The EU SEAHELLARC project: aims and main results

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ABSTRACT The SEAHELLARC project, supported by the European Commission, aimed at evaluating and computing seismic hazard and risk, as well as modelling tsunamis for the town of Pylos, in the western Peloponnese and neighboring region. This paper describes the main scopes and results of the project.

Key words: seismicity, OBS network, seismic hazard, seismic risk, tsunami, Peloponnese, SEAHELLARC.

1. Introduction

Between Pirgos and Pylos (western Peloponnese), the western domain of the Hellenic Arc has repeatedly been affected by large magnitude earthquakes which caused severe destruction and even human loss. Some of the largest regional tsunamis in the Mediterranean Sea have been reported within this area in association with large earthquakes affecting remote coastal areas; many other earthquakes have caused local, but strong, tsunami waves.

This area of Greece (Fig. 1), with its extensive coastal zones, is economically important for its tourist and agricultural activities and despite significant progress in construction and earthquake engineering standards, its population growth and extensive urbanization have caused the risk from earthquakes to significantly increase during the last years. Large quantity of existing buildings were constructed before the introduction of Greece's first building code in 1959, and are therefore vulnerable. This situation requires urgent solutions for an effective risk management and mitigation plan.

The 6th Framework Programme on Research, Technological Development and Demonstration of the European Commission funded the project "SEismic and tsunami risk Assessment and mitigation scenarios in the western HELLenic ARC" (SEAHELLARC). The project started in June 2006 and ended in November 2009.

The main aim of the SEAHELLARC project was to develop a new approach in assessing seismic and tsunami hazards by combining geological, geophysical and engineering researches and by using new hardware. The coastal zone of western Peloponnese was used as a pilot area since the south-western Peloponnese margin is one of the most seismic and tectonic active regions of Europe [see SEAHELLARC Working Group (2010) for the preliminary results].
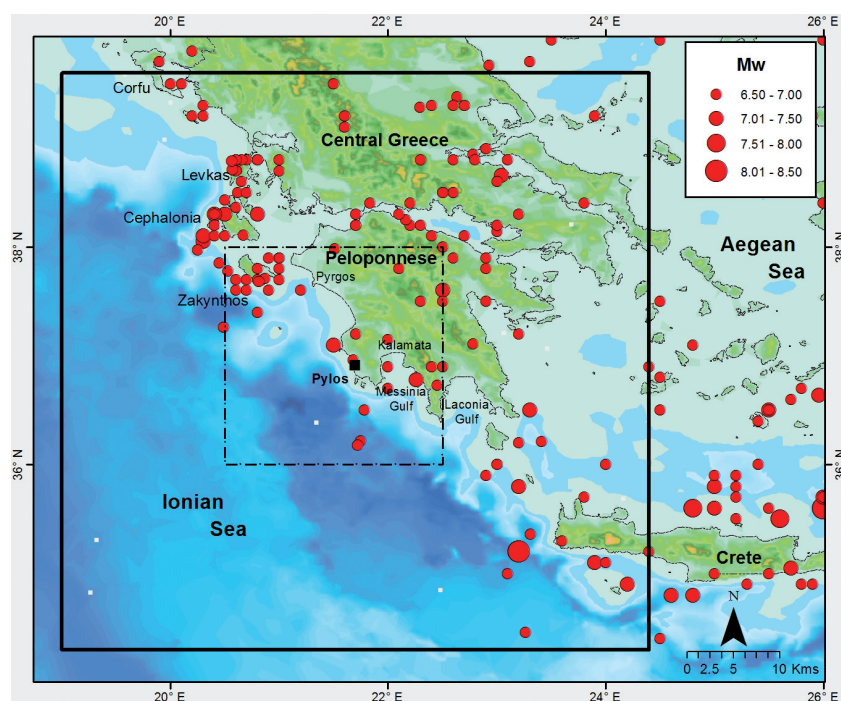
Fig. 1 - Map of the study region: the large solid square indicates the area where seismicity and tectonics were studied (study region), the small dot-dashed square shows the area where seismic hazard was assessed (Pylos broader area). The epicentres of the earthquakes with an $M_W \geq 6.5$ in the SEAHELLARC catalogue are reported as well.

Motivation to undertake this project was the necessity to develop technological tools, which permit to define accurately, and in near real time, seismological parameters in offshore areas. Monitoring seismicity at sea is currently still underdeveloped and almost all seismic networks are land based. Consequently locating seismic parameters at sea is to a great extend biased and systematically wrong. This significantly affects the assessment of seismic hazard and risk in coastal zones.

In the U.S., Japan, and Russia, research Institutes are seriously engaged in developing technology and analytical methods that can address the above issues. The knowledge and expertise developed from the implementation of the project is thus not only of local importance but can be applied to other countries around Mediterranean Sea for better safety of population and constructions as well as for reduction of vulnerability to consequences of earthquakes and tsunami.

2. Project structure

In addition to the management (Work package 1), the research tasks of SEAHELLARC were divided into seven scientific work packages with principal goals and objectives as follows:

- **WP2: Active seismic experiment.** The main objective of WP2 was to develop accurate velocity models of the crustal basement and sedimentary cover offshore south-western Greece,

by applying the technique of "Wide Aperture Reflection Refraction Profiling" (WARRP) and using node technology. Using velocity models and depth migration of seismic data we were able to delineate the main faults at depth and to associate them with the tectonic processes of western Greece. In addition, the active seismic experiment was essential for defining the boundaries between the continental domain of western Greece and the oceanic domain of the deep Ionian Sea (Makris and Papoulia, 2014).

- **WP3: Microseismicity.** Aim of WP3 was to study the microearthquake activity of the Kyparissiakos Gulf, in south-western Peloponnese, using local "amphibious" [composed by ocean bottom seismographs (OBSs) and stand-alone land stations] seismic networks. More than 3,500 seismic events, above a threshold M_L magnitude of 0.3, were recorded in a two-month period. The high quality of the seismic data helped in locating the active faults and defining reliably focal mechanisms (Papoulia *et al.*, 2014). Thus it was possible to better assess the tectonic deformation at the continent ocean transition between western Peloponnese and the bordering Mediterranean Ridge.

- **WP4: Bathymetry Swath mapping, sub-bottom profiling, high-resolution seismics.** The objectives of WP4 were to produce a series of maps and interpreted seismic sections depicting the detail of the morphology, the shallow (sedimentary) structures and the tectonic framework of the western Peloponnese continental margin (Barison *et al.*, 2014; Camera *et al.,* 2014; Fountoulis *et al.*, 2014; Wardell *et al.,* 2014). The final goal was to produce reliable documents to better locate active faulting able to potentially generate important ruptures and subsequent onshore catastrophic events (earthquakes and tsunamis). During the study we also discovered that local, and potentially dangerous, tsunamis may also be triggered by relatively large-scale sedimentary submarine destabilizations that have to be taken into account in any risk assessment scenarios. In the same area in progress, syn-sedimentary faulting can be detected along the shelf edge; this process could trigger future sedimentary collapse and local tsunamis.

- **WP5: Seismic hazard assessment.** Aim of WP5 was to assess seismic hazard at the top level of the present knowledge, also on the basis of a revision of the historical and recent earthquakes (Papadopoulos *et al.*, 2014a). This goal was reached thanks to new data from the passive and active experiments (WP2, WP3 and WP4), the revision of the earthquake catalogue, and the multidisciplinary interpretation of all available geophysical data. In such a way, the seismogenic sources that determine the seismicity of the western Peloponnese were delineated (SEAHELLARC Working Group, 2014) and the seismic hazard estimated accurately together with the uncertainties involved in the computation (Slejko *et al.*, 2014).

- **WP6: Tsunami modelling.** Tsunami modelling was one of the essential components of tsunami investigations. WP6 was dedicated to use this tool for: i) identifying the main tsunamigenic sources (Papadopoulos *et al.*, 2014b), ii) understanding the mechanisms of tsunami generation in the project region, iii) assessment of the tsunami potential, iv) determination of the tsunami hazard in the Pylos region. During the WP6 activities, the tsunami modelling and hazard analysis were performed using the selected tsunami scenarios generated by seismic or non-seismic (submarine landslide) sources. The results of simulations were extended to western Greece from Pylos to Zakynthos (covering the coastal towns of Pylos, Filiatra, Kyparissia and Zakynthos). Inundation maps for each town were plotted using simulation results of the selected tsunami scenarios (Yalçiner *et al.,*

2014). These were achieved in close cooperation with other team members who assessed the seismic hazard in the area and provided high-resolution bathymetric data.

- **WP7: Risk mitigation and earthquake scenarios.** The main goals of WP7 were: i) to develop, for the first time, vulnerability functions for Greek low-rise building structures based on the rich experience of the last two and a half decades; ii) to use these results to derive potential losses in the study zone (the town of Pylos) from future earthquakes and iii) to examine the potential effect of realistic vulnerability mitigation policies by assessing their cost-benefit potential. These goals were achieved (Pomonis and Gaspari, 2014; Pomonis *et al.*, 2014).

- **WP8: Real time seismology and tsunami observations.** The goal of WP8 was to develop a near real time network for onshore/offshore operations. Marine stations were additionally equipped with pressure sensors that allowed recording tsunami and tidal effects and transmitting these data in near real time (Makris *et al.*, 2014). This information can be integrated in a warning system for tsunamis and earthquakes in order to protect lifelines and sites of public importance.

3. Progress in science

The most important achievement of the SEAHELLARC project was the integration of multidisciplinary and multiscale geophysical data (from seabed map to deep crust and upper mantle images) to better understand the overall structure, tectonic and geological hazards on an active margin segment. The SEAHELLARC partners strongly believe that this segment of the western Peloponnese margin can be thereafter regarded as a model of data integration.

More specifically, the following achievements were successfully reached.

- The crustal structure between the Mediterranean Ridge and the western Peloponnese was imaged for the first time with a very high resolution. The new acquired and processed seismic lines were essential for understanding the geological development at the collision front between the Ionian oceanic domain and the thinned continental crust of western Greece. Until recently crustal models of this area were unreliable and very sparse. Thanks to the SEAHELLARC project we succeeded in producing geological models that explain most the tectonic structures and processes.

- The large number and narrow spaced shot points and ocean bottom seismographs, reduced with wave equation procedures to a common datum, has allowed to obtain near vertical reflection profiles and reflectivity images of the structures. These may help to improve the geological models for the analysis of collisional mechanisms and provide a key indication of areas where earthquakes and tsunamis can potentially be generated.

- By combining an "amphibious" network of 17 OBSs and 17 land stations we recorded the local seismic activity of the western Peloponnese continental margin and along the eastern domain of the oceanic Ionian Sea. In two months of field observations, 3,500 events were recorded. The seismicity appears confined along a few major tectonic elements delineating thrust belts and strike-sleep faults. For the first time we were able to map sub-crustal events extending to nearly 100 km depth and close from the collision front of the backstop. For the first time it could be demonstrated by field observations that the subducted slab

of the Ionian oceanic lithosphere below the western Peloponnese is affected by important fractures that disrupt the oceanic lithosphere. Due to the high accuracy of micro earthquake activity location the active deformations occurring at the level of the crust and within the sediments were also accurately delineated.

• Seismic hazard for the south-western Hellenic Arc was computed according to the most updated approach (the logic tree approach, that incorporates both aleatory and epistemic uncertainties involved in the computation) and considering a new seismogenic zonation, established during the SEAHELLARC project on the basis of the results of passive and active experiments. The soil seismic hazard map defined for the town of Pylos represents a accurate basis for the consequent risk assessment. Moreover, the seismic sources, that have generated or could generate tsunami, were identified and characterized from the geographical and seismic point of view.

• Development in tsunami modelling was achieved by introducing new modules as follows: i) using multiprocessor capability of computers (faster computations for operational purposes), ii) solving larger domains with finer grid size (accurate computations for academic purposes), iii) computing important tsunami parameters in inundation zone for better understanding of tsunami effects, and iv) accelerating 3D visualization capability for making the results to be more informative.

• The tsunami simulations due to all critical seismic sources and also due to a submarine landslide in the Kyparissia region are performed. The evolution of the wave due to landslide motion is simulated by using a two-layer model which specifically solves the motion of landslide and adjacent water body. It is also coupled with the numerical model which solves the tsunami propagation, coastal amplification and inundation. The comparison of the tsunami near shore parameters among the results of all simulations showed that submarine landslide with 50 m thickness can cause 10 m height of tsunami in the nearshore zone with the arrival time of less than 10 minute in the Kyparissiakos Gulf.

• A new damage database from earthquakes in Greece was developed. It contains data on damage to 29,000 buildings affected by four recent earthquakes in western Greece (1986-2008). A thorough homogenization of the data has been carried-out so that these would be useful for the derivation of empirical vulnerability functions for all the types of low-rise building structures that exist in the western Peloponnese. The European Macroseismic Scale (EMS) was used as the common denominator for intensity estimation.

• An "amphibious" network for near real time seismicity observations was established on/ offshore the western Peloponnese. The marine station is a new development that permits to record earthquakes and tsunamis. The marine system transmits the seismic and pressure data in real time by GPRS connection of locale mobile phone networks. Data can also be transmitted by radio link if the distance to the coast does not exceed 70 km. One permanent seismic station equipped with a broad band seismometer was installed on the remote Island of Strophades. Seismic data transmission was established by satellite connection. The seismic array recordings are transmitted to a central recording station and are available, in real time, through the Internet at any location. This technical solution is economic and can be extended to satellite communication if the marine station has to be located outside mobile phone networks.

4. Main results of public utility

The SEAHELLARC project aimed at reaching results of scientific relevance, as well as results of public utility in the frame of seismic risk reduction. This last objective can be used by policy makers as well as by users, practitioners and managers, and are summarized in the following.

4.1. Results that can be used by policy makers
- The crustal velocity models in association with the seismicity information and the tectonic elements of the SEAHELLARC area can be used in developing seismic hazard models essential for planning parts of the infrastructure of the western Peloponnese.
- The Earthquake Planning and Protection Organization of Greece can use the seismicity results, and the delineation of the active faults, in reconsidering the seismic zonation of south-western Greece.
- The seismic hazard map of the western Peloponnese represents the basis for updating the national seismic code, i.e., the guidelines for seismic designing the future buildings. The seismic risk map of Pylos identifies the areas with priority for seismic retrofitting. The tsunami scenarios could be taken as a reference for the definition of emergency plans.
- The arrival time curves, plots of tsunami height distributions, inundation maps, and basic information about the possible effects of tsunamis are of great potential use for people in charge of local governance.
- The derived vulnerability functions can be applied to all parts of Greece that lie within the 2004 Greek earthquake code zone II (where 40% of the country's population resides).
- Finally, the technical solutions provided for the real-time marine seismic station can be used in various countries around the Mediterranean Sea for seismological and tsunami warning and observations.

4.2. Results of relevance for users, practitioners and managers
- The crustal structure and the structure of the sedimentary basins are crucial for understanding the geological development of western Greece. This is also important in estimating the hydrocarbon potential offshore. The results can be used by the hydrocarbon exploration industry and the seismological community that develop seismic hazard models.
- The seismic hazard of the western Peloponnese and the eastern Ionian Sea were very accurately evaluated due to the high quality of the mapped seismicity. The seismic zonation, defined by the active faults, significantly improved the quality of seismic hazard results. The Earthquake Planning and Protection Organization of Greece, the Civil Defense, and any other instances that are involved in earthquake risk management and crisis operations, can effectively use this information.
- The results of tsunami modelling are clear and informative for better understanding the tsunami effects by the users and managers.
- In Pylos town the developed earthquake risk scenarios can be used for preparedness and mitigation by the local authorities. In addition a GIS-based buildings database for the town of Pylos has been proposed containing vulnerability assessment for more than 800 buildings.

• The developed "amphibious" system, which is now equipped with broadband sensors, can be integrated into the National Seismological Network of Greece, and extend its capacity up to the Island of Strophades.

5. Examples of results successfully used

The velocity seismic models were used for defining the distribution of the micro earthquakes offshore western Greece with a very high accuracy. In this way the active faults were well defined and earthquakes were located with accuracy of the order of 1000 metres. This has helped to increase the accuracy and resolution in producing seismic hazard models. The results were also used to constrain gravity modelling that delineated the density distribution between the Mediterranean Ridge and the western Hellenides.

The results produced by the local micro seismicity study were used to define the seismic zonation of western Greece and were implemented in re-evaluating the seismic hazard accurately. The new hazard maps are now in use for estimating the seismic risk at the small cities and habitations of the western Peloponnese.

Models for tsunami impacts on the coastal areas, 3D visualizations of the propagation and coastal amplification of selected tsunamis, inundation maps of selected scenario tsunamis are useful as basic information in preparedness plans.

The Pylos vulnerability in a building-by-building survey has been connected with QuickBird satellite imagery of the town to help, in the future, development of automatic techniques of Greek building stock attribute identification. The damage data are already incorporated in the Cambridge University Earthquake Damage Database, which is a free database for researchers worldwide and is expected to be used in the development of the Global Earthquake Model (GEM).

6. Key material/deliverables

Within the SEAHELLARC project, a densely spaced network of crustal cross sections and the geometry of the sedimentary basins were produced. This helped to develop tectonic models from the Common Station Gathers and the depth migrated seismic observations and to delineate active faults.

Detailed morphological maps of the western Peloponnese margin were provided, together with interpreted seismic and Chirp lines, and a series of maps under ArcGis files. All documents are printed in an Atlas depicting morphological and structural characteristics of the continental margin from the shelf (circa 50 m) to the deep basins (up to 4000 m water depth).

Micro seismicity and active fault maps, focal mechanisms and definition of the seismic hazard zones were established with very high accuracy for the first time for the western Peloponnese and the eastern Ionian Sea.

Plots of tsunami propagations, maps of tsunami heights, arrival time curves, inundation maps, and plots of flow depth distributions in inundation zone were developed. State-of-the-art in 3D video images are available for use in educational and training purposes.

Risk assessment and mitigation scenarios were developed, and a damage database of

earthquakes in western Greece (since 1986). EMS based vulnerability functions for Greek low-rise unreinforced stone masonry and reinforced concrete frame buildings were also developed.

Finally, a marine seismic station was designed, produced and deployed and its connection to a surface buoy that houses the power supply and electronic components. The buoy is connected by cable to an OBS placed on the sea floor recording earthquakes and pressure variations in the water column (tsunami). The buoy transmits the recorded data to an onshore station via mobile phone networks, radio telemetry and satellite connection. Software was developed for the real time connection to a regional seismological network.

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