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Work Package 2: Identification of Risk scenarios

Activity 2.1: Evaluation of hazard, exposure and vulnerability

Report on the evaluation of seismic hazard, seismo-induced landslide hazard and earthquake ground motion scenarios in the Maltese islands

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Foreword

The collaboration between the scientific community and Civil Protection authorities is extremely important. One of the pillars of this communication is the evaluation by the scientific community of the probabilistic assessment of natural hazards, as well as the projection of likely scenarios in the case of a disastrous event. The results of such scientific studies must be communicated to the Civil Protection authorities in a clear, understandable and timely manner so that the best action can be taken in the shortest possible time in an effort to save lives and mitigate damage. One of the aims of Work Package 2 is to make evaluations ofgeohazards in particular areasof the cross-border region.

This deliverable presents three scientific reports of work undertaken by the University of Malta, Physics Department (PP5). The first report is a probabilistic seismic hazard assessment for the Maltese islands, based on established seismic source regions in and around the Sicily Channel. The second report uses results of shear-wave velocities in Maltese rocks obtained in D2.1.1 as part of the input to compute expected ground motion parameters as a result of likely earthquake scenarios. The third report considers the topography and geology of the Maltese islands to compute the hazard over the Maltese islands of landslides induced by given earthquake scenarios.

PRELIMINARY PROBABILISTIC SEISMIC HAZARD ASSESSMENT FOR THE MALTESE ARCHIPELAGO

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Introduction

The Maltese islands form an archipelago of three major islands (Malta, Gozo and Comino) lying in the Sicily channel at about 140 km south of Sicily and 300 km north of Libya. So far very few investigations have been carried out on seismicity around the Maltese islands and no maps of seismic hazard for the archipelago are available. Assessing the seismic hazard for the region is currently of prime interest for the near-future development of industrial and touristic facilities as well as for urban expansion. A culture of seismic risk awareness has never really been developed in the country, and the public perception is that the islands are relatively safe, and that any earthquake phenomena are mild and infrequent. This is probably due to the fact that no loss of life has ever been documented as a direct result of earthquake activity, and the last occurrence of serious damage to buildings was almost a century ago (Galea, 2007). Meanwhile, the local building density has increased dramatically over the past few decades, and the building footprint has spilled over to geologically diverse and more unstable areas (Panzera et al. 2012, Galea et al, 2014). Although recent constructions of a certain structural and strategic importance have been built according to high engineering standards, the same probably cannot be said for all residential buildings, many higher than 3 storeys, which have mushroomed rapidly in recent years. Such buildings are mostly of unreinforced masonry, with heavy concrete floor slabs, which are known to be highly vulnerable to even moderate ground shaking. The lack of recent earthquake damage has led, to a certain extent, to complacency in the construction industry as well as a lack of knowledge about the behaviour of local buildings during ground shaking.

Method used and preliminary results.

In this study we attempt to compute a first and preliminary probabilistic seismic hazard assessment of the Maltese islands in terms of Peak Ground Acceleration (PGA) and Spectral Acceleration (SA) at different periods. Seismic hazard has been computed using the Cornell (1968) approach which is the most widely utilized probabilistic method. It is a zone-dependent approach: seismotectonic and geological data are used, coupled with earthquake catalogues to identify seismogenic zones (SZs, active areas) within which earthquakes occur at certain rates. We assumed that earthquakes have the same probability of occurrence at any location and they occur at rates defined by a recurrence relationship (e. g., Gutenberg and Richter, 1954; 1956). Therefore the earthquake catalogues can be reduced to three main parameters: the activity rate, the b-value of the Gutenberg-Richter relationship and an estimate of the maximum magnitude. Seismic hazard computations have been performed within the island boundaries over a grid of sites. An SHA based on the Esteva-Cornell method, was performed using the open source code CRISIS2012. This code requires as input data a source-zone model where the seismic rate of each considered zone and a ground motion predictive equation are used.
Figure 1 shows the logic tree used for the seismic hazard analysis. The two main sections of the logic tree (A and B) were built taking into account different seismogenic sources in the central Mediterranean. The first six branches consider just one single seismogenic source (SCZ). In the last 6 branches SCZ was broken down into 4 different seismogenic sources FSZ1, FSZ2, FSZ3, and FSZ4).

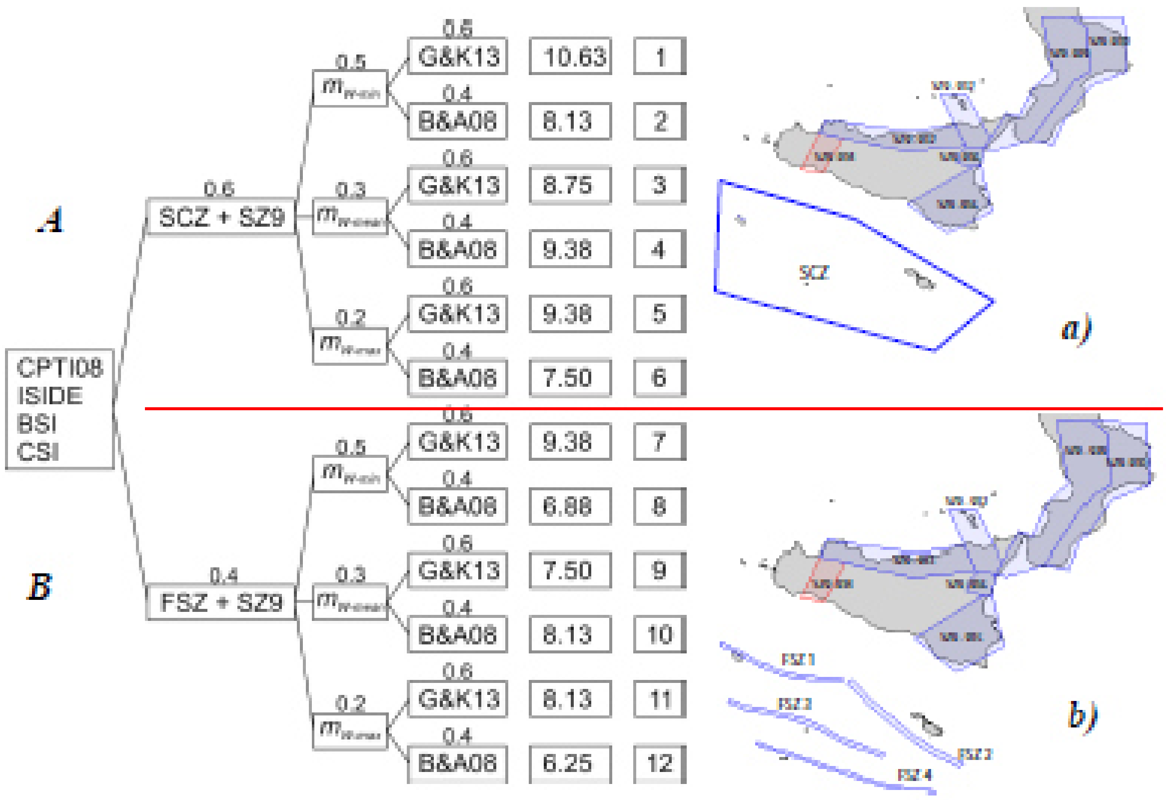

Figure 1. Logic Tree approach used and seismogenic sources used in the present study. We employed two different attenuation relationships: G&K13(Grazier and Kalkan, 2013) and B&A08 (Boore and Atkinson 2008)

Figure 2 shows hazard curves (at the bedrock) for Malta using the logic tree approach. They represent the probability of exceedance of a given PGA in the next 50 years. The curves in panel (a) were computed using the single seismogenic zone in the Sicily Channel. Panel (b) shows results obtained for each branch and using the four different seismogenic zones in the Sicily channel proposed by the SHARE working group (http://www.shareeu.org). The PGA values in the second case are considerably higher. In fact the value of PGA corresponding to 10% probability of exceedance in 50 years (equivalent to 475 year return period) is around 0.22g for logic tree branches considering the 4 seismogenic zones of Figure 1b. Figure 3 shows a preliminary seismic hazard map at the bedrock computed using CRISIS 2012. In this map, the effect of a seismogenic source zone close to the southern coast of Malta is evident.

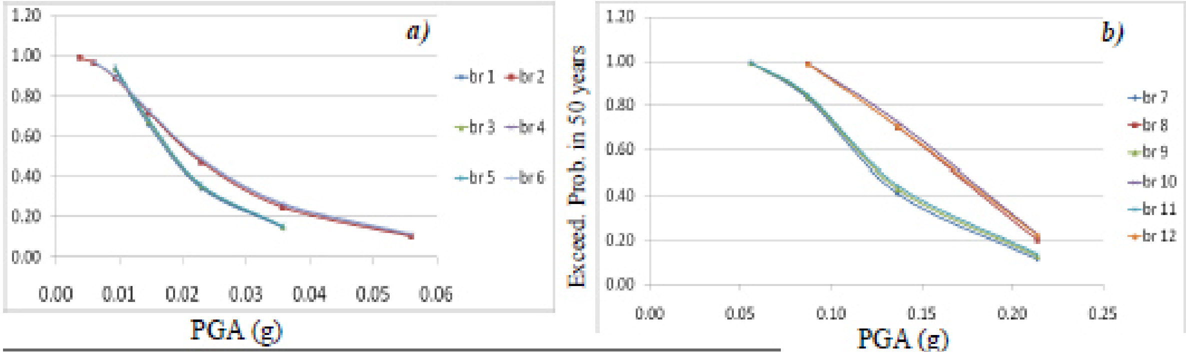

Figure 2.Hazard curves (at the bedrock) for Malta using the logic tree approach

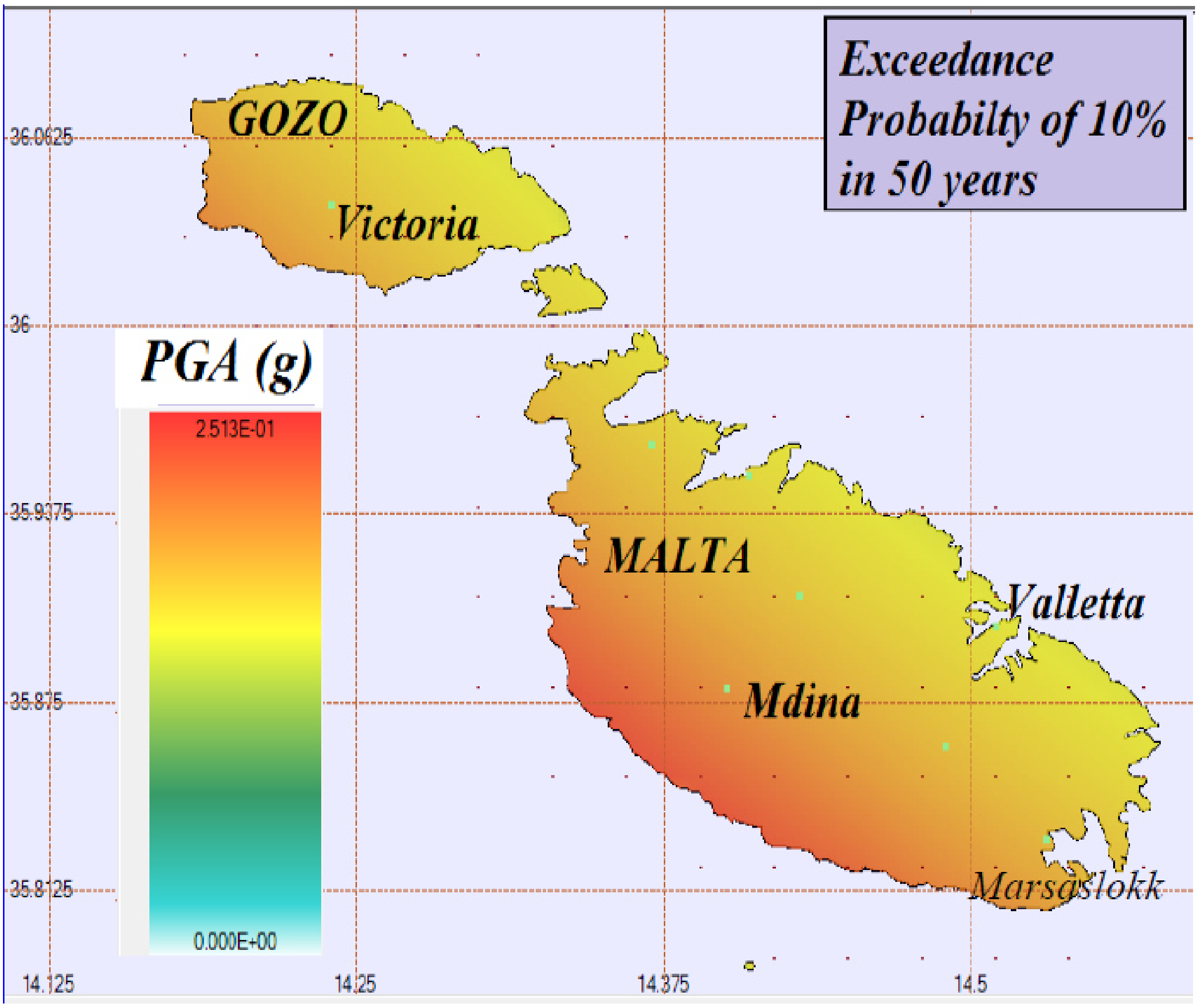

Figure 3.Preliminary seismic hazard map at the bedrock (D'Amico et al., 2013)

Figure 4 shows mean UHRSA (Uniform Hazard Response Spectra) for 90, 250, and 475 years return periods for the whole logic tree computed at four different locations on the Maltese islands (Mdina, Valletta, Marsaxlokk and Victoria –Gozo).

Figure 5 shows a hazard curve computed for the Maltese Islands using a different approach - using the SASHA code (D'Amico and Albarello (2008). This approach is based only on the catalogue of earthquake felt intensities derived from a macroseismic catalogue, independently of the seismicity catalogue of earthquake locations. The blue line indicates the relevant Iref value corresponding to 10% exceedance probability in 50 years, and indicates that this corresponds to intensity VII on the EMS98 scale. The computation is based on the historical seismic catalogue available for the archipelago and compiled by Galea (2007).

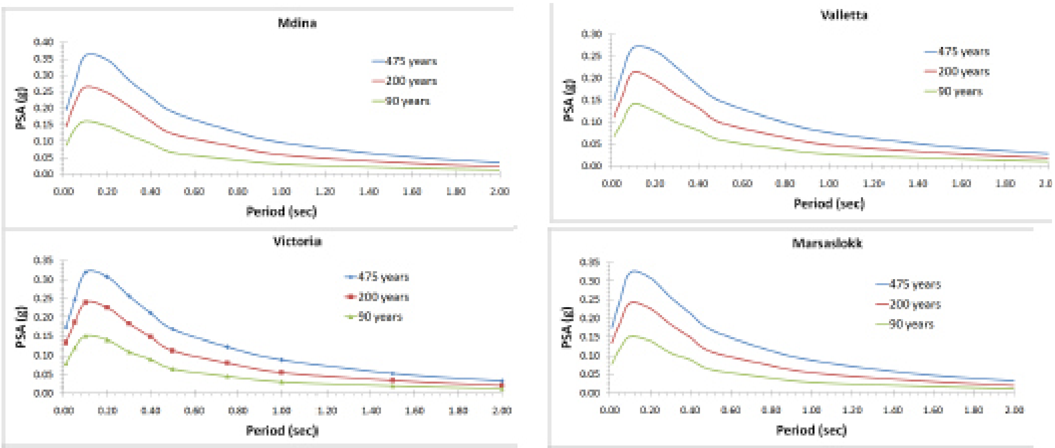

Figure 4: mean UHRSA for 90, 250, and 475 years return periods for the whole logic tree computed at four different locations on the Maltese islands

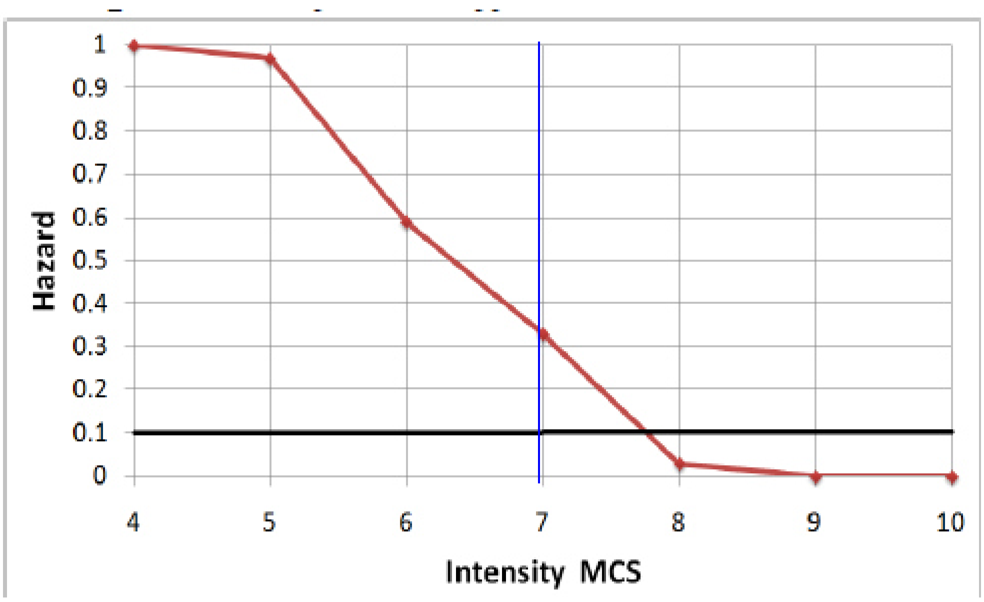

Figure 5: Hazard curve computed for the Maltese Islands using the SASHA code

Concluding remarks.

Over the past years, a number of reports about the seismic hazard and seismic risk for the Maltese islands have been put forward. It is not surprising that there is an amount of inconsistency between such reports. Since the seismic history of the islands is sparse, and documentation does not go back much further than 500 years, probability estimates are subject to large uncertainties. Seismicity patterns in the region around the islands have only begun to be properly studied in the past decade. Although this seismicity does not appear to generate large and potentially destructive earthquakes, it is still important to understand the seismogenic structures and their behaviour, especially because there are at least two historical cases of damage caused by earthquakes whose epicenters were most likely in the Sicily Channel. Other properties like seismic (spectral) site response due to diverse underlying geology, shear wave velocity profiles and regional attenuation properties have only now begun to be investigated, and only when the results are established can a proper assessment of the risk to local building stock be carried out.

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EARTHQUAKE GROUND-MOTION SIMULATIONS FOR THE MALTESE ARCHIPELAGO

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Introduction

Large and moderate earthquakes that have occurred in recent years in densely populated areas of the world dramatically highlight the inadequacy of a massive portion of the buildings erected in and around the epicentral areas (e.g.: Izmit, Turkey, 17 August 1999; Duzce, Turkey, 12 November 1999; Chi-Chi, Taiwan 20 September 1999, Bhuj, India, 26 January 2001; Sumatra, Indonesia 26 December 2004; Wenchuan, China, May 12, 2008; L'Aquila, Italy, April 6, 2009; Haiti, January 2010; Emilia, Italy, May 2012). It has been observed that many houses, industrial complexes and cultural heritage sites were unable to withstand the ground shaking. In this context, earthquake ground motion scenarios, combined with a probabilistic seismic hazard analysis and proper source characterizations can be used to better understand the expected earthquake impact, and help plan for the future (D'Amico et al., 2010a, b, 2012a, b; Ugurhan et al., 2012; Secomandi et al. 2013). In particular, they could help decision makers to better visualize specific problems that are based on scientific and engineering knowledge. Furthermore, a scenario improves awareness of what an earthquake can do to a community as a whole.The main goal of this study is to provide earthquake ground motion simulations for the Maltese archipelago in order to generate earthquake scenarios mainly based on the ground motion parameters. Malta represents a site of particular historical interest, and it has an important role in the tourism industry. In general, buildings are located in a diversity of topographical and geological settings, and a variety of building types and ages can be identified. Therefore, although this study deals mainly with ground motion parameters, the area 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 seismic risk, which has not been adequately tackled so far.Modern broadband seismic recording has been available on Malta only since 1995, and therefore no instrumental data for strong events is available. It is therefore necessary to adopt the approach of artificial earthquake simulation using numerical methods and realistic earthquake scenarios. Such methods have been used with success in numerous other regions (e.g. Taiwan, D'Amico et al. 2012a; Western Anatolia, Akinci et al., 2013; Central Italy, Ugurhan et al., 2012; Southern Italy, D'Amico 2012c; D'Amico et al. 2011).

Method used and results.

The estimation of ground motion for a particular region and also site-specific investigation is essential for the design of engineered structures. Estimates of expected ground motion at a given distance from an earthquake of a given magnitude are fundamental inputs to earthquake hazard assessments. It has been proven that it is possible to make numerical predictions of ground motion parameters for regions where strong-motion data are lacking or where even data for moderate and large earthquakes are not available (e.g. D'Amico et al. 2012a, b, c). In order to predict the expected ground motion parameters, for example peak ground acceleration (PGA) peak ground velocity (PGV), and Spectral Acceleration (SA), as a function of distance and magnitude we used the latest version of the EXSIM program (for details see Boore, 2010; Motezedian and Atkinson, 2005).In this simulation, we argue that the Maltese islands and Malta Channel (separating the islands from Sicily) belong to the same geological domain as the southeastern tip of Sicily (Malta-Hyblean plateau) and it is justified to use the crustal propagation parameters that were derived for SE Sicily by Scognamiglio *et al* (2005). These parameters were derived following a regression procedure on local earthquake waveform data that defined the excitation, propagation and site terms.

In addition, in our simulation we considered also the potential seismic effect due to the local geology (Vella *et al*. 2013) which will permit to create reliable earthquake scenarios. Site effects at a specific station are very important and may be used for engineering purposes to define the regional predictive law and the seismic hazard. A generalized site response concept is useful to create a detailed shaking map for a region where the different outcropping lithologies are known. The generic site response represents the average response expected for a site with specific superficial geologic characteristics. In this study in order to consider different site conditions, we use estimates of generic shear wave velocities in different lithologies (see report D2.1.1) and refer to the NEHRP classification (BSSC, 1994; Boore and Joyner 1997). We selected two potential faults: the first located on the northernmost segment of the Hyblean-Malta Escarpment offshore eastern Sicily, and the second at about 20 km south of Malta (Fig. 1).
On the first fault we simulated a magnitude M_W =7.6 event, intended to replicate the 11 January 1693 earthquake that caused the highest impact on the Maltese islands in historical times. A similar event had also occurred in 1169 on the same fault (Azzaro and Barbano, 2000). On the second fault we modelled a magnitude 5.0 event motivated by the occurrence of a band of seismicity located instrumentally during the last decades (Fig. 1). This source region appears to lie on the Malta graben which passes very close to the south of Malta, and is seismically active. Although no event of magnitude 5.0 has been recorded in this region in recent times, a magnitude 5.0 earthquake on the faults bounding other parts of the Sicily Channel rift is likely to have occurred at least once (Galea, 2007). The dimensions of the faults were derived in the EXSIM code using the Wells and Coppersmith relations (Wells and Coppersmith, 1994). Another important parameter is the stress drop, which may cause differences in the ground motion levels at short distances. In order to properly represent the source characteristics we adopted a stress drop value of 210 bar for the M5 earthquake as suggested by Di Bona et al. (1995) and a value of 280 bar (Malagnini, 2012, personal communication) for the M7.6 earthquake located on the Malta escarpment. This is reasonable, and in fact, Mayeda and Malagnini (2009) hypothesized a step-like change in the stress parameter around Mw 5.5 using different data sets from Hector Mine (USA; Mayeda et al. 2007), Wells (USA; Mayeda&Malagnini 2010), San Giuliano (Italy, Malagnini&Mayeda 2008). The ground motion simulation was run at each grid point, outputting the peak ground acceleration (PGA), peak ground velocity (PGV) and spectral acceleration (SA) at each of four chosen frequencies – 0.33Hz, 1.0Hz, 3.0Hz and 5.0Hz. This range of frequencies is considered adequate for engineering purposes. The results of the simulations on a nation-wide scale for each hypothetical source are shown in Figures 2 and 3. For the eastern Sicily earthquake, about 150km away, (Fig. 3), the effect of geology is the most conspicuous. The distinction between the eastern and western sides of the archipelago is immediately clear, since only the western side is characterised by the presence of Blue Clay and therefore contains mostly C and D sites. Peak ground accelerations reach their maximum value

(approximately 0.2*g*) at sites where the BC is directly exposed. However, PGA values exceeding 0.1*g* are seen to be common in almost all areas of the archipelago, including the urbanised areas in the eastern half of the island, and in particular also the high elevation areas comprising Rabat, Mdina and Mellieha, as well as the whole of Gozo. Spectral effects show that the maximum expected ground motions occur around frequencies of 1Hz

On the other hand, the magnitude 5.0 event produces effects that are predominantly linked with distance, since the epicentre is only about 20km away (Fig. 4). In fact maximum ground motion is observed towards the south of the island, although the added effects of the lithology in that area cannot be excluded. Even in this case, however, peak ground accelerations exceeding 0.2*g* are observed on the island of Malta, whereas on Gozo, PGA values are limited to below 0.1*g*. The frequency content of the ground shaking is also different to the M7.6 event, being shifted more towards higher frequencies.

Ground Motion simulations in the Xemxija test site

Within the SIMIT project, the Xemxija Bay area has been selected as a test site. For this reason the ground motion simulation has been run on a smaller scale, using a much denser grid of simulation points (Figure 4). The Xemxija area is geographically defined by the presence of a graben in between two horst blocks. The graben is filled with alluvial sediments and is highly agricultural. The hillside on the northern side of Xemxija Bay is heavily urbanised, consisting mainly of residential apartment blocks, most of which are used as summer residences. The area's population undergoes a large increase in the summer months. The same two scenario earthquakes as for the nation-wide simulation have been used. In the Xemxija area, the geological structure and shallow subsurface properties are known in more detail, following studies of site response using ambient seismic noise as well as active and passive geophysical experiments (Panzera et al. 2013). The results of the simulation for each earthquake are shown in Figure 5. As expected the maximum ground shaking occurs in the valley area, where sediment thickness is high. However on the bordering hillsides, the ground accelerations are also elevated. For the M7.6 earthquake, the pga reaches 0.2*g* in the valley, and exceeds 0.1*g* on the hillside. For the M5.0 earthquake the pga values are similar to the large earthquake, however the spectral accelerations at high frequency are higher. For example, SA at 3.0Hz reaches 0.35*g* in the valley, and may exceed 0.2*g* on the hillsides.

Regional Attenuation relations derived from the earthquake simulations

Using the same procedure, a further exercise was carried out in which the ground motion parameters were computed for a larger set of realistic earthquake events, and over a grid of larger dimensions, covering the Maltese archipelago up to southeast Sicily. The grid consisted of 225 grid points at a spacing of 22km. In this way a set of regional attenuation relationships could be plotted and compared with other such relationships published in the literature. The computation parameters for the simulations were kept as in the previous sections. Figure 6 shows the study area as well as the earthquake sources (faults) simulated, with the maximum earthquake magnitude considered on each fault. Faults F1, F2 and F3 are based on real earthquake sources, while F4, F5 and F6 are hypothetical sources based on observed seismicity patterns and representative focal mechanisms. The EXSIM program was looped over a number of parameters for each event – random rupture path on the fault, source depth, magnitude range, while the ground motion parameters at the grid sites were computed for four different site classes.

Figure 7 shows an example of the computation results. The graph shows PGA values at all the grid points, computed at sites classes A and D for M4.0, M5.5 and M7.5 earthquakes.

In order to validate the theoretical results, the simulated ground motion parameters were compared with real accelerometer data for a number of earthquakes for which such data was available on the ITACA database (www.***itaca***.*mi*.***ingv***.*it*). Figure 8 shows an example for an earthquake occurring on the Malta Escarpment (24/11/2006, M4.4), in which the predicted PGA agrees closely with that recorded at a number of stations in SE Sicily.

Another kind of validation was carried out by using the historical intensity data available for the 11/01/1693 earthquake in E. Sicily (M7.4). The DBM11 database (www.*emidius.mi.**ingv**.it/DBMI11*)contains historical intensity values at a number of localities in Sicily. The simulated PGA values at sites corresponding to these localities were converted to intensity using the relationship of Decanini *et al* (1995) and compared with the historical intensities (Figure 9). Both the intensity values as well as the conversion relation are subject to considerable uncertainty, however the comparison is encouraging.

Concluding remarks

These results are highly significant with respect to the evaluation of seismic risk on the Maltese islands. Such simulations pave the way towards a combined methodology that will take into account both the seismic hazard evaluation (which yields the probability that such an event will occur in a given time period) as well as the deterministic prediction of the effects of any given earthquake source. Moreover they constitute a required input to the civil engineering community which is responsible for evaluating the interaction of the predicted ground motion with local building stock. Because of the inherent brittleness, lack of ductility and lack of tensile strength of unreinforced masonry buildings (URM), it is expected that even moderate ground accelerations could cause significant damage in these buildings (Hess, 2008). In this study, we have shown that in the Maltese archipelago, the ground motion from the repeat occurrence of historically recorded earthquakes, as well as earthquakes on close off-shore faults, coupled with existing geological conditions and building typologies have the potential to cause significant structural damage on the islands. These results provide a motivation to continue working towards the formulation of a framework for functional seismic vulnerability assessment.

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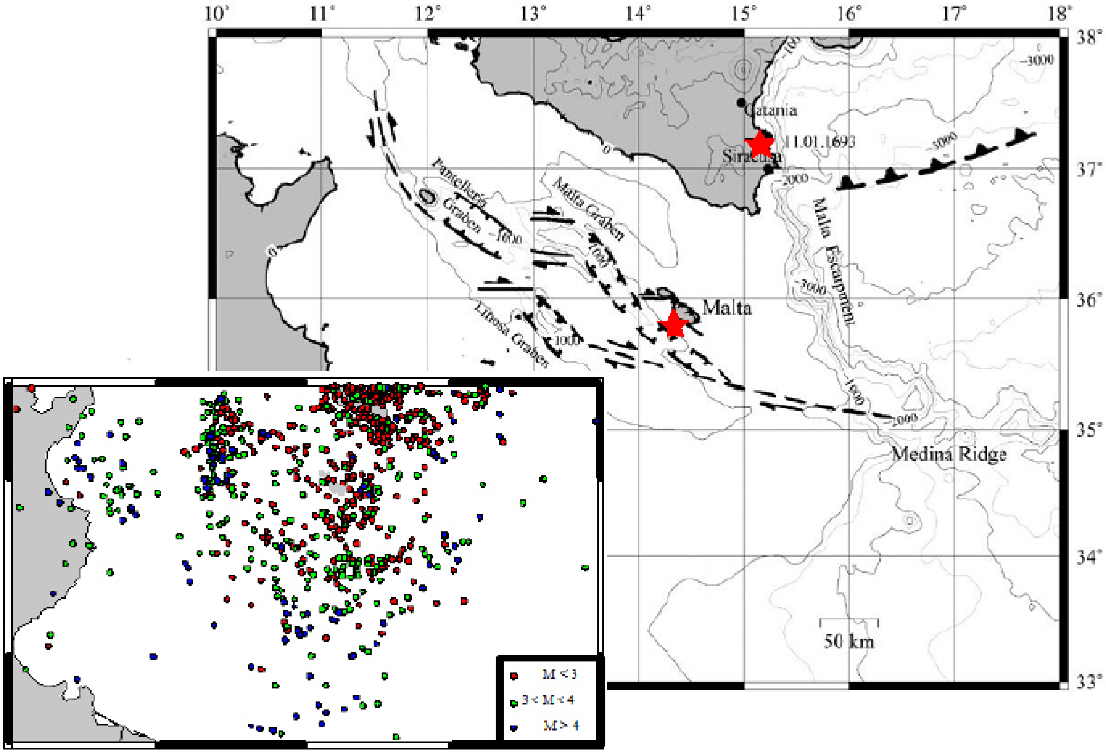

Figure 1: Bathymetry of the Sicily Channel and main tectonic features of the Sicily Channel Rift Zone-bounding normal faults and strike-slip lineaments. Also shown are the Calabrian Arc subduction zone and epicentre of the 11=01=1693 earthquake (Galea 2007), as well as the location of the second simulated earthquake (red stars). The inset (same lat/long range of the main figure) shows seismicity around the Maltese islands in the last 10 years (data are from INGV catalogue http://iside.rm.ingv.it/ and the catalogue of the Seismic Monitoring Research Unit, University of Malta http://seismic.research.um.edu.mt/)

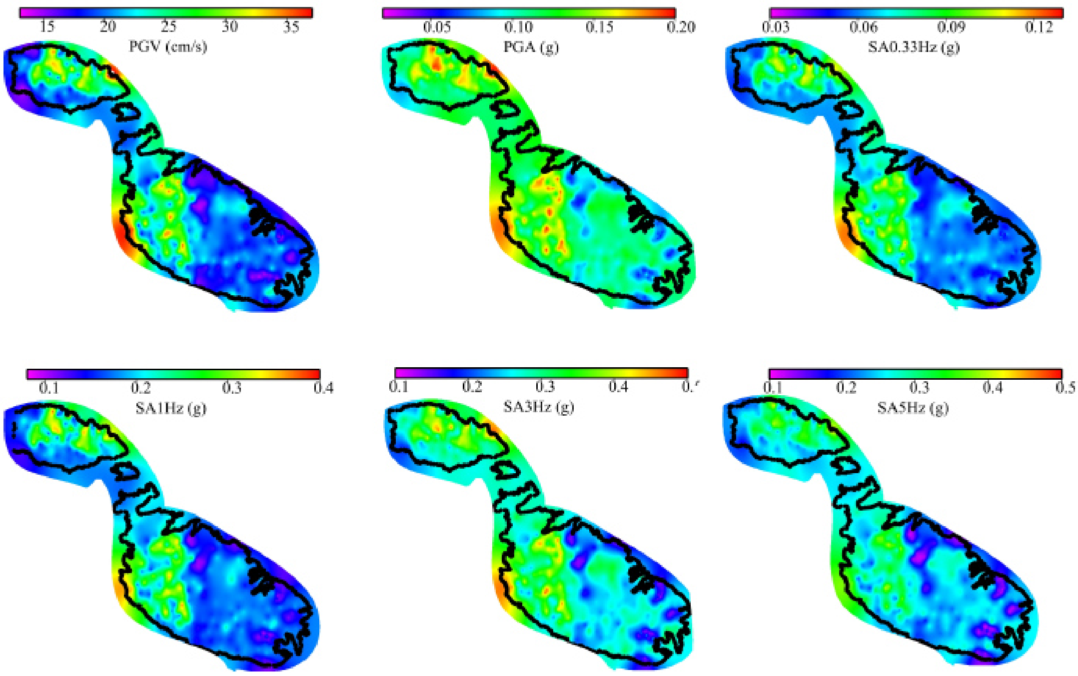

Figure 2: Ground motion scenarios for earthquake of Mw=7.6 located on the Hyblean-Maltese escarpment.

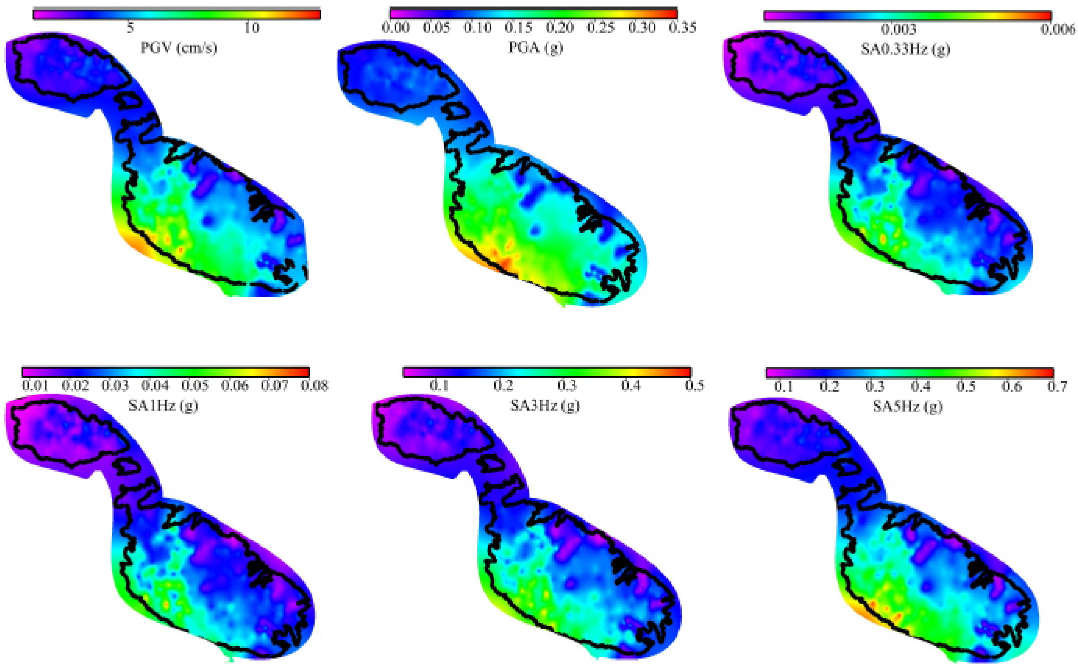

Figure 3: Ground motion scenarios for earthquake of Mw = 5:0 located about 20k south of Malta.

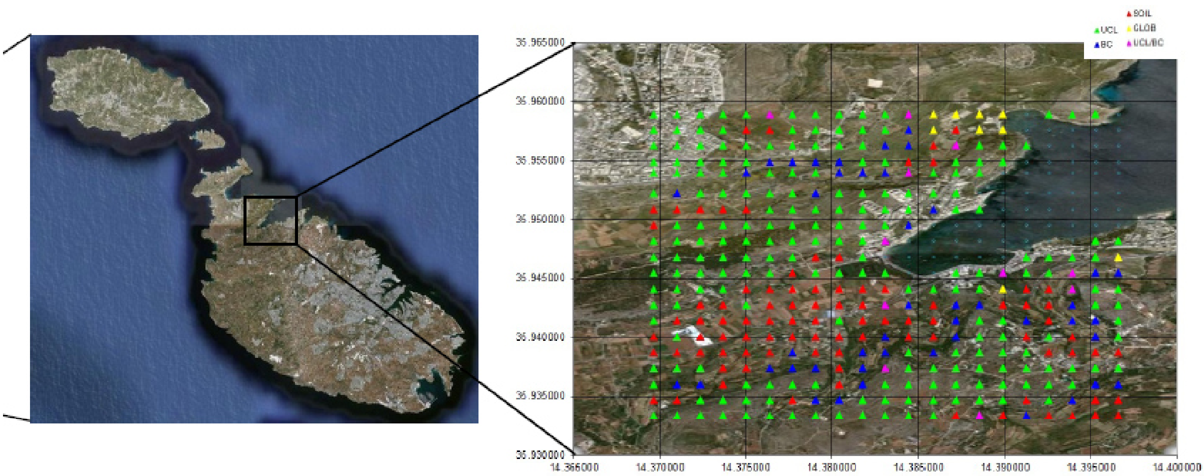

Figure 4: Left: location of the study area in Xemxija ; Right: the surface geology

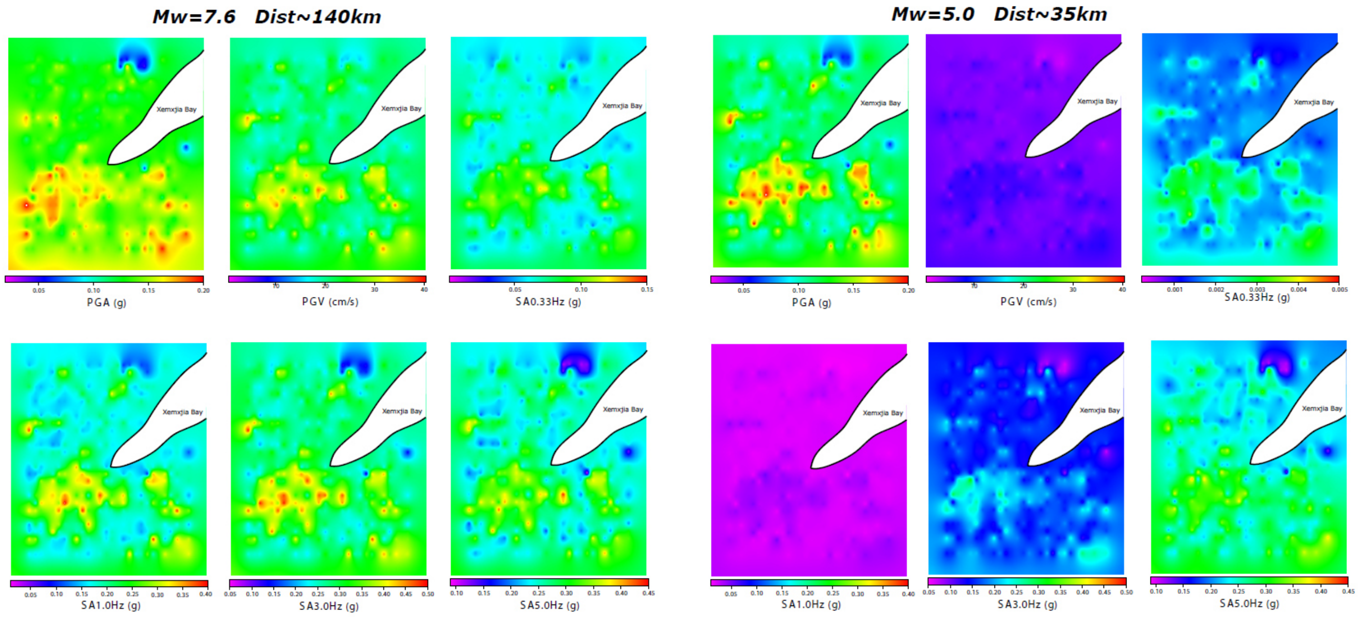

Figure5: The maps show the ground motions for (left group) a M7.6 earthquake scenario event at about 140km from the study area and (right group) a M5.0 earthquake at a distance of 35km from the study area. The figures show PGA, PGV and Spectral Acceleration at different frequencies.

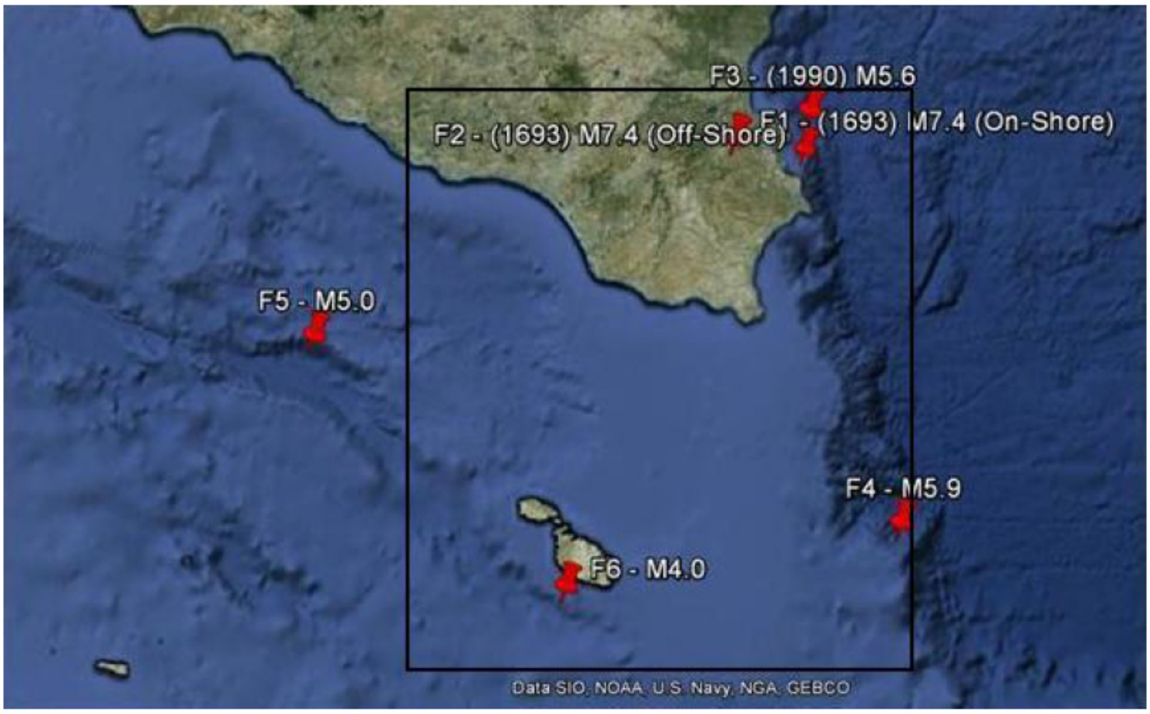

Figure 6: The hypothetical fault sources used in the regional earthquake simulation exercise for obtaining attenuation relations. The square shows the edges of the grid of sites at which the simulations were computed.

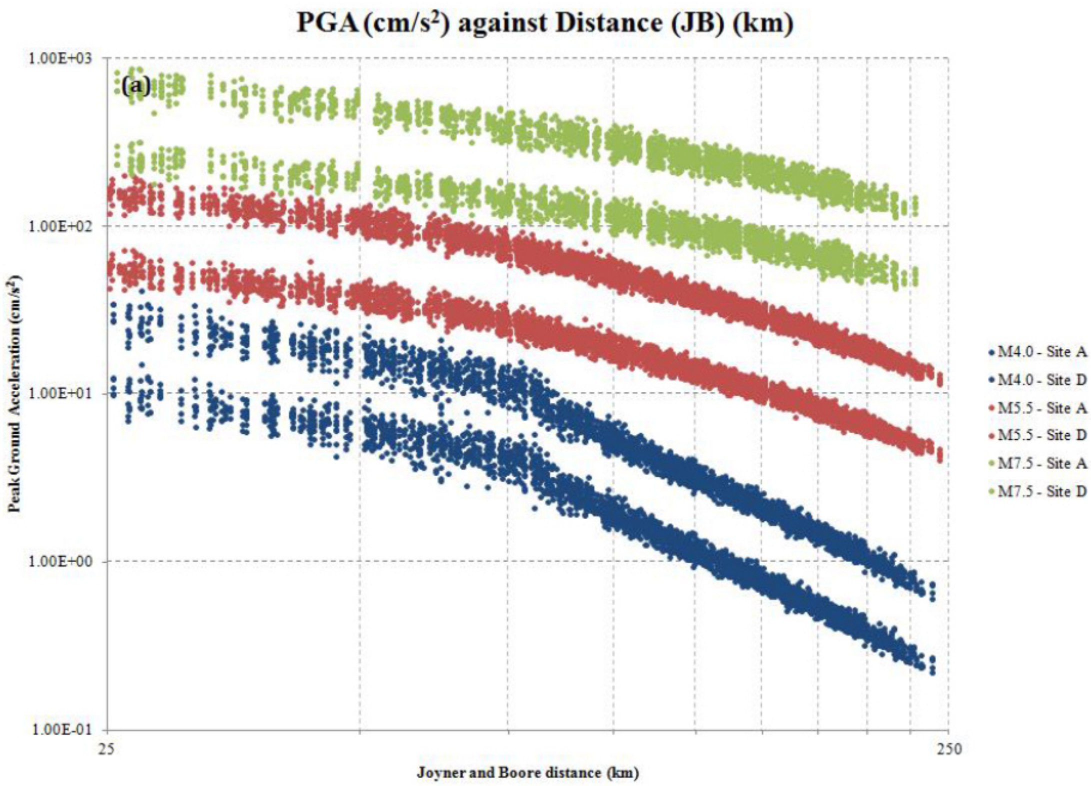

Figure 7: Theoretically computed PGA values for earthquakes of magnitudes 4.0, 5.5 and 7.5, at site classes A and D. Each point of the graphs represents a ground motion simulation for a different set of parameters (depth, magnitude, distance, site class, etc)

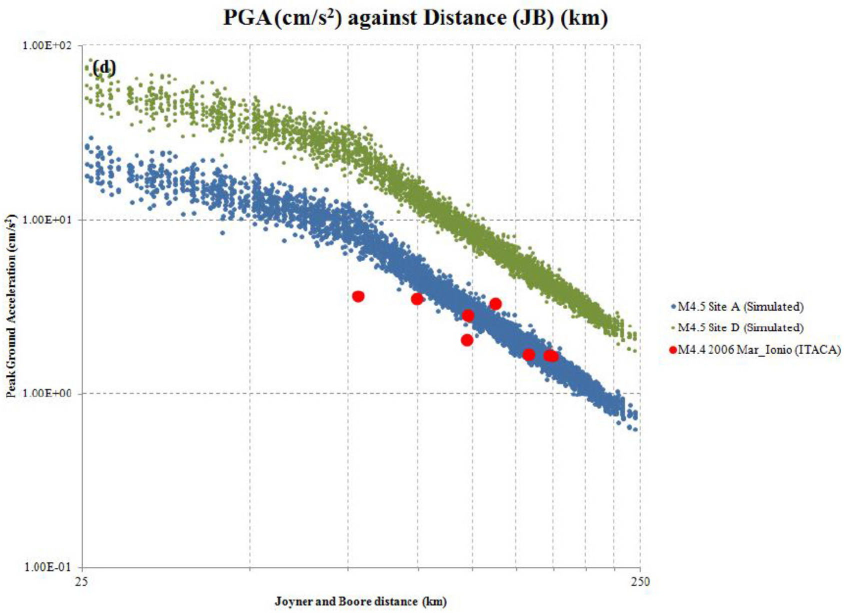

Figure 8: Observed PGA values from accelerometric data from a M4.4 event in the Ionian Sea. Recorded at stations in Sicily, and compared with theoretically simulated ground motion.

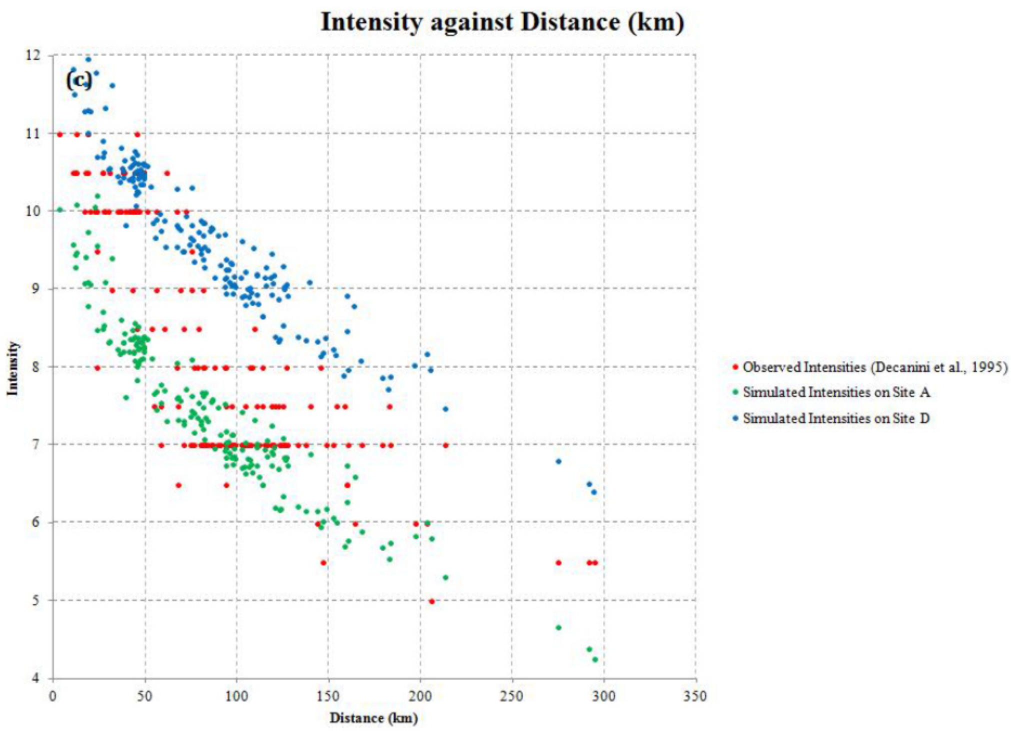

Figure 9: Intensity values at Sicilian localities (red dots) listed in the DBMI11 databse for the 11/01/1693 earthquake compared with intensity values converted from the simulated PGA curves.

SEISMO-INDUCED LANDSLIDES FOR THE MALTESE ARCHIPELAGO

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Aims

The aim of this study is to determine what areas, if any, in Malta and Gozo would be susceptible to earthquake induced landslides if an earthquake with a local intensity of *VI*, *VII*, *VIII* or *IX* was to affect them, and what is the probability of a landslide occurring in each of the four scenarios in the areas identified as being susceptible to the hazard.

Objectives

- To produce landslide susceptibility maps for the Malta and Gozo
- To identify potential areas that could be subject to landslides
- To determine what intensity is required to trigger landslides
- To provide maps to be used by civil protection in case of such an emergency

Method Overview

The method employed is a GIS-based heuristic one, developed by Rapolla et al. (2010). It considers three parameters for the evaluation of seismic-induced landslide susceptibility; them being lithology, slope angle and seismic input. The equation of these three parameters will determine the susceptibility level of landslides triggered by earthquakes as a percentage. This method was successfully employed in several regions (e.g. Rapolla et al. 2010; 2012; Paoletti et al., 2013). The results from these three studies were successful in matching areas of calculated higher susceptibility levels to areas of historic seismic-induced landslides. The results obtained by using this method are of a qualitative nature, and thus are expressed in relative terms (Fell et al., 2008). We initially implemented the study on SAGA (System for Automated Geoscientific Analyses) version 2.1.0 which is a GIS platform easy to install and that does not require any licence. SAGA was used for creating an elevation map from as shapefile of scale 1:25 000, digitising the Geological Map of the Maltese Islands, Sheet 2 by the Oil Exploration Directorate, Office of the Prime Minister, Malta (1993), for calculating the susceptibility levels and produced the relevant maps for the study.

For the implementation of the method we considered three main parameters: surface geology and the slope in degrees as the predisposing factors (time-independent) and seismic intensity as the triggering factor (time-dependent).For this study, it was assumed that both the predisposing factors; the lithology index (parameter A) and the slope index (parameter B) have the same contribution to landslide susceptibility, and therefore their average will determine the *Predisposing Factor*, which will then be multiplied by the seismic index (parameter C), the *Triggering Factor*. The level of seismic-induced landslide susceptibility of an area will be given by:

$$S_l(\%) = \frac{SA+SB}{2} Sc \qquad (1)$$

Where:

$S_l$is the susceptibility level (in %),

$S_A$is the significance of Parameter A

$S_B$is the significance of Parameter B

$S_C$is the significance of Parameter C

The level of significance for each of the three parameters has a value between 0 and 1, where 0 is the minimum significance and 1 is the maximum significance.

Another important triggering factor that can be considered is the rain type and intensity, which is seasonally variable in the Maltese Islands. However, the study area is relatively small and would be accepted for a grade-2 study, therefore annual rain episodes and climatic conditions are generally considered to be the same throughout the study area. Hence, it was assumed that this triggering factor is constant in time and space and will not be considered for the evaluation of landslide susceptibility. With the size of the study area being circa 316 km2 and the availability of both topographical and geological data at a scale of 1:25,000, a 40m × 40m mesh was used. The mesh size was chosen to exploit the detail of the inputted data, thus allowing a grade-2 study.

For the first parameter, the spatial distribution of the surface geology used was based on the Geological Map of the Maltese Islands, Sheet 2 by the Oil Exploration Directorate, Office of the Prime Minister, Malta (1993). However, only four of the five geology formations were taken into account for the study. Greensand formation does not have the required thickness to significantly affect topography (Pedley et al., 2002); and since it acts as a base for the Upper Coralline Limestone, any Greensand formation surface outcrops were considered to be Upper Coralline Limestone.The available geological map was in raster format, which was scanned, digitised and georeferenced using SAGA and Google Earth. A number of locations (points) in Malta and Gozo were selected in Google Earth and had their respective longitudes and latitudes recorded. The selected points were then located on the geological map (previously loaded on SAGA on a 40m x 40m grid) using the *Create Reference Point [interactive]* module. Finally the *Georeferencing - Grids* module was executed to obtain a digital, georeferenced geological map. With the geological map digitised, it was then possible to input the different geology formations. This was done by creating polygons for the geology formations using the *Create New Shapes Layer* module over the created digital map, where each cell was now representing a geological formation (Figure 1). This enabled different data values to be inputted for each geological formation. In particular, each geological layer of the archipelago has been assigned with a value of Vs30 (e.g. Panzera et al. 2013).

For the calculation of the slope index for Parameter B, a DEM (Digital Elevation Model) is usually used; however the available data for the study area was a georeferencedshapefile of scale 1: 25,000 showing elevation contours at 10 metre intervals. The shapefile was converted into a grid having 40m × 40m cells using the *Shapes to Grid* module. The *Inverse Distance Weighted* module was then executed on the created grid so that each cell has a value for elevation (Figure 2). The *Slope, Aspect, Curvature* module, using the *Least Squares Fitted Plane* method was then executed, calculating the slope angles for the study area (Figure 3).

With earthquakes being the only triggering factor considered for the study, a seismic factor based on MCS intensities was employed; where linearity between MCS values and the significance of Parameter C (S_C) is assumed following Rapolla et al. (2010, 2012) and Paoletti et al. (2013). According to Keefer (1984) and Rodriguez et al. (1999), the minimum MCS intensity required to trigger a landslide is V, and therefore it was set as the lowest limit of the above mentioned correlation. The upper limit was set at intensity IX, as the highest intensity felt on the Maltese Islands was VII-VIII in 1693 (Galea, 2007) and it was decided to set the upper limit slightly higher even though such intensity was never experienced locally in the recent years.

The susceptibility level was calculated using the equation (1), where the average of the sum of the lithology and slope indices (computed according the relationships given by Rapolla et al. 2010) was multiplied by the seismic index.
The susceptibility level is given as a percentage; where the higher the percentage in an area, the more susceptible the area is to landsliding triggered by seismic activity. A susceptibility map is presented for each of the four intensity scenarios considered (Figures

4).

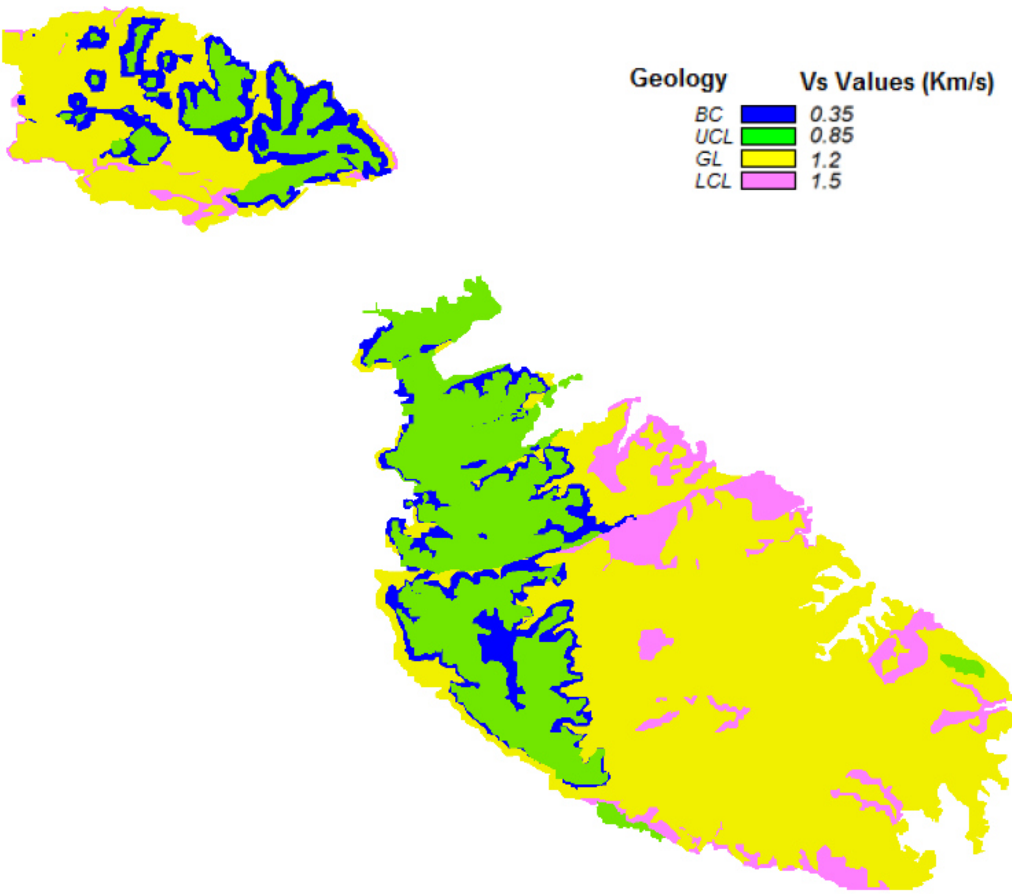

Figure 1 – Map showing the geology formations and their respective Vs values for Parameter A

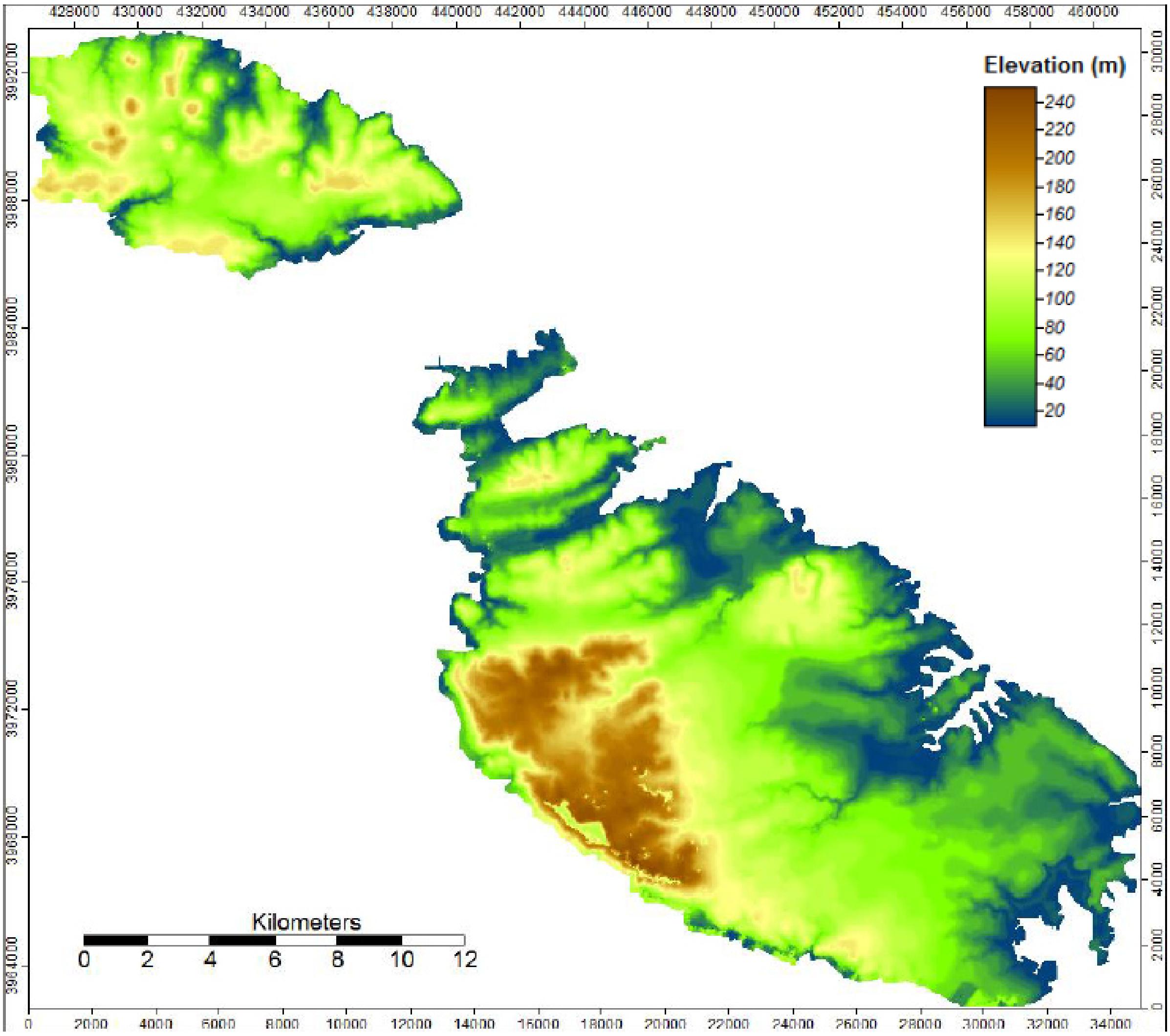

Figure 2 – Map showing the elevation in meters for the study area

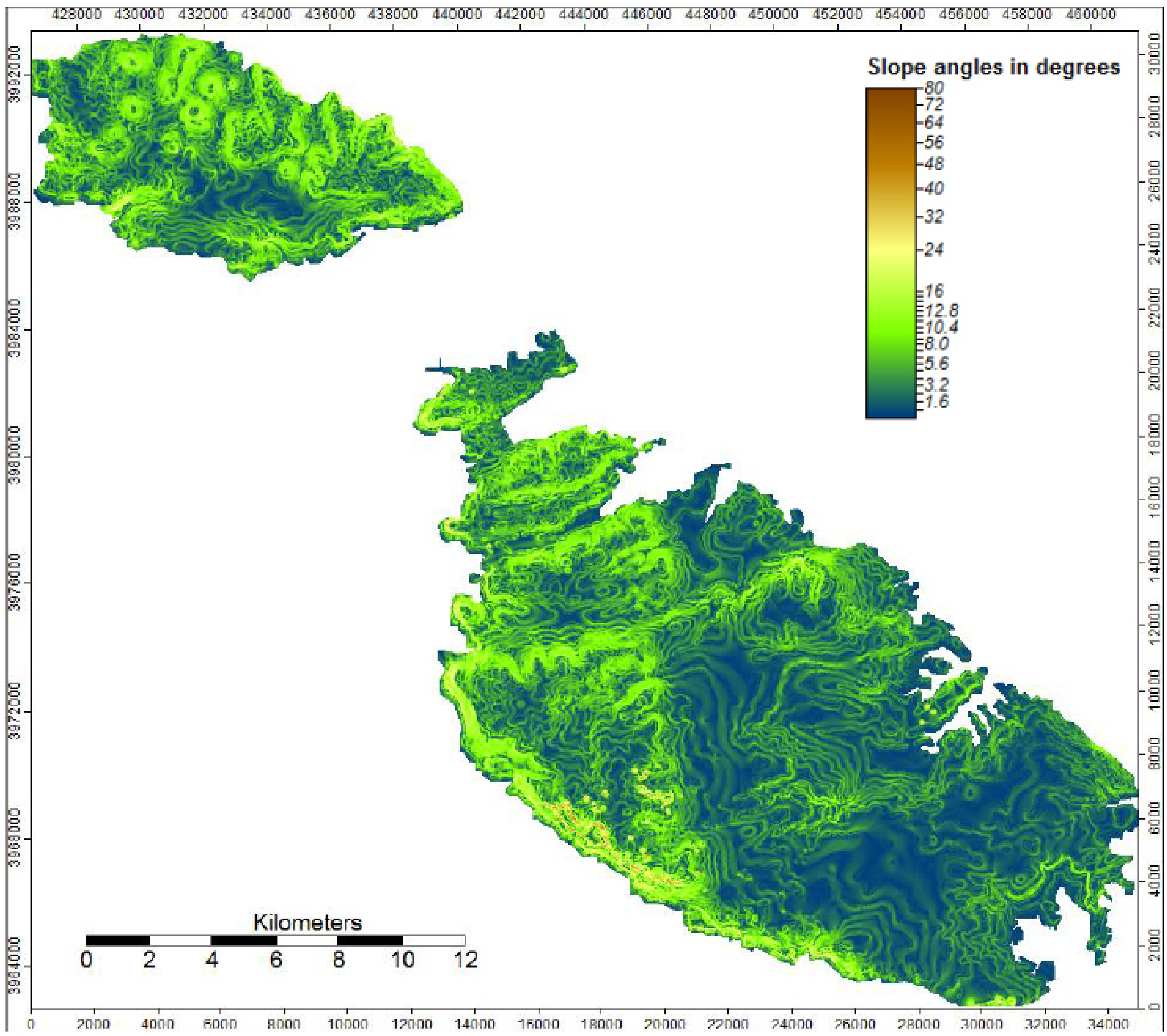

Figure 3 – Map showing the slope angles in degrees, where a logarithmic (up) stretch factor of 5 was used to better illustrate the higher values

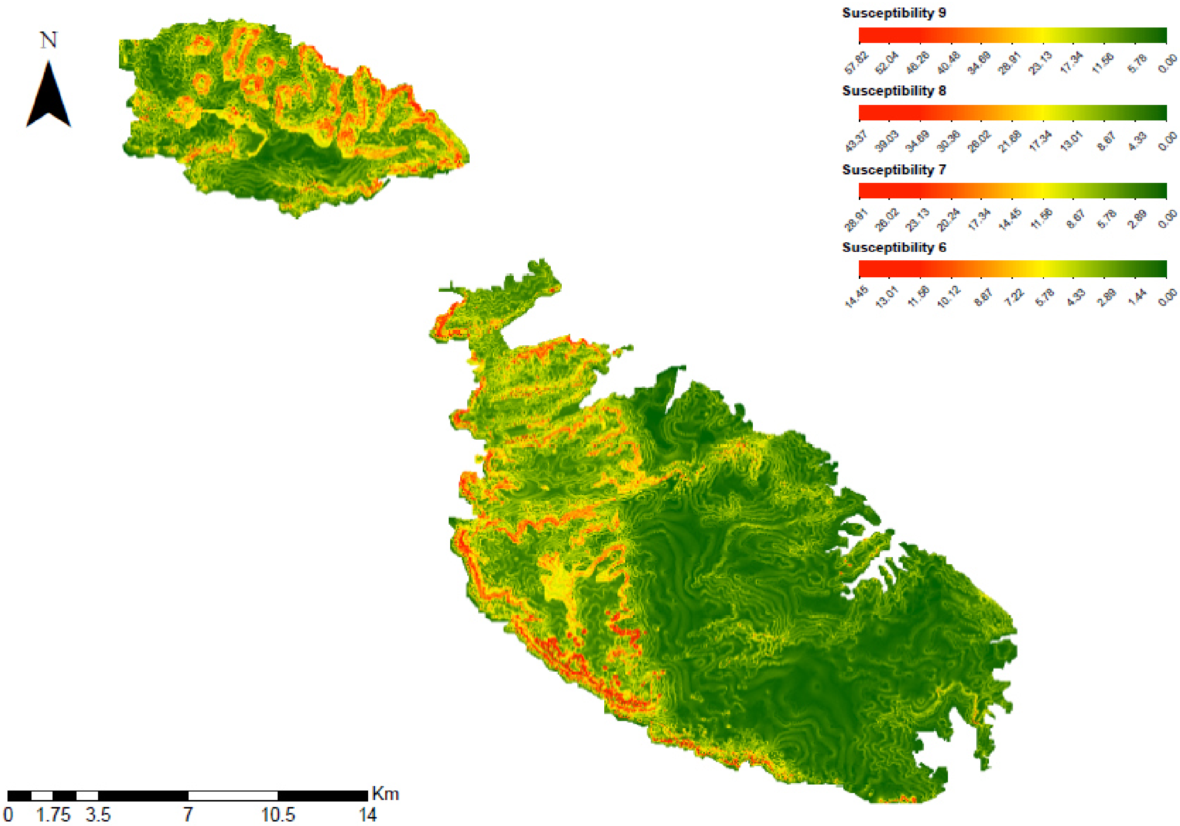

Figure 4 – Map showing susceptibility levels for each of the four intensity scenarios considered.

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