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SUSCEPTIBILITY AND HAZARD ASSESSMENT IN THE IONIAN ISLANDS FOR HIGHLIGHTING SITES OF SIGNIFICANT EARTHQUAKE-RELATED HAZARDS

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ABSTRACT
The identification of the earthquake environmental effects by using various methods has become significant in recent years due to the fact that among others it serves as a valuable tool for revealing and highlighting sites of significant earthquake-related hazards. In the frame of the project entitled "Tilemachos - Innovative Operational Seismic Risk Management System of the Ionian Islands" included in the Priority Axis "Environmental Protection and Sustainable Development" of the Operational Programme “Ionian Islands 2014-2020”, the landslide, liquefaction and tsunami hazards in the Ionian Islands are analyzed and assessed by combining different methods. Landslide, liquefaction and tsunami inventories for all Ionian Islands were initially created. Along with the inventories, different thematic maps were used and combined in order to test the earthquake-induced landslide and liquefaction susceptibility and the tsunami hazard of the Ionian Islands. The main result is the identification of sites of significant earthquake-related hazards in the Ionian Islands. This study and its results could constitute a basic guide for the future urban design and planning and the sustainable local development since all scientists and agencies competent to the prevention and management of natural disasters can be informed and guided.

Keywords: earthquake environmental effects, hazard assessment, susceptibility assessment, Ionian Islands

1. INTRODUCTION
The Ionian Islands are located in the northwestern part of the Hellenic Arc and constitute one of the most seismically active areas in the Mediterranean region and worldwide [1]. The high seismicity is controlled by the occurence of the Cephalonia Transform Fault Zone (CTFZ), which is the main active tectonic structure in the Ionian Islands. The high seismicity of the Ionian Islands comprises historical and recent shallow seismic events with moment magnitude up to 7.4, macroseismic intensities up to X+ in MM scale and significant impact on the population, on the natural environment as well as on buildings and infrastructures of the islands. The most recent episodes of the seismic activity in the Ionian Islands are the Cephalonia Isl. earthquakes of January 26, 2014 (Mw 6.0) and February 3, 2014 (Mw 5.9), the November 17, 2015 Mw 6.4 Lefkada earthquake and the October 26, 2018 Mw 6.8 Zakynthos earthquake. The 2014 Cephalonia earthquakes caused extensive environmental effects and damage on the building stock of the western Cephalonia [2, 3]. The 2015 Lefkada earthquake triggered mainly slope movements in the western and southern part of the island and building damage in its southwestern part [4]. The 2018 Zakynthos earthquake caused slight non-structural damage to buildings and infastructures and limited environmental effects in the southern part of Zakynthos Island [5].
For the detailed reassessment of the seismic hazard in the Ionian Islands, the project titled "Tilemachos - Innovative Operational Seismic Risk Management System of the Ionian Islands" was included in the Priority Axis "Environmental Protection and Sustainable Development" of the Operational Program “Ionian Islands 2014-2020”. Implementing partners are the Region of the Ionian Islands, the National and Kapodistrian

University of Athens (NKUA), the Ionian University, the Technological Educational Institute of the Ionian Islands, the Regional Union of Municipalities of Ionian Islands, the Earthquake Planning and Protection Organization and the National Observatory of Athens.
The contribution of NKUA to the implementation of this project comprises two subprojects entitled "Hazard analysis and assessment" and "Supply of specialized software". The first scientific subproject has been organised in 12 work packages (WPs). This paper focuses on the WP 1.5 "Development of maps with earthquake-induced environmental effects", which deals with the analysis and assessment of landslide, liquefaction and tsunami hazards in the Ionian Islands in order to reveal and highlight sites of significant earthquake-related hazards. The applied methodologies and the achieved results in the frame of the WP 1.5 are presented in this paper.

2. METHODOLOGY

The liquefaction susceptibility assessment included (a) inventory of liquefaction phenomena induced by historical and recent earthquakes, (b) geological and geotechnical reconnaissance of all areas prone to liquefaction phenomena and (c) application of a liquefaction hazard assessment in a Geographic Information Systems (GIS) environment.
The landslide susceptibility assessment included (a) inventory of slope movements induced by all known earthquakes in the Ionian Islands, (b) geological and geotechnical reconnaissance of all areas prone to landslide phenomena and (c) application of the Analytical Hierarchical Process (AHP) used along with the Weighted Linear Combination (WLC) method in the frame of a multi-criteria decision analysis.
The tsunami hazard assessement along the coastal areas of the Ionian Islands included (a) inventory of tsunamis induced by all known earthquakes in the Ionian Islands, (b) generation of a TanDEM-X elevation model of the Ionian Islands based on data produced by TanDEM-X and TerraSAR-X satellite pair, which was used in the next steps for the detail tsunami hazard assessment, (c) geological and geotechnical reconnaissance of all coastal areas exposed to tsunami effects, (d) assessment of the maximum tsunami run-up based on historically reported and instrumentally recorded maximum tsunami run-ups in the Ionian Islands (e.g. tsunami run-ups induced by the 1867, 1899, 1914, 1915 and 1948 earthquakes), (e) detailed definition of inundation zones based on different possible tsunami run-ups (0-5.0, 5.1-10, 10.1-15, 15.1-20 m) and (f) assessment of the building vulnerability and damage in case of tsunami generation.

3. RESULTS

Based on the methodology applied for the assessment of susceptible areas to liquefaction we reached at the next findings (Figure 1a):

- In Kerkyra Isl., the highly susceptible areas are composed of recent coastal deposits, recent and old dunes, while medium susceptibility is associated with recent alluvial deposits along river beds and river banks.
- In Paxoi, Antipaxoi and Meganissi islands the susceptibility of the geological formations is low.
- In Lefkada Isl., the highly susceptible areas consist of Holocene coastal and lagoonal deposits, while Holocene alluvial deposits, terra rossa and lake deposits are characterized by medium susceptibility.
- In Cephalonia Isl., the medium susceptible areas consist of Holocene alluvial deposits and alluvial fans.
- In Ithaci Isl., the medium susceptible areas comprise Holocene alluvial deposits.
- In Zakynthos Isl., the highly susceptible areas are composed of Holocene coastal deposits, while the medium susceptible areas of Holocene alluvial deposits.

Based on the results of the aforementioned methodology for the landslide susceptibility assessment we found that (Figure 1b):

- In Kerkyra Isl., the highly and very highly susceptible areas correspond mainly to the morphological discontinuities along active faults in the central and southern part of the island.
- In Paxoi and Antipaxoi islands, the values of LSI are very low and thus there are no susceptible areas.

- In Lefkada Isl., the highly and very highly susceptible areas are the abrupt coastal slopes and scarps in the western part of the island as well as along morphological discontinuities formed along the Ionian Thrust [4] and along active faults in the eastern and southeastern part of the island.
- In Cephalonia Isl., the highly and very highly susceptible areas are observed along morphological discontinuities formed by the Agia Efimia fault and the Kontogourata-Agonas fault in the northern part [2], the Aenos fault zone in its middle part and the Paliokastro fault [2] in its southeastern part.
- In Ithaci Isl., highly susceptible areas are observed along morphological discontinuities attributed to active faults and inactive tectonic structures in the northern part of the island.
- In Zakynthos Isl., high and very high values of the LSI are mainly presented along active and possible active faults and their morphological discontinuities. More specifically, along a possible active fault in the middle of the island, along the Kamaroti fault zone and the Keri faults [5] in the southern part of the island and along the slopes of Mt Skopos located in the eastern part of Zakynthos, where the majority of the slope movements induced by historical and recent earthquakes is observed [5]. High susceptibility is also observed along coastal slopes in the western Zakynthos such as in Navagio area.

Based on the methodology applied for the tsunami hazard assessment, inundation zones (Figure 1c) were defined based on the maximum tsunami run up along the coastal areas of the Ionian Islands:

- In Kerkyra Isl., significant inundation zones are observed in the northern part of the island (Sidari, Astrakeri, Agnos, Roda and Acharavi areas), along the entire central eastern and southeastern coastal areas (Kontokali, Kerkyra town, Messonghi, Lefkimmi, Kavos areas) and along the western coastal areas (Megas Choros, Palaeokastritsa, Agios Georgios bay and Afionitika-Agios Stephanos areas).
- In Paxoi Isl., the inundation zone with the maximum run up of 5 m extends along the perimeter of the island, while its maximum inland extend of 400m is observed in the southern part of the island.
- The maximum elevation of the Antipaxoi Island does not exceed 5 m. Thus, the entire island is expected to be attacked by a tsunami with maximum run-up of 5 m.
- In Lefkada Isl., the maximum inland extend of the inundation zone is observed in the northern part of the island and especially along the coastal part of Lefkada town. Inundation zones are also detected along the eastern coastal Lefkada (Nydri area) and in southern Lefkada (Vassiliki village). In Meganissi, inundation zones are observed in the eastern part of the island (east of Vathy Bay).
- In Cephalonia Isl., inundation zones with small inland extend are observed along the entire eastern coastal part. Inundation zone with large inland extend of about 300 m is observed in Sami coastal area. Inundation zones with smaller inland extends are also observed in Agia Efimia, Antisamos and Poros coastal areas. In southern Cephalonia, Lefkes port and Skala coastal areas are also exposed to tsunami hazard. In western Cephalonia, the coastal areas from Lixouri to Livadi swamp and from Argostoli bay to Platis Gialos beach constitute extensive inundation zones.
- In Ithaci Isl., its eastern coastal part (Vathy area) is characterized by a gentle morphology with low-angle slopes. Thus, it is highly susceptible to tsunami waves with inundation zones with maximum inland extend of 150 m for a maximum run-up of 5 m.
- In Zakynthos Isl., the coastal area from Zakynthos town to Argasi and the area around the cape Geraki form extensive inundation zones. The coastal zone of Laganas bay is another extensive inundation zone, while zones with smaller inland extend are also observed in western Zakynthos.

4. CONCLUSIONS – DISCUSSION

The mapping of the earthquake environmental effects by using various methods has become significant in recent years due to the fact that among others it serves as a valuable tool for revealing and highlighting sites of significant earthquake-related hazards. The abovementioned approach can contribute to the reduction of the vulnerability of island and mainland urban areas against earthquakes and the earthquake-induced effects on the natural environment and as a result to the reduction of the earthquake disaster risk and the

subsequent risks of the earthquake environmental effects. Many more island and mainland regions can benefit from this study as it could constitute a basic guide for the future urban design and planning and the sustainable local development since all competent to the prevention and management of natural disasters can be informed and guided. For developing modern and novel risk mitigation strategies, it is fundamental to emphasize the role and the contribution of the earthquake environmental effects on the assessment of the national and regional seismic hazard.

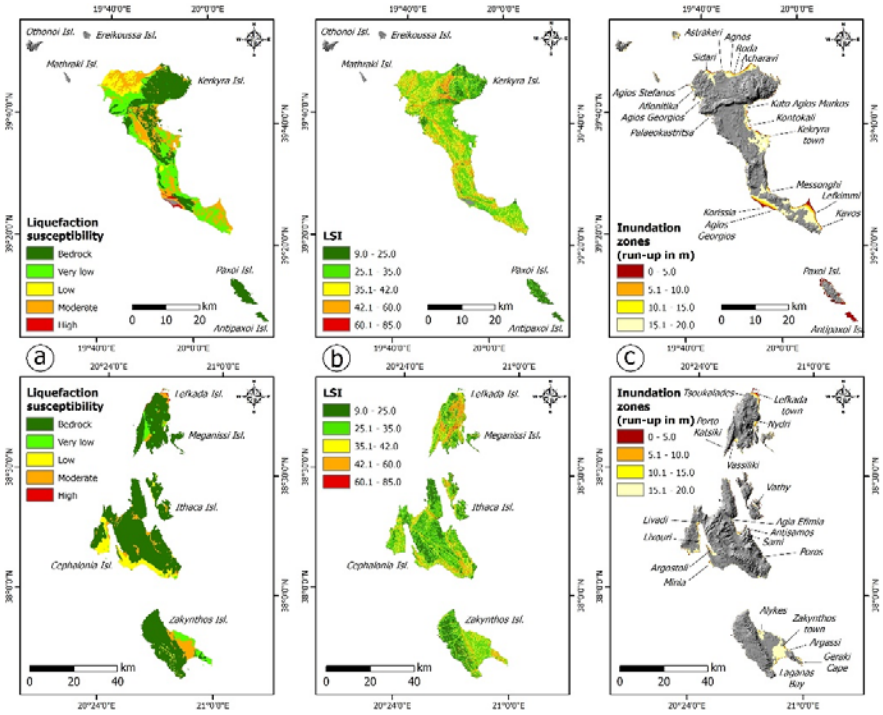

Figure 1. (a) The liquefaction susceptibility map, (b) the landslide susceptibility map and (c) the inundation zone map for the Ionian Islands.

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