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Evaluation of seismic intensities of historical earthquakes in the southern and southwestern Peloponnese (Greece) based on the Environmental Seismic Intensity (ESI 2007) scale

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Abstract: *The southern and southwestern Peloponnese is one of the most seismically and tectonically active areas in the Eastern Mediterranean. Based on historical and recent seismicity data, the area has been often struck by destructive earthquakes with significant impact on the natural and built environment. Taking into account various sources, the complete catalogue of destructive historical earthquakes from 550 BC to 1899 AD is presented for the first time with all induced earthquake environmental effects (EEE). Based on the application of the Environmental Seismic Intensity (ESI 2007) scale, the most susceptible areas to EEE are the Kalamata (Kato Messinia) basin followed by Sparta basin, the eastern slopes of Taygetos Mt, the Ionian coast of Messinia and the Kyparissia Mts. The maximum assigned local environmental seismic intensities are $X_{ESI\ 2007}$ for Sparta basin, VIII-$IX_{ESI\ 2007}$ for Kalamata basin, $VIII_{ESI\ 2007}$ for the Ionian coast of Messinia and VII for Kyparissia Mts.*

Keywords*: historical earthquakes, environmental effects, ESI 2007, Peloponnese, Greece*

INTRODUCTION

Earthquake environmental effects (EEE) are the effects induced by an earthquake on the natural environment (Michetti et al., 2007). They are classified into two types: (a) primary EEE, which include surface faulting, coseismic surface ruptures and permanent ground dislocations of tectonic origin and any other surface evidence of coseismic tectonic deformation (Michetti et al., 2007) and (b) secondary EEE classified into eight main categories: (i) hydrological anomalies, (ii) anomalous waves including tsunamis, (iii) ground cracks, (iv) slope movements, (v) trees shaking and vegetation damage, (vi) liquefaction phenomena, (vii) dust clouds and (viii) jumping stones (Michetti et al., 2007). The EEE can be used for the evaluation of the seismic intensity not only of recent but also of historical and palaeo- earthquakes and furthermore for the comparison among future, recent, historical and palaeo-earthquakes. The ESI 2007 scale has been already applied in historical earthquakes in various tectonic environments around the world, not only in individual events in order to enrich the existing database for countries [e.g. Greece (Papanikolaou & Melaki, 2017)], but also in a set of chosen historical events in the same region [e.g. southern Apennines in Italy (Serva et al., 2007)] in order to reassess the historical events in the region and to contribute to the reduction of the seismic risk. Although other efforts have been made to record the EEE of individual recent earthquakes in Greece and evaluate their ESI 2007 seismic intensity (e.g. Fountoulis & Mavroulis, 2013; Mavroulis et al., 2013; Lekkas & Mavroulis, 2015; Papanikolaou & Melaki, 2017; Lekkas et al., 2018), no one has focused on the complete seismic history of an area and the respective intensities based on the induced EEE. The southern and southwestern Peloponnese (Fig. 1) was considered appropriate for the development of this approach.

This study comprises the presentation of the complete catalogue of all destructive historical earthquakes covering a time period extending from 550 BC to 1899, generated in the southern and southwestern Peloponnese (Fig. 1), which is one of the most seismically and tectonically active areas of Greece. Furthermore, it includes the detailed and accurate description of all the available EEE induced by these earthquakes and the application of the ESI 2007 scale for these events based on the quantitative characteristics of their EEE.

The complete and detailed knowledge of the historical earthquakes, the past EEE and the respective seismic intensities serves as a valuable tool for revealing and highlighting subareas of significant earthquake-related hazards where no macroseismic damage data are available, testing the susceptibility and the vulnerability of the affected area to the same EEE and improving preparedness and land-use planning to cope with and overcome the changes that an earthquake induces on the natural environment of the affected area.

SEISMOTECTONIC SETTING

Onshore and offshore studies conducted by various researchers (Mariolakos et al., 1986; Papanikolaou et al., 1988; Papanikolaou et al., 2007) revealed that the southern and the southwestern part of Peloponnese is composed of major neotectonic macrostructures bounded by N-S and E-W trending fault zones (Fig. 1). These onshore macrostructures are from E to W the following: (a) the NW-SE striking Sparta basin, (b) the N-S striking Taygetos Mt mega-horst, (c) the Kalamata-Kyparissia mega-graben striking N-S in its southern part and E-W further to the north, (d) the very complex morphotectonic mega-structure of Kyparissia Mts-Lykodimo Mt striking N-S and

(e) the Gargallianoi-Pylos mega-horst located along the western coast of Messinia (Mariolakos et al., 1986; Fountoulis & Mavroulis, 2013) comprising smaller fault blocks (Fig. 1). These onshore structures are bounded by active fault zones and seismic faults (Fig. 1, e.g. the eastern marginal fault of Kato Messinia basin ruptured in 1986 Kalamata earthquake, the Sparta fault ruptured in 464 B.C. devastating Sparta). Offshore fieldwork in Messinian (Papanikolaou et al., 1988) and in Kyparissiakos Gulfs (Papanikolaou et al., 2007) demonstrated that active faults observed onshore continue in several cases offshore in the study area (Fig. 1).

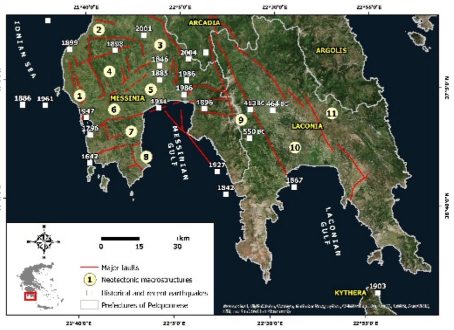

Figure 1: The southern Peloponnese along with the historical and recent earthquakes with impact on human, natural and built environment of the study area as well as the major onshore and offshore faults and the major neotectonic macrostructures: (1) Gargallianoi-Pylos mega-horst, (2) Kyparissia basin, (3) Ano Messinia basin, (4) Kyparissia Mts, (5) Kalamata (Kato Messinia) basin, (6) Vlahopoulo graben, (7) Lykodimo Mt horst, (8) Falanthi basin, (9) Taygetos Mt, (10) Sparta (Evrotas) basin, (11) Parnon Mt based on Mariolakos et al. (1986), Papanikolaou et al. (1988) and Fountoulis (1994).

METHODOLOGY

For the present study, data and information on historical and recent earthquakes and their EEE in the southern and southwestern Peloponnese were obtained from the following sources: (a) official earthquake catalogues from universities, seismological institutes and observatories, (b) books and scientific articles containing catalogues or information of earthquakes and their EEEs in Greece (e.g. Shebalin et al., 1974; Papazachos & Papazachou, 1989, 1997, 2003; Soloviev et al., 2000; Ambraseys, 2009) or in southwestern Peloponnese (e.g. Galanopoulos, 1947, 1981; Papadopoulos et al., 2014), (c) scientific articles referring to the impact of individual earthquakes in southwestern Peloponnese (e.g. Galanopoulos, 1940, 1941a, 1941b, 1949, 1960; Pirli et al., 2007; Ganas et al., 2012; Fountoulis & Mavroulis, 2013; Sakellariou & Kouskouna, 2014; Kouskouna & Kaviris, 2014), (d) official field survey and reconnaissance reports and (e) official reports of applied scientific research projects (e.g. Mariolakos et al., 1986; Plessa & Ganas, 2014).

HISTORICAL EARTHQUAKES, EEE & ESI 2007 INTENSITIES

The 550 BC and 464 BC Sparta earthquakes

The data referred to earthquakes from 550 BC to 1838 are limited to occurrence date and the most affected areas as well as limited information of secondary EEE comprising only slope movements including mainly landslides and rockfalls without any further quantitative information. The listed earthquakes occurred in (a) 550 BC causing the destruction of Sparta and the collapse of the Taygetos Mt. summit indicating rockfalls and landslides and (b) in 464 BC, when the most destructive earthquake of Sparta took place resulting in 20000 fatalities. The 464 BC Sparta earthquake triggered ground cracks and slope failures along the eastern slopes of Taygetos Mt. The exact geographic locations of the triggered effects are not available. Consequently, the areal distribution of the secondary effects cannot be extracted neither directly nor indirectly. Moreover, further quantitative information including either the volume of the mobilized materials or dimensions (length, width and frequency) of ground cracks are not available.

The 1842 April 18 earthquake

This earthquake generated ground cracks, slope failures, hydrological anomalies and tsunami waves were generated in and affected various sites. In Eva [previous name (p.n.) Naziri], located within the Pamisos River valley, ground cracks with width of 40 cm and depth of 7 m ($VIII_{ESI\ 2007}$) were observed close to geotechnically unstable areas and were related to coseismic landslide phenomena. Detachment of large rock masses and rockfalls occurred in Eva resulted in building damage and related fatalities. In Evrotas River valley, the earthquake caused detachment and fall of large rock masses in the archaeological site of Menelaion. Hydrological anomalies included water turbidity within the Pamisos River valley and more specifically water turbidity in Pamisos springs in Agios Floros ($VIII_{ESI\ 2007}$) and overflowing of wells. The flow of Pamisos River was disturbed and the river was locally overflowed. Liquefaction phenomena were reported in Analipsi (p.n. Tsitsori) ($VII_{ESI\ 2007}$). The coast close to Koroni was inundated and ships were washed on the shore by the earthquake-induced tsunami ($VIII\text{-}IX_{ESI\ 2007}$).

The 1846 June 11 Messinia earthquake

Liquefaction phenomena occurred in several sites in the form of ground cracks accompanied by ejection and flowing of sand-water mixture that covered large parts of fields ($VII_{ESI\ 2007}$). A large lake made of silt-water mixture was formed in Ammos (p.n. Mpaliaga) and sulfur odor was noticeable ($VIII_{ESI\ 2007}$). Ground cracks were observed in Mikromani within the post-alpine formations of Pamisos River valley with width varying from 5 to 8 cm along with the formation of craters with diameter of 10 cm with surging liquid material ($VII_{ESI\ 2007}$). Ground cracks with large width and partially filled with silt were also reported in the Pamisos River estuary ($VII_{ESI\ 2007}$). Hydrological anomalies were also observed in Messese area ($VII_{ESI\ 2007}$) and caused the outbreak of infectious diseases.

The 1867 September 20 earthquake

The earthquake severely affected the coastal areas of Laconian and Messinian Gulfs. It also affected the coast of Cephalonia Island (Ionian Sea) causing damage to Lyxouri port and the Cyclades complex in the Aegean Sea and especially Syros and Serifos Islands. They also reached the Italian coasts and affected Brindisi, Messina, Sicily and Catania coastal areas. Gytheio was destroyed by the waves, which had a significant impact on the Cape Pagania, on the western shore of the Laconian Gulf and on the Messinian Gulf. In Gytheio, changes to sea level were observed. The sea initially receded from the shore and the sea bed was dried up. Afterwards, the sea rose for 6 m above its usual level and it looked like boiling ($X_{ESI\ 2007}$). In Kalamata located in the northern part of the Messinian Gulf, low and high water were similarly observed with the sea receding slowly from the coast approximately for 15 m ($IX_{ESI\ 2007}$). Lower values of sea level fall were observed in Petalidi coastal area, where then the sea water level rose up to 2m and caused inundation of the coastal area ($VIII_{ESI\ 2007}$). In Neapoli, the sea bed was also dried up causing boats touching the sea bed more than once ($VII_{ESI\ 2007}$).

The 1885 March 28 Messene earthquake

Rockfalls were triggered by the earthquake. No further information and details on the exact location and the areal distribution of the induced rockfalls and the volume of the mobilized geological material are available. Thus, the epicentral intensities and the local intensities cannot be estimated due to the absence of the exact location and the quantitative characteristics of the earthquake-induced rockfalls.

The 1886 August 27 Filiatra earthquake

The EEE include ground cracks, liquefaction phenomena, submarine landslides, tsunami waves and hydrological anomalies. Ground cracks were observed in the area between Katakolo and Gargalianoi ($V\text{-}VI_{ESI\ 2007}$). Ground cracks along with liquefaction phenomena (ejection of ground water) were observed in Marathopolis area ($VII_{ESI\ 2007}$). Submarine landslides resulted in disruption of submarine cables connecting Zakynthos and Crete. Tsunami waves were generated and affected a 35km long N-S coastal segment extending from Agrilos located north of Filiatra to the Pylos bay. The waves swept several boats onto the coast of Gialova ($VII\text{-}VIII_{ESI\ 2007}$) located north of Pylos, the sea close to Argilos, located to the north of Filiatra, advanced resulting in coastal inundation ranging from 10 to 15 m for a short time period ($VII\text{-}VIII_{ESI\ 2007}$). It was reported that the tsunami was observed up to Izmir. Hydrological anomalies comprised water turbidity in Evinos River, whose estuary is located north of Patras Gulf, in a distance of 120 km north of Filiatra. These hydrological anomalies in Evinos River were considered as an isolated effect of the 1886 earthquake generated in the far field. Thus, it has not been taken into account in the assessment of the environmetal seismic intensities.

The 1898 November 9 Kyparissia earthquake

Hydrological anomalies were observed in Aetos village located in Tryfillia province and included increased discharge and water turbidity (muddy water) in a spring ($VII_{ESI\ 2007}$).

The 1899 January 22 Kyparissia earthquake

Slope movements included mainly landslides and rockfalls located south of Kyparissia and east of Filiatra, more specifically in Perdikoneri and Rouzaki villages. Hydrological anomalies included water discharge variations in springs as far as Kalamata town ($VII_{ESI\ 2007}$), Varvitsa and Dimitsana villages. Liquefaction and slumping of geological material was induced along the Ionian coast of Messinia ($VII_{ESI\ 2007}$). In Messene marshes located west of Kalamata, extensive liquefaction phenomena occurred resulting in damage to railway embankments and telegraph lines ($VII_{ESI\ 2007}$).

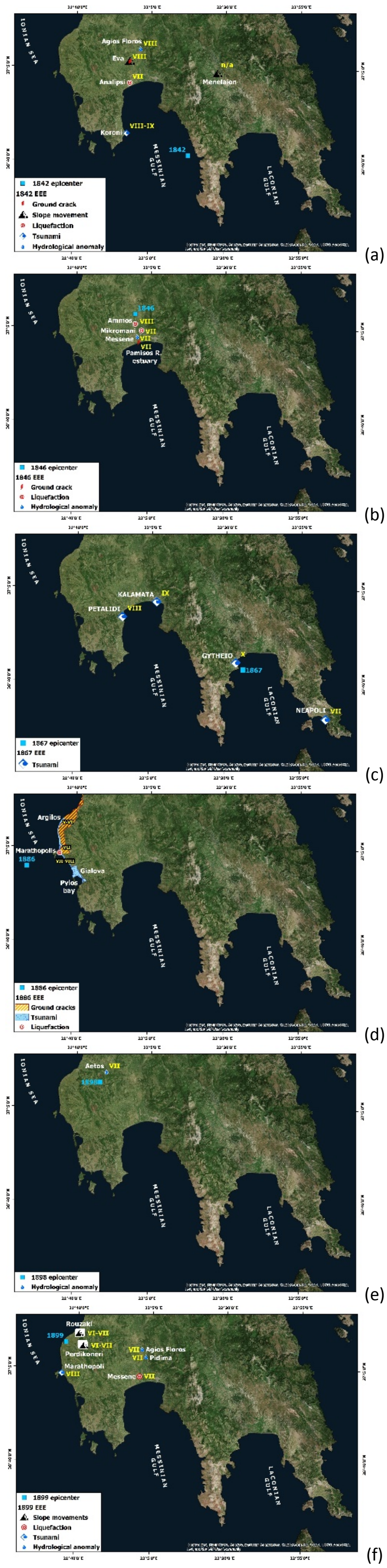

Figure 2: EEE induced by the (a) 1842, (b) 1846, (c) 1867, (d) 1886, (e) 1898, (f) 1899 earthquakes in southern and southwestern Peloponnese.

The subsequent earthquake-induced tsunami was about 1m high and resulting in inundation of Marathopolis coastal area ($VIII_{ESI\ 2007}$), while in Zakynthos Island was about 20-40 cm ($VII_{ESI\ 2007}$). The tsunami was possibly triggered by submarine slumps, but no damage occurred to the submarine cables between Zakynthos and Western Peloponnese. The hydrological anomalies observed in Varvitsa and Dimitsana villages located in Laconia and Arcadia prefectures respectively were also considered as far field effects of the earthquake and were not considered in the intensity assessment.

CONCLUSIONS

Based on the aforementioned data, slope movements were the most frequently reported EEE reported in 5 historical earthquakes followed by liquefaction phenomena, tsunami waves and hydrological anomalies reported in 4 historical earthquakes and ground cracks in 3 historical earthquakes. The most susceptible areas to the generation of EEE are the Kalamata (Kato Messinia) basin, which has been affected by EEE during 4 historical earthquakes, followed by Sparta (Evrotas) basin with EEE during 2 historical earthquakes, the eastern slopes of Taygetos Mt affected by slope movements during 2 historical earthquakes, the Ionian coast of Messinia suffered by EEE during 2 historical earthquakes, and the Kyparissia Mts also suffered by EEE during a historical event respectively. The maximum assigned local environmental seismic intensities are $X_{ESI\ 2007}$ for Sparta (Evrotas) basin, $VIII\text{-}IX_{ESI\ 2007}$ for Kalamata (Kato Messinia) basin, $VIII_{ESI\ 2007}$ for Ionian coast of Messinia and VII for Kyparissia Mts. These analysis is not only of historical interest, but significantly contribute to the completeness of the earthquake and the induced EEE catalogue, which is the very important for seismic hazard analysis and as such benefits all scientists and agencies competent to the prevention and management of natural disasters.

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