Xjenza Online - Journal of Malta Chamber of Scientists
http://www.mcs.org.mt/
Doi: http://dx.medra.org/10.7423/XJENZA.2013.1.01

Research Article

EARTHQUAKE GROUND-MOTION SIMULATIONS FOR THE MALTESE ARCHIPELAGO

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Abstract. The main goal of this paper is to provide earthquake ground motion simulations for particular earthquake scenarios, in terms of ground motion parameters for the Maltese islands. We used a stochastic approach to simulate high-frequency strong-ground motions, using an extended-source model code. This code was developed for earthquake simulations using stochastic finite-fault modelling and a dynamic corner frequency approach. The extended-source model code is a reliable and practical method to simulate ground motion records of moderate and large earthquakes especially in regions where structural damage is expected, but sparse ground motion recordings are available. In this paper, we show that in the Maltese archipelago, the ground motion from the repeat occurrence of historically recorded earthquakes, or from other potential sources, coupled with existing geological conditions and building typologies has the potential to cause significant structural damage in the area.

Keywords Ground motion; Numerical Simulations, Malta, Central Mediterranean

EXSIM: Extended Finite Fault Simulations

NEHRP: National Earthquake Hazards Reduction Program

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Received: 24/1/2013 - Revised: 15/2/2013 - Accepted: 18/2/2013 - Published: 31/03/2013

1 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, 17th August 1999; Duzce, Turkey, 12th November 1999; Chi-Chi, Taiwan 20th September 1999, Bhuj, India, 26th January 2001; Sumatra, Indonesia 26th December 2004; Wenchuan, China, May 12th, 2008; L'Aquila, Italy, April 6th, 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, D'Amico et al. 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.

Malta is a zone of low-to-moderate seismic hazard, and earthquake awareness is culturally not strong. However the Maltese islands have been affected by a number of earthquakes in the historical past, the epicentre of these earthquakes being in Eastern Sicily, Sicily Channel or as far away as the Hellenic arc. Some of these earthquakes produced considerable damage to buildings (Galea 2007). The fact that the last damaging earthquake occurred around a hundred years ago probably explains the general complacency that exists. Consequently, general seismic preventive and preparedness plans have not been properly developed.

The main goal of this paper is to provide, for the first time, 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 paper 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 2012; D'Amico et al. 2011)

2 Methodology

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). 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 (Boore 2010; Motezedian et al. 2005).

2.1 THE EXSIM Procedure

The EXSIM code is based on Boore's stochastic method for simulating high frequency ground motion using a finite fault geometry (Boore 1983). The Fourier acceleration amplitude spectrum of ground motion at a distance r from a source of seismic moment Mo, may, in a general way, be written as the product of three factors: the source spectrum, S(f, M), the propagation term, G(r,f), and the site amplification term, Site(f):

$$\mathrm{A}\,(\mathrm{f},\mathrm{r},\mathrm{M}) = \mathrm{S}\,(\mathrm{f},\mathrm{M}) \cdot \mathrm{G}\,(\mathrm{r},\mathrm{f}) \cdot \mathrm{Site}\,(\mathrm{f}) \tag{1}$$

where f,r, and M represent frequency, distance and magnitude respectively.

In the finite fault simulation, the source is represented by a rectangular plane fault, whose dimensions are proportional to the moment magnitude M_W. The fault is discretized into a grid of rectangular sub-faults, and the rupture is considered to begin at the centre of one of the sub-faults (in this case randomly chosen), and spread with a rupture velocity 0.8 times the shear wave velocity at the source. The acceleration time series from each sub-fault is derived by inverse Fourier transform, and the time history at the site is obtained by summation of the individual time series, with appropriate time delays. It has been shown that only the gross features of slip distribution on a fault plane that does not diverge significantly from the average value of slip may be reliable; all other complexities could be extremely uncertain (Berensev et al. 2002). We thus find it reasonable to assume a random slip distribution, since we have no constraint on the particular faults that we shall be modelling. For each sub-fault, the source spectrum follows Brune's ω^2 source model

$$\frac{\mathrm{CM}_0\,(2\pi \mathrm{f})^2}{1+(\mathrm{f}/\mathrm{f_c})^2} \tag{2}$$

where C is a scaling factor (Boore 2003), M_o is the subfault seismic moment (proportional to the stress drop $\Delta\varsigma$, and f_c is the corner frequency). In this application, a dynamic corner frequency approach is adopted, whereby the corner frequency changes with the subfaults being activated in order to reflect the decrease in frequency content during the rupture history (Motazedian and Atkinson, 2005).

The propagation term contains the geometrical spreading term $g(r) = r^n$ where n is a function of distance, the inelastic attenuation term given by $e^{-\pi fr/Q(f)\beta}$, where Q is the average, frequency-dependent quality factor for the whole path ($Q(f) = Q_o f^n$), and the upper crustal attenuation factor $e^{-\pi\varkappa f}$ where $\varkappa$governs the high frequency decay of the spectrum at the site.

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. The best-fit values yielded by the above regression, and adopted in this study, are summarised in Table 1.

Table 1. Source, path and site parameters used for the EXSIM simulations.

Parameter identification	*Parameter value*
Dimension of the faults	According to Wells and Coppersmith (1994)
Pulsing area	50%
Slip distribution	Random
Crustal shear wave velocity	3.5 km/s
Density (crustal)	2.8 g/cm^3
Rupture velocity	0.8×shear wave velocity
Anelastic attenuation, Q(f) and	$Q_o = 400$, $\eta = 0.26$ (Scognamiglio et al. 2005)
Geometrical spreading	$g(r) = r^{-1} r < 40$ km $g(r) = (1/40)(40r)^{-0.4} r > 40$ km (Scognamiglio et al., 2005)
Kappa (sec)	0.035
Windowing function	Saragoni-Hart
Stress drop ($\Delta\varsigma$)	For Mw = 5.0 $\Delta\varsigma = 210$ bar For Mw = 7.6 $\Delta\varsigma = 280$ bar
Site Geology/ NEHERP Amplification factors/ Number of sites	LC/Site Class 4A/74 GLOB/Site Class B/160 UC/Site Class C/74 BC/Site Class D/101

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 will refer to the NEHRP classification (BSSC 1994; Boore et al. 1997).

2.2 Source Models

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 M_w 5.5 using different data sets from Hector Mine (Mayeda et al. 2007), Wells (USA; Mayeda et al. 2010), San Giuliano (Malagnini et al. 2008). The necessary parameters for ground motion simulations used in this study are given in Table 1.

3 Results and Discussion

The Maltese Islands are made up of a geological sequence of sedimentary rocks, mainly limestones and clays. The sequence is made up of distinct layers of varying hardness and resistance to erosion. In the order of deposition, the main layers in the sequence are the Lower Coralline Limestone (LC), Globigerina Limestone (GL), Blue Clay (BC), and Upper Coralline Limestone (UC) (Pedley et al. 2002). The simulations were run at a total of 409 points defined over the whole of the archipelago in such a way that all types of outcropping geology were represented. Preliminary investigations of

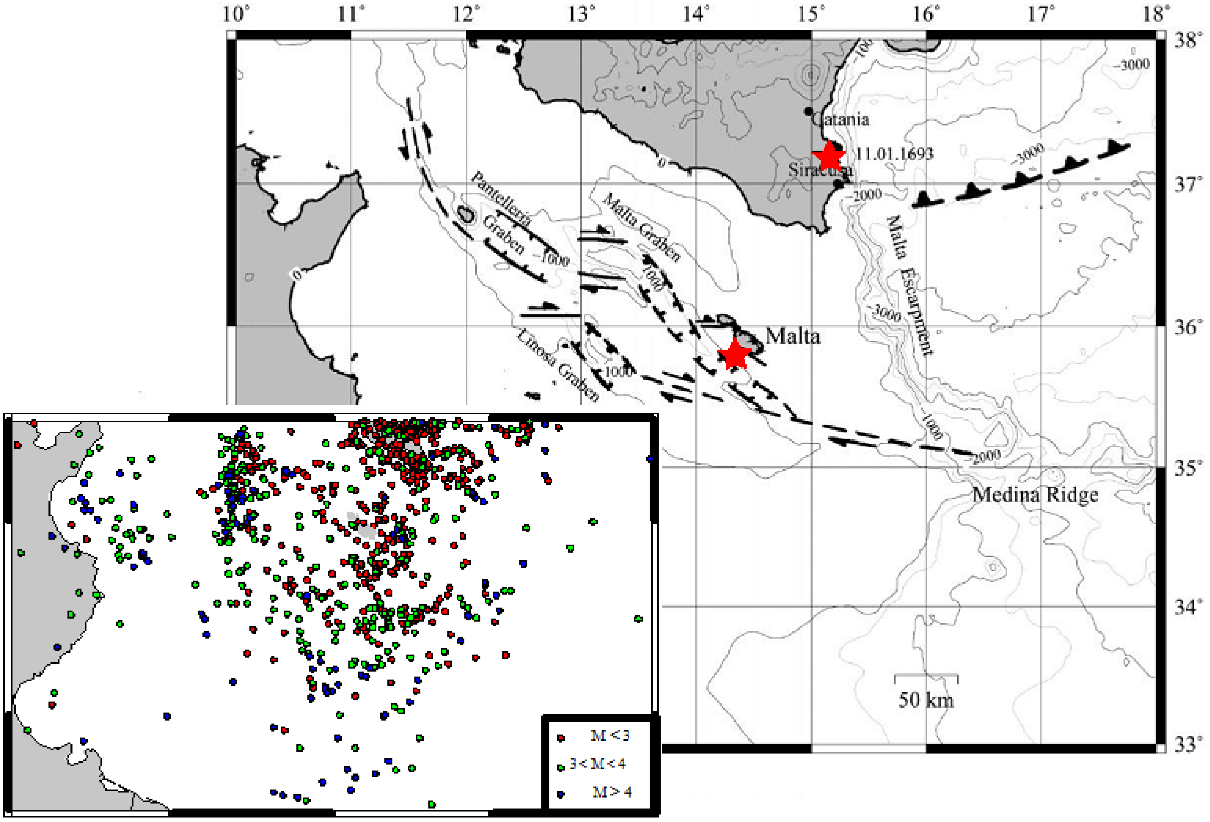

Figure 1: Bathymetry of the Sicily Channel and main tectonic features of the Sicily Channel Rift Zone-bounding normal faults and strike-slip lineaments. Also shown are the Calabrian Arc subduction zone and epicentre of the 11/01/1693 earthquake (Galea 2007), as well as the location of the second simulated 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/)

shallow crustal properties on the Maltese islands indicate a high variability of outcrop categories (Panzera et al. 2012; 2013). In this simulation, the average shear wave velocities that characterise the uppermost layers were used to assign site classes to each point. As a preliminary attempt, NEHRP site class A, B, C, D were assigned to the LC, GL, UCL and BC respectively, and the generic site response applied for each class (Fig. 2). The assignment of site class C to sites of outcropping UCL (mainly in the west of the archipelago) is justified by recent results showing that seismic site response at these sites exhibits considerable amplification owing to the presence of underlying clays (Vella et al. 2013). However, further studies will be necessary in order to properly characterize the soil classification for the Maltese Islands including parameters such as the soil fundamental frequency. In fact, it has been recently shown (e.g Luzi et al. 2011) that the use of average shear wave velocity of the uppermost layers to discriminate soil categories is not the best tool to use in building-code or preparation of seismic hazard maps, although it is a parameter internationally used.

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 - 0.33 Hz, 1.0 Hz, 3.0 Hz and 5.0 Hz. This range of frequencies is considered adequate for engineering purposes. The results of the simulations for each hypothetical source are shown in Figures 3 and 4.

For the eastern Sicily earthquake, about 150 km 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 1 Hz

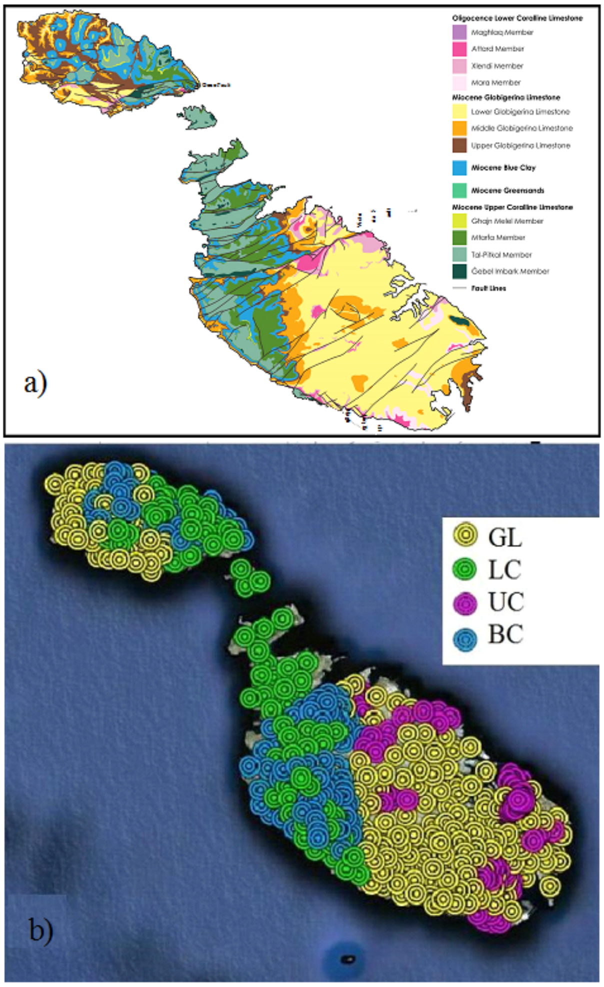

Figure 2: Location of the points used for the stochastic simulation; each point is colour coded according to the local geology (see text for details).

On the other hand, the magnitude 5.0 event produces effects that are predominantly linked with distance, since the epicentre is only about 20 km 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 M 7.6 event, being shifted more towards higher frequencies.

These results are highly significant with respect to the evaluation of seismic risk on the Maltese islands. Admittedly they represent scenarios of rare events, however 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).

Finally, in order to double-check the performance of our simulations we converted the predicted PGA and PGV into seismic intensity and compared with the observed one. For the conversion from PGA to seismic intensity we used the formula implemented within the ShakeMap® packages (Wald et al. 1999). This relationship is valid in the range of V-VIII of Modified Mercalli intensities. Our estimates for the simulation related to the 1693 event yield a maximum intensity of VII-VIII and are therefore in complete agreement with the observed seismic intensity data reported by Galea (2007). Seismic intensity is an important parameter that has been traditionally used worldwide as a method for quantifying the shaking pattern and the extent of damage for earthquakes, especially for past earthquake for which there is no instrumental record. However, even if nowadays large instrumental recordings are available, it still provides a useful means of describing information contained in these recordings (e.g. Secomandi et al. 2013).

4 Concluding Remarks

These scenarios are for only two particular earthquake events. Events on other sections of the rift system (eg the western extremity of the Malta and Pantelleria grabens, or indeed a large magnitude event on the Hellenic arc) will have different effects in terms of both spectral response as well as geographical distribution. This deterministic approach will need to be combined with a probabilistic hazard assessment in order to provide a better picture of the risk faced by the islands.

Despite some uncertainties mostly due to source complexity, stochastic finite-fault modeling based on a dynamic corner frequency approach appears to be a reliable and practical method to simulate ground motion records of moderate and large earthquakes especially in regions where structural damage is expected, but only sparse ground motion recordings are available. In this paper, we have shown that in the Maltese archipelago, the ground motion from the repeat occurrence of historically recorded earthquakes, coupled with existing geological conditions and building typologies has the potential to cause significant structural damage on the islands. These preliminary results motivate us to carry out more detailed studies, in particular a comprehensive microzoning exercise with respect to shallow structure and ground response, and the formulation of a framework

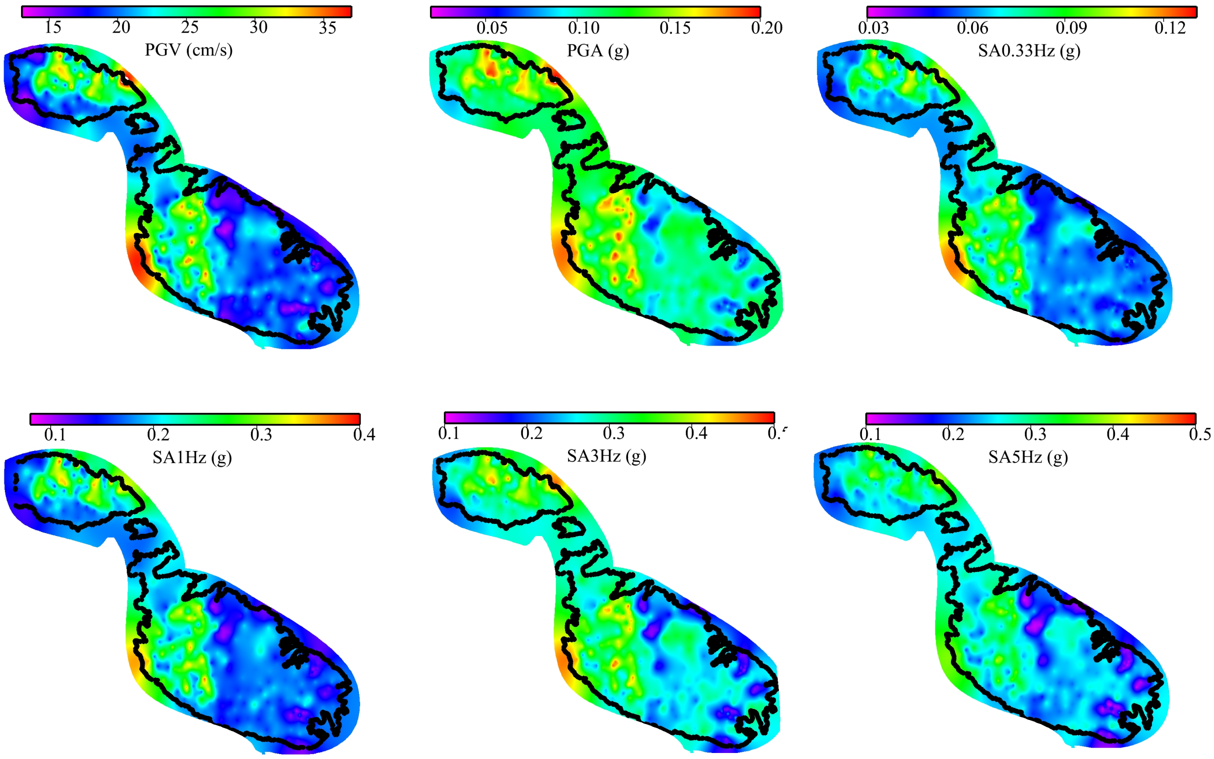

Figure 3: Ground motion scenarios for earthquake of Mw=7.6 located on the Hyblean-Maltese escarpment.

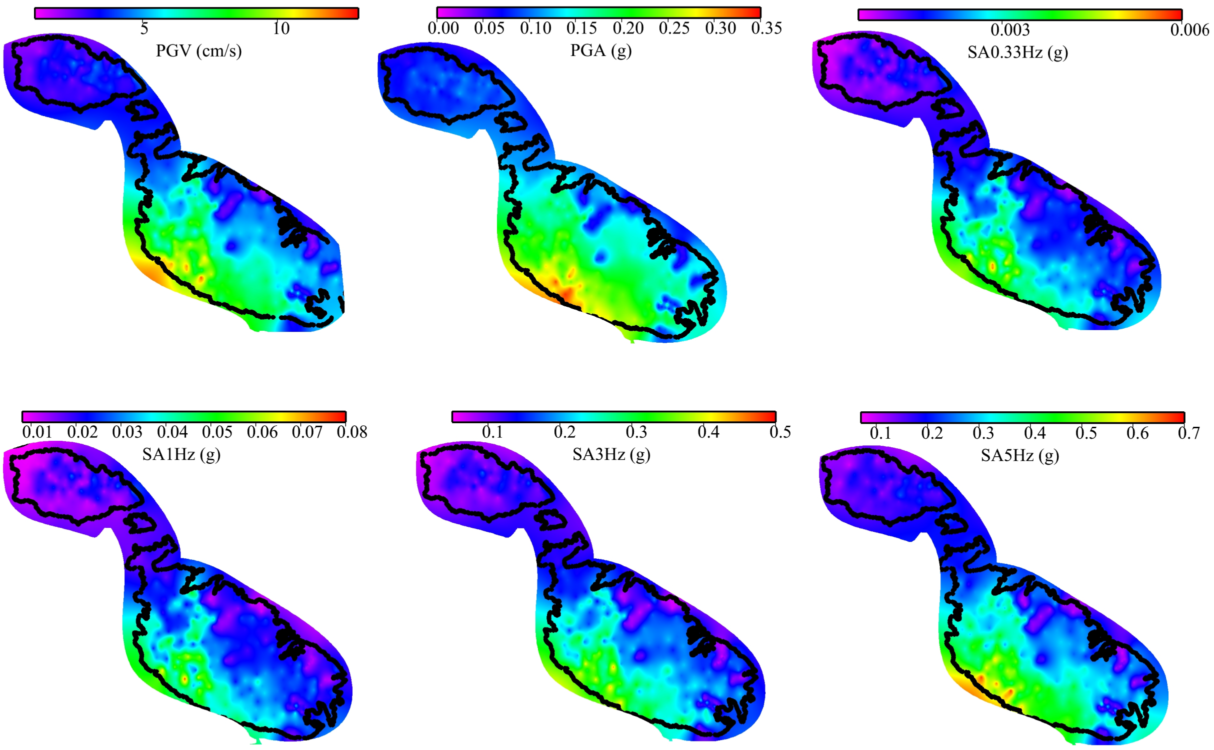

Figure 4: Ground motion scenarios for earthquake of Mw = 5.0 located about 20k south of Malta.

for the functional seismic vulnerability assessment.

We can conclude by saying that a well-crafted scenario provides a powerful tool for decision makers, emergency planners, private industry, and the general public to begin to draft mitigation policies and programs. It will help the community weigh various risks associated with the earthquake and begin to set priorities that will systematically reduce the impact of a likely future event.

5 Acknowledgments

This research was carried out using computational facilities procured through the European Regional Development Fund, Project ERDF-080 "A supercomputing laboratory for the University of Malta": http://www.um.edu.mt/research/scienceeng/erdf_080.

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