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Environmental effects and ESI-07 seismic intensities of the October 26, 2018, Mw 6.8 offshore southwestern Zakynthos earthquake and comparison with all known destructive historical and recent earthquakes in the southern Ionian Islands (Greece)

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Zakynthos Island is located in the external part of the Hellenic Arc and in the east of the Hellenic Trench, which represents the convergence boundary between the African and Eurasian plates, and is one of the most tectonically and seismically active parts of the Mediterranean region (Papazachos and Papazachou, 1989, 1997, 2003; Lekkas et al., 1996-1997).

Based on the seismicity catalogues of the permanent regional seismological network operated by the Aristotle University of Thessaloniki (AUTH, 2019) covering the period from 550 BC to 2018, it is concluded that many earthquakes with magnitudes larger than 5.0 have been concentrated in four zones around Zakynthos Island. These zones include significant seismic sources with high productivity and frequent occurrence of destructive earthquakes during historical and recent times (Lekkas et al., 1996-1997; Papazachos and Papazachou, 1989, 1997, 2003) and they are the following:

(a) The western offshore Cephalonia and Lefkada area, where the prevailing active tectonic structure is the Cephalonia Transform Fault Zone (Scordilis et al., 1985).

(b) Within the Zakynthos channel and the respective structural basin between Zakynthos Island and Peloponnese, which are affected by the westward offshore extensions of onshore faults to onshore western Peloponnese. More specifically for the area offshore eastern Zakynthos, major normal faults bound continental fault blocks and are characterized as active tectonic structures as revealed from the integration results of onshore neotectonic mapping (Lekkas et al., 2000; Papanikolaou et al., 2007) and local seismological observations (Papoulia et al., 2014).

(c) The area south and southeast of Zakynthos Island, where Vp-velocity models and their tectonic interpretation showed that the southwestward extension of the NE-SW striking dextral strike-slip Western Achaia Fault Zone (WAFZ) from Northwestern Peloponnese to offshore southern Zakynthos prevails (Makris and Papoulia, 2014).

(d) The area southwest of Zakynthos Island. This zone constitutes a downthrown block of the external Hellenides at the northern end of the Hellenic Trench and comprises tectonic structures like flat thrusts, strike-slip faults and normal faults, whose reactivations have resulted moderate seismicity (SEAHELLARC Working Group, 2014). More specifically, thrusting prevails over strike – slip or normal faulting (Kokinou et al., 2005, 2006), with the most important feature of this area being a 46-km-long NW-SE trending thrust system (SEAHELLARC Working Group, 2014). This system is responsible for the generation of the 1997 Mw 6.6 earthquake (SEAHELLARC Working Group, 2014) as well as for the October 26, 2018 Mw 6.8 offshore Zakynthos earthquake. Thrust events are also observed along the Hellenic subduction zone located west and southwest of Zakynthos Island (Kiratzi and Louvari, 2003).

The last major episode of the geodynamic evolution of the Central Ionian Islands is the October 26, 2018, Mw 6.8 Zakynthos earthquake. It was generated offshore southwestern Zakynthos and it was predominantly felt on Zakynthos and throughout the Ionian Islands, Peloponnese and the mainland Greece fortunately with no casualties or injuries reported.

As regards the environmental effects induced by the 2018 Zakynthos earthquake, secondary earthquake environmental effects were observed including slope failures, a small tsunami and asphalt-pitch seepages. Landslides and rockfalls were mainly generated in various parts of the island and more specifically along the steep coastal slopes and scarps in its northwestern part (e.g. Navagio beach, $VII_{ESI\ 2007}$), in its southwestern part (e.g. along Mizithres beach, $VII_{ESI\ 2007}$), in its central-eastern part (e.g. Panagoula and Kryoneri areas, VI-$VII_{ESI\ 2007}$ and $VI_{ESI\ 2007}$ respectively). A small tsunami wave was generated offshore southwestern Zakynthos and was detected based on sea level changes (offset: 0.549 m) ($VI_{ESI\ 2007}$) that occurred after the earthquake and were recorded by the Katakolo (offshore central western Peloponnese) station of the Sea Level Station Monitoring Facility (https://goo.gl/wURcNs). Based on several witnesses, an increase in sea level of about half a meter were observed along the coast between Santa Maria di Leuca Cape and Otranto located in the eastern coast of the Salento peninsula (Italy).

Data on historical and recent earthquakes generated in the Central Ionian Sea and the western Peloponnese and on their EEEs induced on Zakynthos Island were obtained from the following sources: (a) all major academic databases, search engines and sources for scientific research including GeoRef, Sciencedirect, Scopus, Springer, JSTOR etc, (b) official earthquake catalogues from universities, seismological institutes and observatories, (c) books and scientific articles containing catalogues or information of earthquakes and their EEEs in Zakynthos (e.g. Papazachos and Papazachou, 2003) or in the broader Zakynthos area (e.g. Lekkas et al., 1996-1997), (d) official field survey and reconnaissance reports (e.g. Lekkas and Mavroulis, 2018) and (e) official reports of scientific research projects (e.g. Lekkas, 1993).

The complete seismic history of destructive historical and recent earthquakes comprises 20 significant earthquakes generated not only onshore Zakynthos Island but also offshore with great impact on population, natural environment, buildings and infrastructures. The impact on the natural environment comprises mainly secondary effects including

hydrological anomalies, anomalous waves/tsunamis, ground cracks, slope movements, tree shaking and liquefaction phenomena. Primary effects have also been reported after strong earthquakes in Zakynthos Island including reactivation of faults and coseismic surface ruptures.

In Zakynthos Island: (a) primary effects comprised fault reactivation during the 1513 earthquake and formation of coseismic surface ruptures during the January 1893 earthquake, (b) the observed hydrological anomalies included rising of the ground water level, increased discharge in wells, increased river flow, overflow of streams and subsequent flooding of the adjacent area and sulphureous gas emissions along with flames and burning of the adjacent vegetation, (c) the anomalous waves/tsunamis included sea withdrawal, roughness and violent agitation of the sea surface and small scale tsunamis resulting in cape sweeping by sea waves, coastal submergence and coastal inundation, (d) the detected ground cracks were observed in areas with loose recent sediments and instability conditions along river banks, close to geotechnically unstable areas and along with liquefaction phenomena and sulphureous gas emissions, (e) the triggered slope movements are classified as rockfalls, rockslides and landslides along high and steep inland and coastal slopes and scarps, (f) severe tree shaking and damage to vegetation due to the earthquake shaking was limited, (g) liquefaction phenomena were also limited to ejection of sand/water mixture along ground cracks and coastal subsidence, (h) phenomena related to the presence of asphalt-pitch in the coastal mire/swamp zone of Keri were also triggered by the generated earthquakes. These phenomena included boiling of asphalt and asphalt-pitch seepages in various sites of the earthquake-affected area and more specifically in the eastern onshore and offshore part of the Keri bay fault block.

The following summarizing and concluding remarks are made. Anomalous waves/tsunamis are the most frequently reported EEE in the 20 historical and recent earthquakes of this study (11 out of 20 events), followed by the slope movements (10 out of 20), ground cracks (7 out of 20), hydrological anomalies (6 out of 20), liquefaction phenomena (4 out of 20) and hydrocarbon-related phenomena (4 out of 20). Primary effects are limited to fault reactivation (1 out of 20 events) and coseismic surface ruptures (1 out of 20).

The maximum assigned local environmental seismic intensities are VIII-IX$_{\text{ESI 2007}}$ for the Northern Zakynthos fault block, VII$_{\text{ESI-07}}$ for the western part of the Central Zakynthos fault block, VIII-IX$_{\text{ESI 2007}}$ for the eastern part of the Central Zakynthos fault block, IX$_{\text{ESI 2007}}$ for the Keri Bay fault block, VII$_{\text{ESI 2007}}$ for the Southern Zakynthos fault block and VIII$_{\text{ESI 2007}}$ for the Skopos Mt fault block.

The most susceptible areas to the generation of EEE are the Skopos Mt fault block, which has been affected by EEE during 11 earthquakes, followed by the eastern part of the Central Zakynthos fault block with EEE during 9 earthquakes, the Keri Bay fault block affected by EEE during 5 earthquakes, the western part of the Central Zakynthos fault block affected 4 times, the Southern Zakynthos fault block affected 3 times and the Northern Zakynthos fault block only once.

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