500 (Galea, 2007). During this period, the islands have suffered earthquake damage exceeding EMS-98 intensity V on seven occasions (1542, 1693, 1743, 1856, 1861, 1911, 1923) and the occurrence of landslides has been reported on several occasions (e.g., 1693 earthquake from Ellul, 1993).

The Xemxija unstable area is characterized by the presence of numerous blocks and boulders along the slopes and cliff base, supporting the idea that the area is prone to a severe landslide risk. The instability processes that could be potentially triggered are linked to both slow mass movements, which might normally occur in tens or hundreds of years, and to sudden rockfall in the case of ground shaking due to moderate-to-strong earthquake activity. To better understand the situation, the most important discontinuities, both in the coastal cliff area and the hill, were identified and mapped, focusing in particular on the main unstable rock masses which might be displaced even in case of moderate earthquakes.

The available literature data and recent instrumental observations indicate that the dynamic response of potentially unstable slopes to seismic shaking can be very complex. In particular, there is evidence that seismic ground motion on landslide slopes can be considerably amplified and such amplification has a directional character (Moore *et al.*, 2011). Such directional effects were seen to be related with topographic, lithologic and structural factors as well as normal mode rock slope vibration (e.g. Del Gaudio *et al.,* 2008; Burjánek *et al.,* 2012). The results of horizontal-to-vertical spectral ratio measurements in the NE part of Xemxija bay, in which there is major evidences of slope instability, indicate that this method could be useful for the recognition of site response directivity phenomena. The use of noise measurements pointed out the existence of three different zones: a stable zone, in which the HVSRs show only a dominant peak at about 1.5 Hz linked to the presence of the BC in the shallow lithologic sequence; a second zone, close to the cliff area, characterized by the presence of spectral ratio peaks linked to both the presence of shallow lithotypes such as the BC and the UCL, as well as to the existence of the fractures in the rock; and a third zone on the landslide body, which puts in evidence the presence of an active slip surface inside the soft clayey material that allows the slow sliding of the upper portion of BC formation.

Moreover, the experimental data highlight the existence of directivity phenomena, affecting in particular the slope areas, centered on the north eastern direction, that seem to be influenced by the simultaneous action of geological factors as well as fractures and block vibration linked to the landslide activity.

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