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SEISMIC HAZARD STUDY IN MESSINIA (SW PELOPONNESE) AREA

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ABSTRACT

Messinia lies in the vicinity of the Hellenic Arc, which is among the most seismically active areas of Europe (Makropoulos et al., 2012), due to the subduction of the African plate beneath the Eurasian. The most recent destructive event in the study area was the 13 September 1986 Ms=6.0 Kalamata earthquake. Neotectonic first-order structures are distinguished in Messinia, while major fault zones of the region strike both E-W and N-S. A seismic hazard study, both probabilistic and deterministic is undertaken for Messinia area:

-The probabilistic approach is applied for the determination of maximum expected magnitude (Mmax), peak ground parameters (PGA, PGV, PGD) and maximum observed macroseismic intensity (Imax), using the zone-free extreme values distribution. The first asymptote is applied to estimate peak ground parameters and maximum intensity, while the third to calculate the maximum expected magnitude values.

-The deterministic approach includes the generation of synthetic seismograms according to the methodology of Sabetta and Pugliese (1996). Simulated time histories of acceleration, velocity and displacement are obtained for the main towns Kalamata, Pylos and Filiatra, in order to compare the variation of peak values due to different distances. This is performed by applying three different shallow earthquake scenarios.

The results are compared with the values proposed by the Greek National Building Code and observed damage distributions.

INTRODUCTION

Messinia (SW Greece) is characterized by intense seismic activity. This is partly due to its small distance from the Hellenic Arc, a zone of approximately 100 km length running 50 to 100 km off the Messinian coast, where the African plate subducts beneath the Aegean microplate (Hatzfeld et al., 1989). Several destructive events have occurred in the study area, as indicated by historical (Papazachos and Papazachou, 1997, Stucchi et al., 2012, Kouskouna and Sakkas, 2013) and instrumental (Makropoulos et al., 2012) data. The 13 September 1986 event (Ms=6.0) earthquake is the most recent destructive event onland, close to Kalamata, the capital of Messinia prefecture (Lyon-Caen et al., 1988). Following, a moderate earthquake (Mw=5.3) took place on 1 March 2004, NE of Kalamata (Pirli et al., 2007). The last major event (Mw=6.7) occured on 14 February 2008 offshore Methoni (Roumelioti et al., 2009). Recently, during August – December 2011, a shallow seismic swarm took place in the area of Oichalia, north of Kalamata. The largest event of the sequence occurred on 14/8/2011 (Mw=4.8) and was followed by more than 1600 events, several of which having magnitude over 4.0 (Kassaras et al., 2013).

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Regarding the seismotectonic setting of the area, the Messiniakos Gulf is characterized by two different trends of active faulting (Ganas et al., 2012). The main faults are trending NW-SE, whereas the subordinate ones E-W or N-S. It should also be noted that the western part of the Gulf is less active than the eastern. The main, normal, west dipping fault, responsible for the 1986 Kalamata earthquake, delimits the inner part of the Gulf to the East. The inland part of Messinia is also characterized by N-S faults. Yet, there is a number of faults into the basin trending NW-SE (Papanikolaou et al., 2007). Pylos area is also characterized by normal faults (Papoulia and Makris, 2004).

Earthquakes, in terms of severity and widespread impact, are one of the most disastrous events of natural origin that characterize Greece. Thus, seismic hazard assessment on a small scale is of significant importance towards seismic risk mitigation. Initially, seismic hazard of the Hellenic Arc, including Messinia, has been examined using seismic gaps (Wyss and Baer, 1981) or by investigating the time variation of large shocks (Karakaisis et al., 2002). Recently, Slejko et al. (2010) performed seismic hazard assessment for the area of Pylos and the surrounding region. In the framework of the present study both the probabilistic and the deterministic approaches are applied for the Messinia area, focusing to the main towns of Kalamata, Pylos and Filiatra, while damage distributions are also taken into account.

METHODOLOGY

Probabilistic Approach

The Extreme Value method is applied to estimate expected maximum values of magnitudes, ground acceleration, velocity, displacement and intensity. Extreme Values follows three different types of asymptote distributions (Gumbel, 1958) independent of the parent population distribution. For seismic magnitude determination, the third asymptote approach is used, referring to the upper limit parameter. The determination of the maximum expected ground motion parameters (i.e. PGA, PGV and PGD) and intensity (Imax) is performed by applying the first asymptote, using the HAZAN software (Makropoulos and Burton, 1986).

The advantage of the applied methodology is that only an earthquake catalogue and attenuation relations are used. In the present study, the epicenters and the source parameters were obtained from the catalogue of Makropoulos et al. (2012), an updated earthquake catalogue for Greece and adjacent areas containing 7352 events, with Mw included, covering the time span 1900-2009. Catalogue completeness is a crucial factor for Probabilistic Seismic Hazard Analysis (PSHA). The above described catalogue has complete reports of surface wave magnitude Ms≥4 events for the last 34 years (1976-2009). No earthquake with Ms≥6 seems to have been omitted for the whole period (i.e. 1900-2009).

Attenuation relations are developed by statistical analysis on a large number of records obtained in tectonically active regions. The ground motion predictive equation (GMPE), used in this paper, to calculate peak ground acceleration (PGA) is the one proposed by Makropoulos (1978) and applied to the Greek territory:

$$A = 2164e^{0.7M} \cdot (R+20)^{-1.8} \tag{1}$$

where A is the acceleration in cm/s^2, M the earthquake magnitude and R the source-site distance in km. It is worth noting that this is an average relation, compared (Papaioannou et al., 2008) to other GMPEs for the Greek territory. As a future step, the application of additional, more recent, GMPEs is foreseen.

The attenuation laws applied in the framework of the present study to determine peak ground velocity (PGV) and displacement (PGD) are the ones proposed by Orphal and Lahoud (1974):

$$V = 7.26 \cdot 10^{-1} \cdot 10^{0.52M} \cdot R^{-1.39} \tag{2}$$

$$D = 4.71 \cdot 10^{-2} \cdot 10^{0.57M} \cdot R^{-1.18} \tag{3}$$

where V is the velocity in cm/s and D the displacement in cm.

HAZAN algorithm has also been applied for analysis using macroseismic intensity data. Previous efforts applying Gumbel I asymptote on macroseismic intensities for specific towns in Greece have been published by Papoulia (1988), Papoulia and Slejko (1997) and Sakkas et al. (2010).

It should be noted that the theory of Extreme Values has been extensively and successfully applied to seismic hazard studies in Greece (e.g. Makropoulos and Burton, 1985a, b; Sakkas et al., 2010; Papadopoulou et al., 2013; Pavlou et al., 2013). All calculations regarding PSHA are performed at the seismic bedrock for a return period of 475 years, corresponding to 90% probability of not been exceeded in 50 years, also used by the Greek Building Code (EAK, 2003).

Deterministic Approach

Synthetic seismograms (acceleration, velocity and displacement) are generated for three earthquake scenarios at three main towns of Messinia (Kalamata, Pylos and Filiatra). The method applied for the simulation of artificial accelerograms, proposed by Sabetta and Pugliese (1996), has two essential features. First, it reproduces the nonstationarity, in amplitude and frequency, of the real ground motions, playing an important role in nonlinear structural analysis. The simulation of nonstationary strong ground motions is achieved through a simple empirical method, summing Fourier series with time-dependent coefficients. Second, it allows the simulation of a family of time histories, similar in general appearance, however different in details, requiring only the magnitude of the reference earthquake, the distance source-to-site and the local site geology as input parameters.

The final functional form adopted for modeling the attenuation is represented by the equation:

$$\log_{10}(Y) = a + b\,M + c\,\log_{10}(R^2 + h^2)^{1/2} + e_1\,S_1 + e_2\,S_2 \pm \sigma \qquad (4)$$

where Y is the ground motion parameter to be predicted, M the magnitude, R the distance (fault or epicentral) in kilometers, h a fictitious depth determined by the regression incorporating all factors tending to limit the motion near the source, a, b and c constants and σ the standard deviation of the logarithm of Y. The parameters S_1 and S_2 refer to the site classification and are taken equal to 1 for shallow and deep alluvium sites and 0 in all other cases.

RESULTS

Probabilistic Approach

Earthquake magnitudes, peak ground motion parameters (PGA, PGV and PGD) and maximum intensities are determined for a return period of 475 years, corresponding to probability 90% of not being exceeded in 50 years. Calculations are performed for Kalamata, Pylos and Filiatra, at bedrock, using the extreme value statistics method and the HAZAN software (Makropoulos and Burton, 1986).

When dealing with macroseismic intensity data, the first step of hazard analysis includes the compilation of seismic histories of towns or areas. Seismic histories are a qualitative approach to hazard evaluation, which may also lead to quantitative hazard estimations. Care must be taken to include, at the best possible degree -taking into account the nature of historical macroseismic data- maximum observed intensities corresponding to mainshocks. The macroseismic intensities produced by aftershocks often represent the cumulative character of intensity.

In the present study, the seismic histories of the three main towns used for hazard analysis were compiled. The available historical data (Fig. 1) date back to 1842 for Kalamata ($I \geq 5$) and 1886 for Pylos and Filiatra ($I \geq 4$). It is observed that Kalamata has the richest seismic history, covering a loner time span (since 1842) and has experienced more than once destructive intensities ($I \geq 7$).

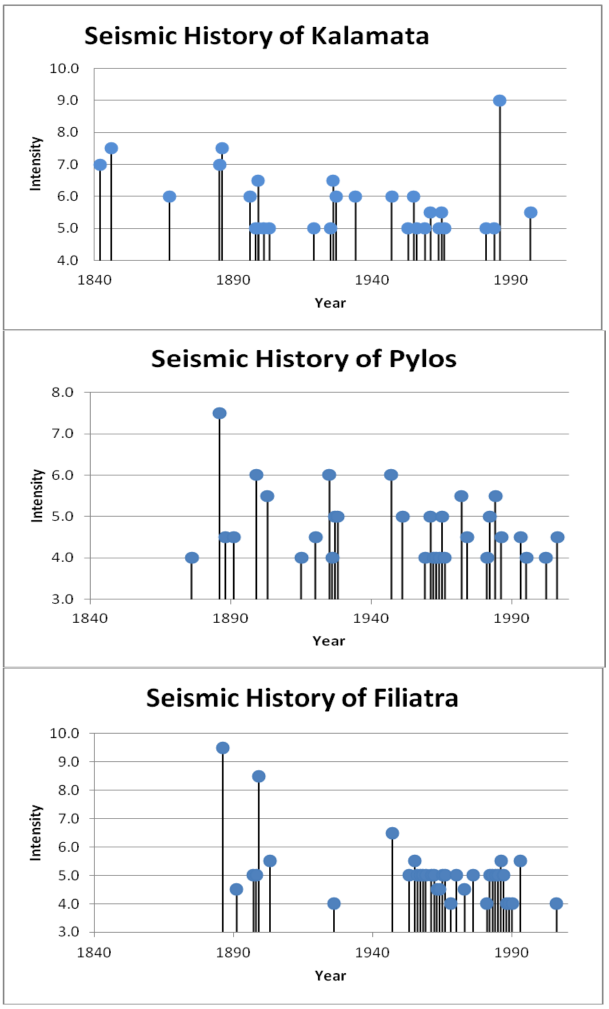

Figure 1. Seismic histories in terms of macroseismic intensity of Kalamata, Pylos and Filiatra towns

The third asymptote approach was applied to estimate maximum expected earthquake magnitude. The results (Table 1) indicate similar values for Kalamata and Filiatra, while significant higher maximum expected magnitude is obtained for Pylos. PGA, PGV, PGD and Imax were determined using the first asymptote distribution of the extreme values theory. Values of PGA, PGV, PGD are comparable for all three towns, with the highest being obtained for Pylos. PGA and PGV results are in a general agreement with those obtained for Messinia by Burton et al. (2003) and by Banitsiotou et al. (2004), who performed seismic hazard studies for Greece. Furthermore, PGA values calculated in the framework of the present study are smaller than those provided by the new Greek Building Code (EAK, 2003), given that all three towns are located in Zone II, corresponding to PGA values of 0.24g (235.44 cm/sec^2). However, regarding macroseismic intensities, which include also data from the 19th century, Imax value for Pylos is the lowest of all, as it has experienced the lowest macroseismic intensities, compared to Kalamata and Philiatra (Table 1 and Fig. 1).

Table 1. Maximum expected earthquake magnitudes (Mmax), peak ground acceleration (PGA), velocity (PGV) and displacement (PGD) and maximum intensities (Imax) with a 90% probability of no exceedance in 50 years

Location	Mmax	PGA (cm/sec^2)	PGV (cm/sec)	PGD (cm)	Imax
Kalamata	6.5	185.42	19.36	3.23	9.45
Pylos	7.1	188.40	22.91	3.94	7.90
Filiatra	6.6	172.07	19.63	3.49	9.20

It is worth noting that all 5 earthquakes with Mw≥6 that occurred in the vicinity of the Messinia prefecture since 1900 are located offshore, along the Hellenic Arc (Makropoulos et al., 2012). These events took place in 1947 (Ms=6.7), 1980 (Mw=6.4), 1997 (Mw=6.6) and 2008 (Mw=6.6 and Mw=6.1). This observation justifies the highest values of both earthquake magnitudes and peak ground motion parameters obtained for Pylos, being the town with the smallest epicentral distances for all these events. In addition, the 1886 (Mm=7.2) and 1899 (Mm=6.5) historical events are also located offshore, while the 1885 (Mm=6.1) is located on land, most probably originating from the same fault that produced the 1986 Kalamata earthquake (Sakellariou and Kouskouna, 2014).

Deterministic Approach

Following, a scenario-based deterministic approach is applied for three events that occurred in the Messinia region, for which no strong motion seismological data are available. The criteria used for the choice of the scenarios are: the earthquake magnitude, the distance of the epicenter from Kalamata, Pylos and Filiatra and the general impact of the earthquakes on the study area. The events used in the present study are the 28 March 1885, 27 August 1886 and 6 October 1947 earthquakes. Epicenter and magnitude for the first two were adopted from Stucchi et al. (2012), while for the third from Makropoulos et al. (2012). Generation of time histories was performed using the methodology proposed by Sabetta and Pugliese (1996).

The 1885 Earthquake Scenario

This earthquake caused local damage, mainly in the region of Kalamata and was felt as far as Athens, Mesolongi and Zakynthos. Severe damage was concentrated at Loi and Ano Karye, where maximum intensity I=9 (EMS98) was observed.

Predicted surface acceleration, velocity and displacement time histories for the 1885 earthquake are presented in Fig. 2, while the corresponding PGA, PGV and PGD values in Table 2. The epicentral distances of Pylos and Filiatra are the same, thus their time histories are identical, since the applied method (Sabetta and Pugliese, 1996) takes into account only the magnitude and the epicentral distance, considering the same soil conditions. Highest values, still significantly lower than the ones obtained by PSHA, are obtained for Kalamata. PGA, PGV and PGD are low for Pylos and Filiatra, given the relatively small magnitude of the 1885 earthquake and their epicentral distances.

Table 2. Epicentral distances and peak ground motion values for the 1885 earthquake scenario

Location	Distance (km)	PGA (cm/sec^2)	PGV (cm/sec)	PGD (cm)
Kalamata	17.1	145.00	10.14	1.68
Pylos	33.8	70.82	3.89	0.71
Filiatra	33.8	70.82	3.89	0.71

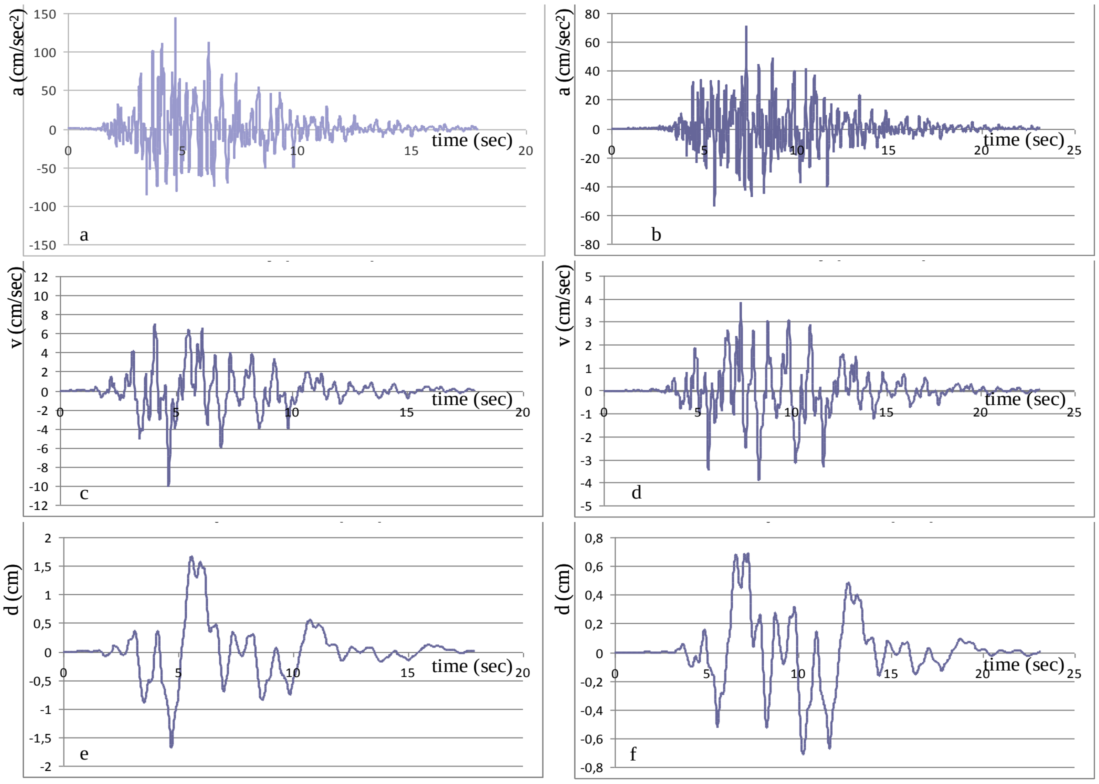

Figure 2. Simulated time histories of acceleration (Kalamata: a, Pylos - Filiatra: b), velocity (Kalamata: c, Pylos - Filiatra: d) and displacement (Kalamata: e, Pylos - Filiatra: f) at a base rock level for the 1885 earthquake scenario

The 1886 Earthquake Scenario

This large earthquake caused severe damage in a wide area of western Peloponnese. Many places were strongly affected, while the maximum intensity (9.5EMS98) was observed mainly in the west coast of western Peloponnese. A total of 6,000 houses were partly or totally destroyed. 334 people were killed and 796 injured. It was felt as far as Chios and Smyrna to the east, Alexandria to the south, Northern Italy to the west and Albania to the north.

The same methodology for the generation of synthetic time histories was also applied for the 1886 earthquake scenario (Fig. 3), for which epicentral distances for Pylos and Filiatra are also identical. Peak ground motion parameters (Table 3) for these towns are high, larger than the ones obtained by PSHA. This is due to the absence of a similarly large event in the instrumental era, covered by the earthquake catalogue used in the framework of the probabilistic approach. Nevertheless, the obtained PGA values are slightly smaller than those provided by EAK (2003).

Table 3. Epicentral distances and peak ground motion values for the 1886 earthquake scenario

Location	Distance (km)	PGA (cm/sec^2)	PGV (cm/sec)	PGD (cm)
Kalamata	57.3	113.35	8.42	2.53
Pylos	21.6	233.48	24.80	5.46
Filiatra	21.6	233.48	24.80	5.46

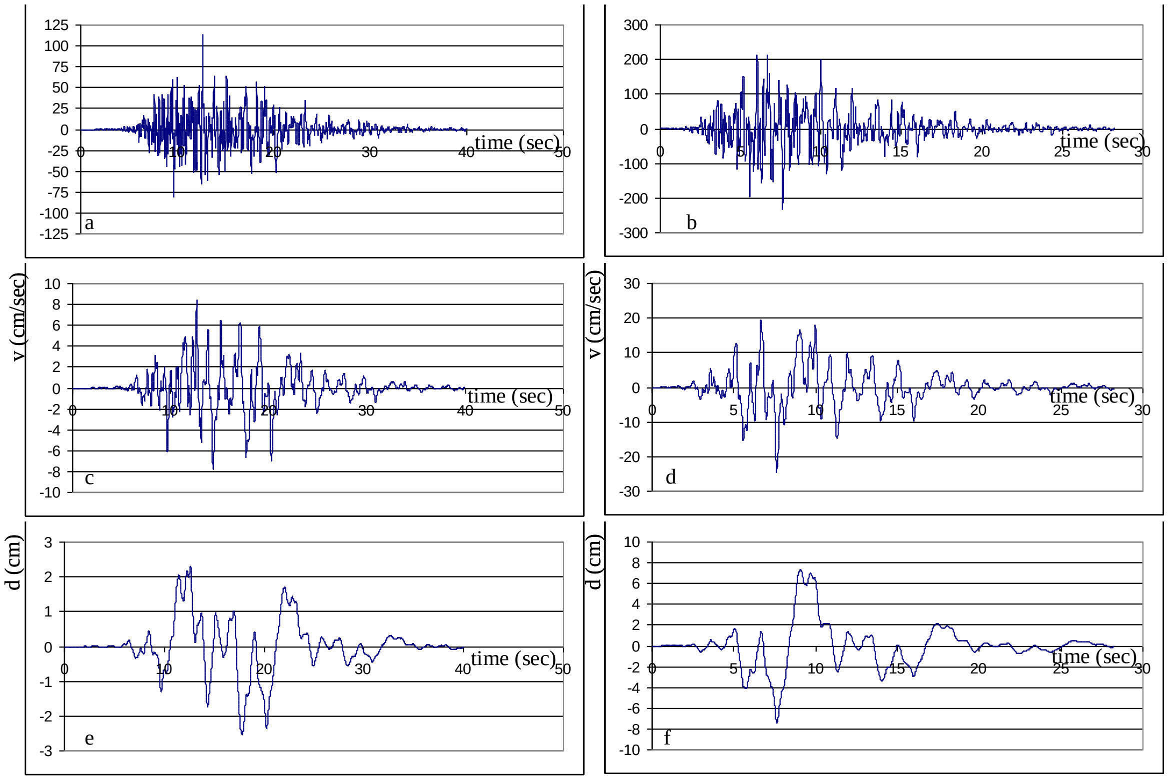

Figure 3. Simulated time histories of acceleration (Kalamata: a, Pylos - Filiatra: b), velocity (Kalamata: c, Pylos - Filiatra: d) and displacement (Kalamata: e, Pylos - Filiatra: f) at a base rock level for the 1886 earthquake scenario

The 1947 Earthquake Scenario

This strong earthquake in SW Peloponese caused severe damage to 54 localities: in total, 302 houses and 4 churches were destroyed and 890 houses, 22 churches and 7 schools were partly destroyed. The casualties were 3 persons killed and 20 injured (4 severely) (Galanopoulos, 1948). For this event, macroseismic intensities in the EMS scale are assessed in the present study (Fig. 4).

Results of the simulations for the 1947 scenario are presented in Fig. 5, while the determined PGA, PGV and PGD in Table 4. In this case epicentral distances for the three towns are not similar, resulting to different synthetic time histories. Higher values, still lower than those determined for a return period of 475 years, are obtained for Pylos. Peak ground motion parameters are significantly lower for Kalamata and Filiatra, as their epicentral distances are approximately double, compared to Pylos.

Table 4. Epicentral distances and peak ground motion values for the 1947 earthquake scenario

Location	Distance (km)	PGA (cm/sec^2)	PGV (cm/sec)	PGD (cm)
Kalamata	45.6	90.42	6.17	1.52
Pylos	24.0	176.36	15.25	3.40
Filiatra	53.4	76.46	5.09	1.44

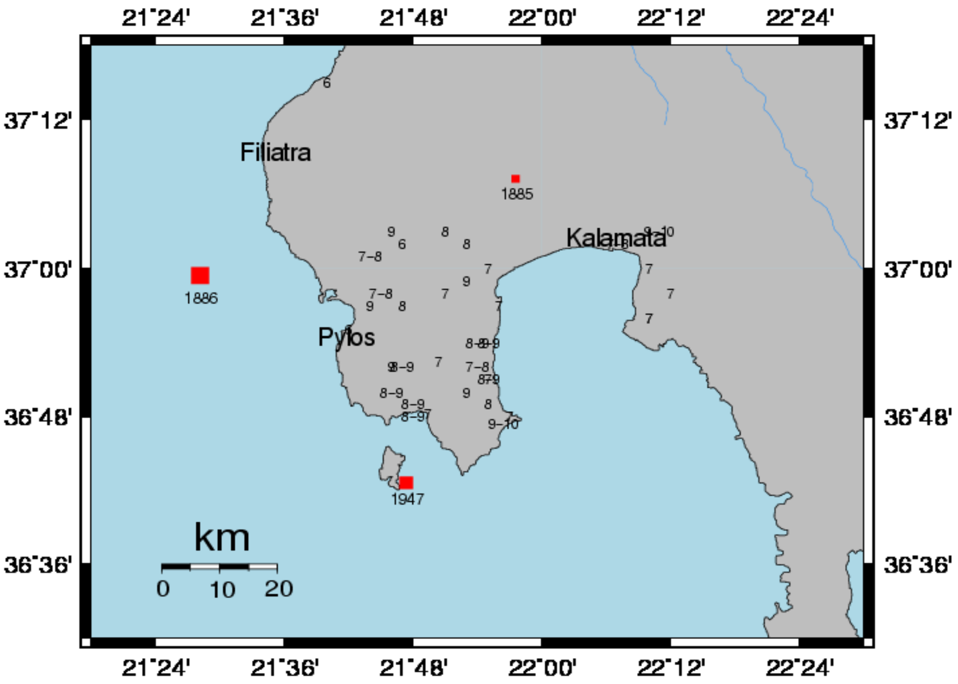

Figure 4. Macroseismic intensity distribution of the 1947 earthquake. Epicenters of the 1885 and 1886 earthquakes are obtained from Stucchi et al. (2012), while for the 1947 event from Makropoulos et al. (2012)

CONCLUSIONS

Messinia is an earthquake prone area, affected by several destructive earthquakes. It lies close to the Hellenic arc, between a subduction zone to the south and the recently re-activated Kefallinia - Lefkas transform fault to the north. A seismic hazard study is performed including both probabilistic and deterministic approaches.

The probabilistic approach for a return period of 475 years provided higher maximum expected magnitude (Mmax) values for Pylos (7.1) and lower for Filiatra and Kalamata (6.6 and 6.5, respectively). The same pattern was obtained for peak ground velocity (PGV) with values equal to 22.91 cm/sec, 19.63 cm/sec and 19.36 cm/sec for Pylos, Filiatra and Kalamata, respectively. Comparable PGD values were obtained for all three towns, ranging between 3.23 cm (for Kalamata) and 3.94 cm (for Pylos). The same approach using the first asymptote resulted in macroseismic intensities of 9.45, 7.9 and 7.2 for Kalamata, Pylos and Filiatra, respectively. These values are highly influenced by the 19th century historical earthquakes for Pylos and Filiatra and the 1986 earthquake for Kalamata.

The PGA results with 90% probability of not been exceeded in 50 years are higher for Kalamata and Pylos (both 0.19g) and lower for Filiatra (0.175g). All these values are smaller than 0.24g, which is the design acceleration value proposed by EAK (2003). The determined values are higher than 0.14g which is the PGA calculated by Makropoulos and Burton (1985b), who also used the extreme values method for the same return period in Messinia area. On the other hand, a higher design ground motion of 0.29g has been proposed by Papazachos et al. (1993) for the western Peloponnese coastal area. In the framework of seismic hazard assessment of SW Peloponnese, Slejko et al. (2010) applied seismic zonation to compute PGA. They alternatively used the Papazachos and Papazachou (1997) and the SEAHELLARC seismogenic zonation and the Papaioannou and Papazachos (2000) and SEAHELLARC earthquake catalogues. They determined significantly higher values, ranging between 0.32g and 0.56g for Kalamata, 0.48g and 0.56g for Pylos and 0.48g and 0.64g for Filiatra.

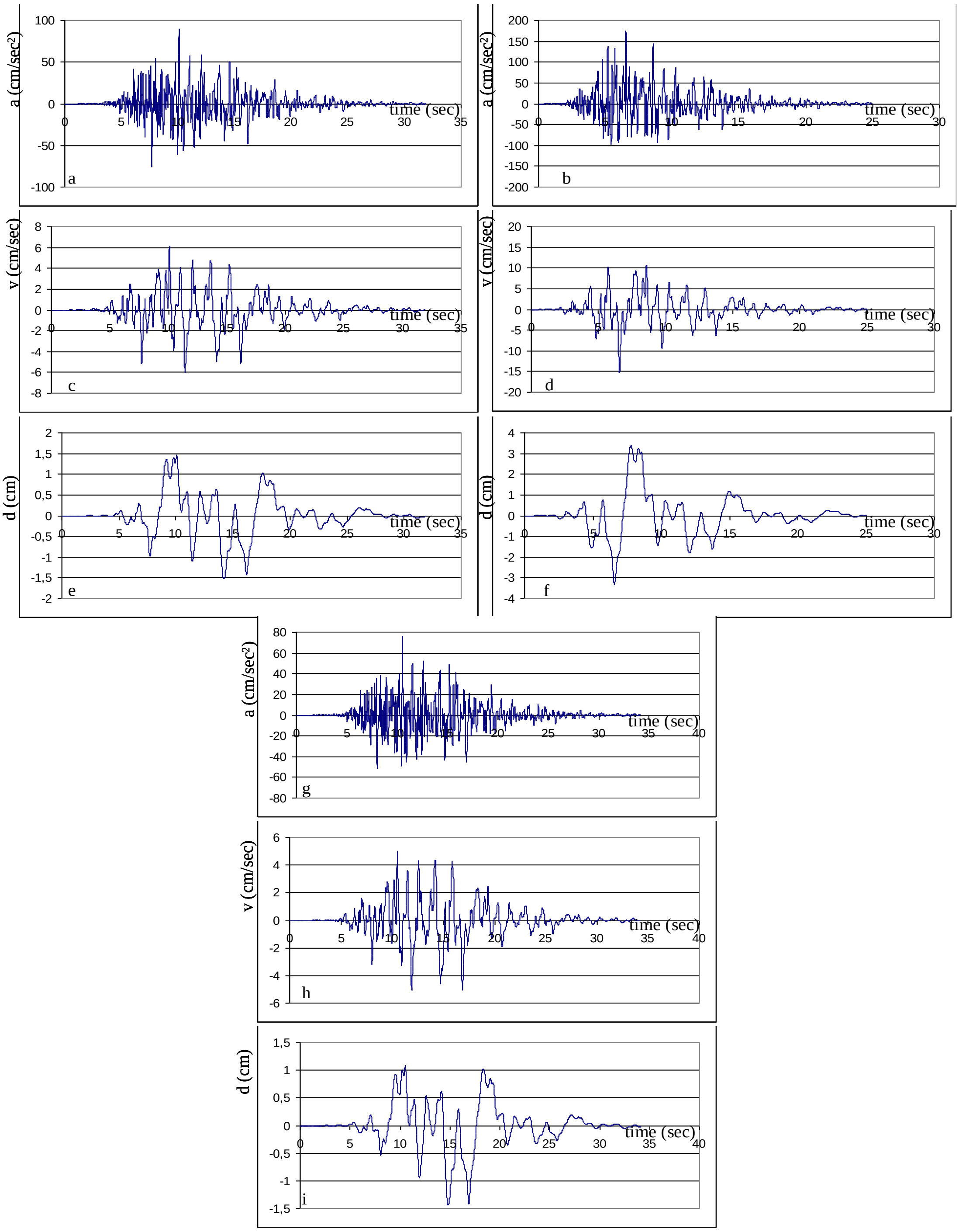

Figure 5. Simulated time histories of acceleration (Kalamata: a, Pylos: b, Filiatra: g), velocity (Kalamata: c, Pylos: d, Filiatra: h) and displacement (Kalamata: e, Pylos: f, Filiatra: i) at a base rock level for the 1947 earthquake scenario

Concerning the deterministic approach three earthquake scenarios were chosen, i.e. the 28 March 1885, 27 August 1886 and 6 October 1947 earthquakes, for which no strong motion records are available. Acceleration, velocity and displacement time histories were computed for all three events in Kalamata, Pylos and Filiatra towns. The effect of the distance is evident, as larger distances are related to smaller peak ground motion values.

Higher PGA, PGV and PGD values for the 1885 earthquake (M=6.1) scenario were obtained for Kalamata. The PGA value is significantly smaller than the one proposed by EAK (2003) for a return period of 475 years. The 1886 (M=7.2) earthquake scenario yielded significantly high peak ground motion values for Pylos and Filiatra, at the same epicentral distance. Nevertheless, the determined PGA value of 233.48 cm/sec^2, even higher than the obtained in the framework of the probabilistic approach, is slightly smaller than the one proposed by EAK (2003) which is 0.24g (235.44 cm/sec^2). The highest PGA, PGV and PGD values for the 1947 earthquake (Ms=6.7) scenario were obtained for Pylos town. These values are considerably smaller than the ones determined for the 1886 scenario, due to the smaller earthquake magnitude, even though epicentral distances for Pylos are similar in both cases.

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