Preliminary seismic hazard assessments for the area of Pylos and surrounding region (SW Peloponnese)

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ABSTRACT The SEAHELLARC project, supported by the European Commission, aims at evaluating and computing seismic hazard and risk, as well as modelling tsunamis for the town of Pylos, in the western Peloponnese. For this purpose, a new seismogenic zonation has been developed for the Pylos area, and broader region, and the most updated seismic hazard assessment is provided. The present paper describes preliminary seismic hazard computations performed with the scope of testing the improvements made during the project. In particular, the influence of an updated version of the Greek earthquake catalogue and of a new seismogenic zonation for the Pylos region are presented. The difference obtained for the expected ground motion, with a 475-year return period, in the town of Pylos is not significantly big (it only decreases from 0.63 to 0.56 g using literature data or the new ones, respectively). Conversely, greater differences concern the Island of Zakinthos.

1. Introduction

Although seismic risk represents a major issue for Greece, tsunami damage also constitutes a severe threat to many coastal communities. This is particularly important for the Ionian islands (Corfu, Leukas, Cephalonia, and Zakinthos) and the coastal border of the western Hellenic Arc, where earthquakes, among the largest ones known in the Mediterranean Sea, have occurred in the past.

The western border of the Peloponnese, between Pyrgos and Pylos (see Fig. 1), has been repeatedly affected by large-magnitude earthquakes that have caused severe destruction and human loss [i.e., M_W 7.3 1886 Philiatra, M_W 6.5 1893 Zante-Keri, M_W 6.5 1899 Kiparissia, M_W 7.0 1947 Pylos, and M_W 6.6 1997 Gargaliani; data taken from Papazachos and Papazachou (1997), where the reported magnitude can be assimilated to an M_W for large events]. Some of the largest regional tsunamis of the Mediterranean Sea have also been reported in association with some large earthquakes (i.e., 1630 B.C., 365, and 1866, all in the south-western Hellenic Arc), affecting near-field as well as remote coastal areas, whereas many other earthquakes have induced local but strong tsunami waves (Papadopoulos *et al.*, 2010).

This part of Greece, with its extensive coastal zones, is economically important for its touristic and agricultural activities. Despite significant progress in construction and earthquake engineering standards in the last 10 to 15 years, the population growth and the extensive urbanization have caused the earthquake risk to significantly increase. A large number of existing buildings were, moreover, constructed before the introduction of Greece's first building code in 1959, and are therefore quite vulnerable. In this context, the town of Pylos (Fig. 1) has been selected as a test site: the town, in fact, presents all the above characteristics and, being small enough, a vulnerability survey is feasible.

Seismic hazard studies for Greece have been widely developed [see Papazachos *et al.* (1993) and references therein]. Restricting our attention to the western coast of the Peloponnese and to the Ionian islands, we can find recurrence estimates for large earthquakes as well as the expected ground motion referring to some return periods. For large quakes, a maximum likelihood estimation of the seismic hazard parameters for the western coast of the Peloponnese was computed by Papadopoulos and Kijko (1991) and by Papoulia and Stavrakakis (1995). Both groups came to very similar estimates for the maximum expected magnitude [7.6+/-0.3 for Papadopoulos and Kijko (1991), and 7.5+/-0.5 for Papoulia and Stavrakakis (1995)] as well as for the recurrence intervals of events with an M_S of 6 [17.5 years for Papadopoulos and Kijko (1991), and 19 years for Papoulia and Stavrakakis (1995)] and 7 [256 years for Papadopoulos and Kijko (1991), and 276 years for Papoulia and Stavrakakis (1995)]. Considering the ground motion, a peak ground acceleration (*PGA*) value of around 0.14 g was calculated by Makropoulos and Burton (1985) in the Pylos area for a return period of 475 years by using statistics of extreme values. For the same return period, Papazachos *et al.* (1993) suggested a design ground motion of 0.46 g for the Ionian islands and 0.29 g for the western Peloponnese coastal area. Jiménez *et al.* (2001, 2003) produced a seismic hazard map of the European – Mediterranean region and calculated a *PGA* value around 0.5 g for the western coast of the Peloponnese for a 475-year return period. Changing from *PGA* to macroseismic intensity, Papoulia and Slejko (1997) calculated the seismic hazard in the Ionian islands on the basis of the observed macroseismic intensities and estimated an intensity around IX MCS with a return period of 100 years in Levkas, which is about 220 km away from Pylos. More recently, Papaioannou and Papazachos (2000) produced hazard estimates in terms of macroseismic intensity and estimated an intensity around VII-VIII MM in Pylos for the return period of 475 years.

The aim of the present paper is to introduce the SEAHELLARC project contribution and to describe the progress, concerning the seismic hazard assessment of the broader Pylos region, reached at mid-project. Some of the results discussed here were already summarized by the SEAHELLARC Working Group (2008), and are documented here in an expanded form.

2. The SEAHELLARC project

The 6th Framework Programme on Research, Technological Development and Demonstration of the European Commission has funded the project "SEismic and tsunami risk Assessment and mitigation scenarios in the western HELLenic ARC" (SEAHELLARC), whose aims were to establish a real time on/offshore network for seismic and tsunami observations and to develop an innovative methodology for seismic and tsunami hazard assessment for the safety of

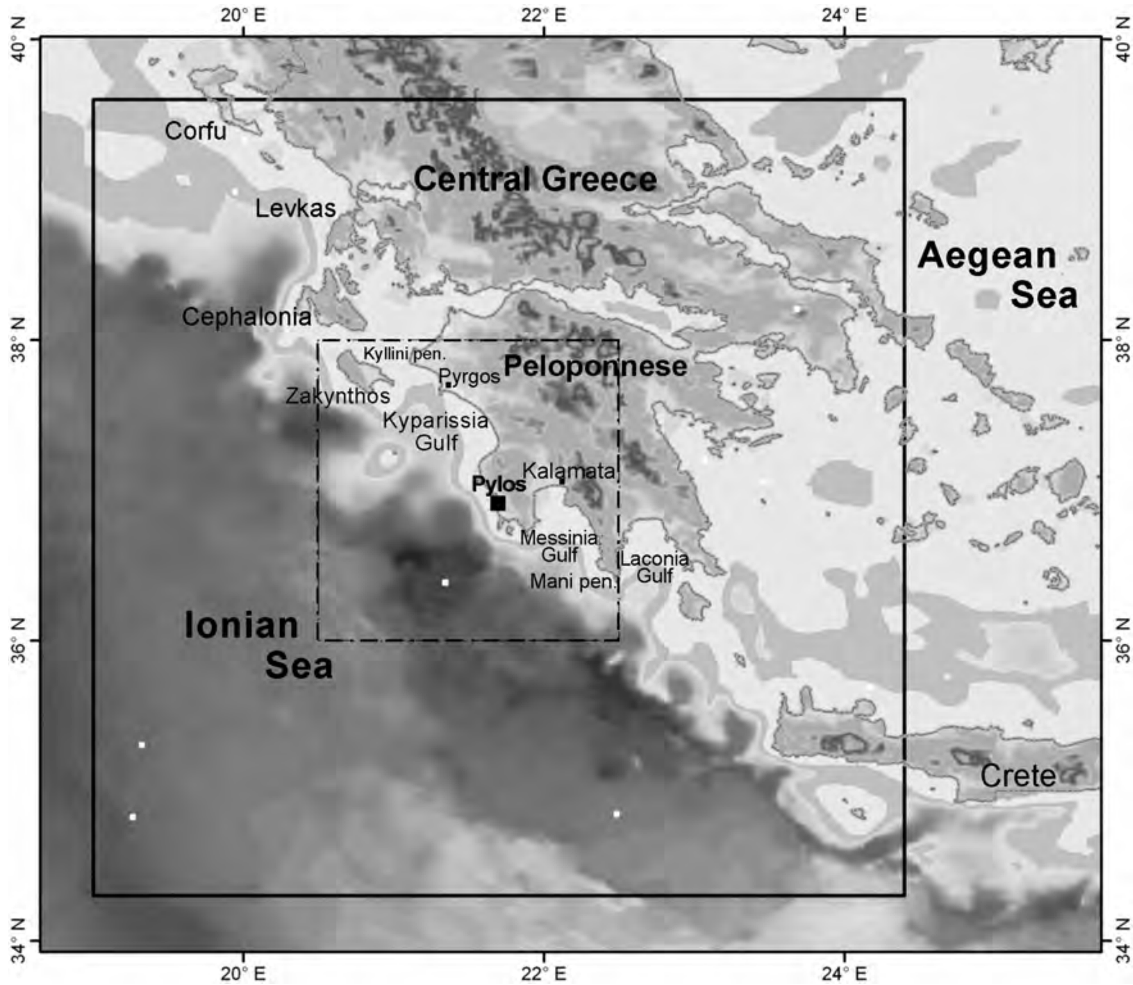

Fig. 1 - Index map of the study region. The large square indicates the area of the SEAHELLARC earthquake catalogue, where the SZs are defined; the small square identifies the area where seismic hazard has been assessed.

constructions in the coastal areas of the western Peloponnese. The project started in June 2006 and will end in November 2009. The following tasks are being performed within the project in the area of the western Peloponnese, between Zakinthos Island and Kalamata:

- establishment of an onshore/offshore seismic array and performance of an active and passive seismic study, in order to develop a 3D velocity model and to accurately define the seismogenic zones (SZs) in the onshore and offshore area;
- deployment of one marine and four land stations that record and transmit seismic data in real time. Additionally, the marine station records pressure changes at the sea floor so that tsunami phenomena can be observed;
- detailed mapping of the bathymetric features offshore the western Peloponnese, in order to define active faults, possible landslides and evaluate some lithological variations of the sea bottom;

- reprocessing and re-evaluation of former multichannel seismic reflection (MSR) data in order to refine our understanding of the overall geological structural framework of the offshore domain;
- seismic hazard assessment, considering simultaneously on/ and offshore data;
- identification of potential seismic and non-seismic tsunamigenic sources and estimation of their geometry and dimensions;
- pilot study for the area of Pylos for seismic and tsunami risk and mitigation scenarios;
- establishment of a permanent marine broadband seismic station, for integration in the permanent national seismological network of Greece.

Roughly, at mid-term project (autumn 2008), most of these tasks were at least started; some of them can be considered done. In particular, for what concerns hazard assessment directly, the passive and active experiments and the structural mapping have been performed; the results obtained are thus contributing to a more precise definition of the SZs of the Pylos broader region. In fact, in autumn 2006, a combined on/offshore seismic network, consisting of 17 ocean bottom seismographs and of 15 land-stations, was deployed in the Kyparissia Gulf and in the surrounding area of the western Peloponnese; the seismic activity was recorded for a period of 2 months. More than 3,500 earthquakes were identified, applying a local velocity model obtained from active seismic observations (Makris and Papoulia, 2010). The focal mechanism was computed for 581 earthquakes. Seismic activity is obviously associated with the active fault network of this area: the shallow seismicity is mainly confined to the continent-ocean crustal transition, approximately 70 km west of the Island of Zakynthos, onshore Zakynthos, in the Killiny peninsula, and in the area of Pylos. The orientation of these fault systems is roughly parallel to the subduction-collision front. Seismicity, associated with the deeper part of the crust, coincides with the tectonically uplifted blocks of Messinia and that of the Island of Zakynthos. Deeper crustal seismicity follows the subduction of the Ionian oceanic lithosphere below the western Peloponnese, showing constantly increasing hypocentral depths eastwards. Focal mechanisms show a dextral strike-slip in the crust and the active faults related to this deformation are perpendicular or nearly perpendicular to the subduction-collision front. The active seismic experiments and the reprocessed MSR data, both of which independently provide pieces of information on the geometry of the sediments and of the crust, clearly show that the internal Alpine Hellenic zones are thrust over the external ones and that the uplifted units, exposed on the Island of Zakynthos and around the Messinia peninsula, consist of uplifted and faulted blocks made of former Alpine thrust belts.

3. Seismotectonic framework of the Pylos broader region

The main geodynamic features of the south-western Hellenic coastal area are given by the thrust faulting (horizontal compression) due to the subduction of the Ionian oceanic crust towards the convex side of the south-western Hellenic Arc, and to the thrusting related to the interaction between two continental lithospheres on the seismic zone along the western coast of central Greece and Albania. These two compressive belts are connected by the Cephalonia dextral transform fault that runs along the Ionian Islands (Papazachos *et al.*, 1993).

The Pylos broader region is thus located between a subduction zone, to the south, and the Cephalonia transform fault zone, to the north, one of the most seismically active areas of the Mediterranean. The Cephalonia transform fault zone is NE-SW-oriented and has a remarkable right-lateral component; it runs about 155 km along the western coasts of Cephalonia and Levkas Islands (Sachpazi *et al.*, 2000) and the main, earthquake associated to it is the M_W 7.4 1867 event that caused extensive damage on the islands (Papazachos and Papazachou, 1997). The Cephalonia transform fault zone is subdivided into two segments: the Levkas fault to the north and the Cephalonia fault to the south. The Levkas fault is characterized by a strike-slip motion with a thrust component, striking in a N-NE direction, diping E-SE and has a length of 40 km; the main, recent earthquake occurred on August 14, 2003 with an M_W 6.2 (Louvari *et al.*, 1999; Papadopoulos *et al.*, 2003; Karakostas *et al.*, 2004; Papadimitriou *et al.*, 2006; Benetatos *et al.*, 2007). The Cephalonia fault exhibits a strike-slip motion with a thrust component, strikes in a NE direction, dips to the SE and has a length of about 90 km; the main recent earthquake occurred on January 17, 1983 with an M_W 6.2 at its southernmost part (Louvari *et al.*, 1999). Events with an M_W larger than 6 occurred however along the whole transform fault zone [see also Baker *et al.* (1997)]. A NW-SE-oriented thrust (Papazachos *et al.*, 2004) has been identified from seismic profiles offshore the south-western coast of Zakinthos. It is about 66 km long and several earthquakes with an M_W larger than 6 are associated with this structure. A specific consideration must be given for two large events located in the easternmost sector of Cephalonia Island: the M_W 6.8 1912 and the M_W 7.3 1953 quakes. Although the epicentral location of these two events is different in the SEAHELLARC catalogue, Stiros *et al.* (1994) locate the 1953 epicenter within the south-easternmost part of the island, where the 1912 event also occurred, according to the damage reported (Papazachos and Papazachou, 1997).

The north-western corner of the Peloponnese is itself characterized by the NNE-SSW-trending right lateral Andravida transcurrent fault also identified offshore from seismic profiles and expressed onshore by clear geological evidence. It is a major fault more or less parallel to the Cephalonia one and 136 km long. The M_W 6.4 earthquake of June 8, 2008 (Koukouvelas *et al.*, 2009) was located not far from the northern edge of this fault system and its focal-mechanism is consistent with a strike-slip faulting, similar to that occurring within the NE-trending zones.

The present morphology of the southern Peloponnese has been determined by the recent opening of the Messinia and Laconia gulfs. Their thrusts have been identified from seismic profiles (Papoulia *et al.*, 2001) and from MSR data during the project and seem to presently act as normal faults do. A NNW-SSE-oriented, 111 km long, thrust, which may have ruptured in 1886 with the M_W 7.5 Filiatra earthquake that destroyed more than 100 villages (Papazachos and Papazachou, 1997), exists offshore the Messinia peninsula. The 1947 M_W 7.0 Messinia earthquake which caused serious damage in 54 settlements in the Pylia province is also worth mentioning: this event was originally located along the eastern coast of the Messinia peninsula (Galanopoulos, 1949). A 70 km long, NNW-SSE-trending fault has been imaged by seismic profiles offshore the eastern coast [see also Mariolakos and Papanikolau (1981) and Fountoulis (1994)] and is likely associated with the M_W 6.8 1642, M_W 6.7 1842, and the M_W 6.6 1846 earthquakes: all those events caused damage over a wide area including Kalamata town. In addition, the Kalamata fault represents a minor, NNW-SSE-oriented normal fault located along the previous thrust front of the Hellenic nappes and runs along the western coast of the Mani peninsula; its northernmost part outcrops on land and has been associated with the M_W 6.0 1986 Kalamata earthquake (Pavlides and Caputo, 2004). Finally, also worthy of note is the presence, on the northern edge of the Messinia peninsula, of an E-W-oriented, 27 km long, Kyparissia active fault, also tentatively identified on offshore seismic profiles (Papanikolaou *et al.*, 2007) as well as from geological land evidence: anyway, its length does not support the likelihood of large magnitude quakes happening.

4. Preliminary seismic hazard assessments of the Pylos broader region

Since Cornell (1968), who published the first theoretical bases of the seismotectonic probabilism, and since scientists from the U.S.G.S. adopted Cornell's (1968) approach in computer codes (Algermissen *et al.*, 1976; McGuire, 1976; Bender and Perkins, 1987) small improvements have been made in probabilistic seismic hazard assessment (PSHA). In recent years, efforts have been particularly devoted to better quantify the uncertainties involved in hazard computation (McGuire, 1977; McGuire and Shedlock, 1981; Toro *et al.*, 1997). Finally, a logic tree approach (Kulkarni *et al.*, 1984; Coppersmith and Youngs, 1986) has been established to handle this problem.

One of the goals of the SEAHELLARC project was, first to develop a new seismogenic zonation for the Pylos broader region, by taking into account previous seismogenic zonations, and secondly, to characterize this new zonation using revised seismological data. For this reason, preliminary attempts have been produced to assess seismic hazard in a homogeneous way considering i) data available from literature, and ii) improving the literature data with new results.

The tectonic framework of the Hellenic Arc implies also that deep seismogenic structures should be taken into account for any seismic hazard assessment. A computer code, suitable for modelling seismogenic sources of different kinds of deep geometry, is the CRISIS code (Ordaz *et al.*, 2003), which allows the use of subduction planes, thus this software was chosen for the seismic hazard assessment in the SEAHELLARC project.

All seismic hazard maps refer to a horizontal *PGA* with a 475-year return period, standard reference for seismic design, on rock. The magnitude scale used to characterize the seismicity is M_S, which can be considered equivalent to M_W for values larger than 6.0 (Reiter, 1990).

4.1. The first step: PSHA using data from literature

A preliminary application of the CRISIS package (Ordaz *et al.*, 2003) was performed using parameters extracted from literature. More precisely, Papazachos and Papazachou (1997) and Papaioannou and Papazachos (2000), revising the work of Papazachos (1990), considered surficial (between the surface and 60 km depth), intermediate (between 60 and 100 km depth), and deep (between 100 and 160 km depth) SZs for their seismic hazard assessment of Greece. For our study area, we used the SZs (Fig. 2a) of Papazachos and Papazachou (1997), for a total of 18 surficial SZs (modelled by a horizontal plane at a 30 km depth), 2 intermediate ones, and 1 deep SZ (Fig. 2b); the seismicity parameters (*a*- and *b*-values, and maximum magnitude) were taken from Papaioannou and Papazachos (2000) and from Papazachos *et al.* (1993). The seismicity parameters of Papaioannou and Papazachos (2000) refer to a value larger than, or

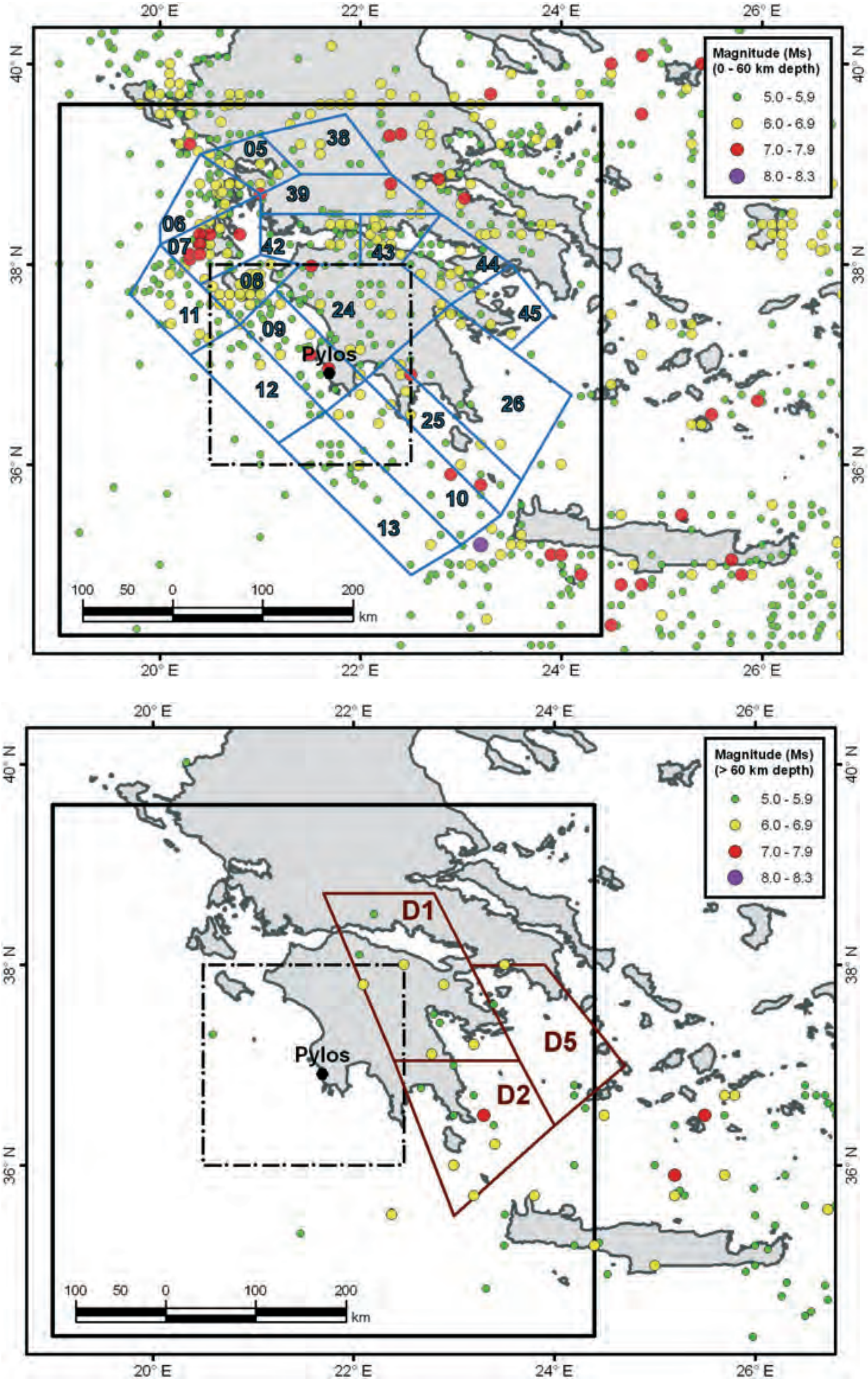

Fig. 2 - Seismogenic zonations from literature used for the preliminary PSHA: a) surficial SZs (from Papazachos and Papazachou, 1997); b) intermediate (D1 and D2) and deep (D5) SZs (modified from Papazachos and Papazachou, 1997). The large square indicates the area of the SEAHELLARC earthquake catalogue, where SZs are defined; the small square identifies the area where seismic hazard has been assessed.

equal to, 5 in a magnitude scale considered by the authors equivalent to M_W; in our study they are considered equivalent to M_S as a slight difference between the two scales would interest only the narrow interval 5 to 6.

The choice of the attenuation relations required a specific analysis because of the way it is treated by the CRISIS code (Ordaz *et al.*, 2003).

Several possible attenuation relations have been proposed for Greece (Theodulidis and Papazachos, 1992, 1994; Papazachos *et al.*, 1993; Papaioannou and Papazachos, 2000; Margaris *et al.*, 2002; Skarlatoudis *et al.*, 2003, 2004b). In particular, Papazachos *et al.* (1993) have proposed different *PGA* attenuation relations for surficial, intermediate (along the axis of the Hellenic Arc), and deep (inner part of the Hellenic Arc) earthquakes with reference to a stiff soil. These relations derive from a previous work by Theodulidis and Papazachos (1992), where a similar relation was defined for rock and where the standard deviation, missing in Papazachos *et al.* (1993) study, was provided.

The CRISIS code (Ordaz *et al.*, 2003) requires a table with *PGA* vs. epicentral (or hypocentral) distance values and then computes the site-to-source distance and takes the related attenuated *PGA* value. When using the epicentral distance, putting the SZ at the surface or at depth makes no difference. Some tests that we did indicated that the Papazachos *et al.* (1993) relation for intermediate events refers to an average depth of 115 km while that for deep events, refers to an average depth of about 125 km; in the CRISIS code (Ordaz *et al.*, 2003) they can be substituted by the relation used for surficial events when the SZ is located at its actual depth.

In the present work, the Theodulidis and Papazachos (1992) attenuation relation for surficial earthquakes (defined for events with a focal depth of less than, or equal to, 18 km) has been used with reference to rock. The hypocentral distance was considered for all the surficial, intermediate, and deep SZs, because these SZs are modelled with planes deeper than 20 km.

The resulting hazard map is shown on Fig. 3. It can be seen that Pylos and its neighbourhood are characterized by *PGA* values between 0.56 and 0.64 g, while values exceeding 0.80 g are expected on Zakinthos Island (in its northernmost part values larger than 0.88 g are even forecasted).

Considering the test site of Pylos, Fig. 4 shows the complete seismic hazard curve, where it is possible to observe that for a 475-year return period (annual exceedence probability of 0.0021) the expected ground motion is 0.63 g.

4.2. The second step: PSHA with seismogenic zonation derived from the literature and new seismicity data

Up to the mid 19^{th} century, information on earthquakes came mainly from macroseismic effects of large shocks. In 1911, a first seismometer was installed in Athens and since then modern seismometers have been operating continuously. In the 1950s, the first seismological stations of the permanent network were installed in Greece, and in the following decades the first telemetric network of seismological stations and the network of strong motion instruments were established (Papazachos and Papazachou, 1997).

The catalogue used in the present study derives from three data files: (1) the historical earthquake catalogue of Greece, which covers the period between 550 BC to 1963 (Papazachos and Papazachou, 1997), (2) the instrumental earthquake catalogue of Greece, which covers the period from 1964 to 2006, and (3) the recent earthquake locations from 2007 to April 2008. All

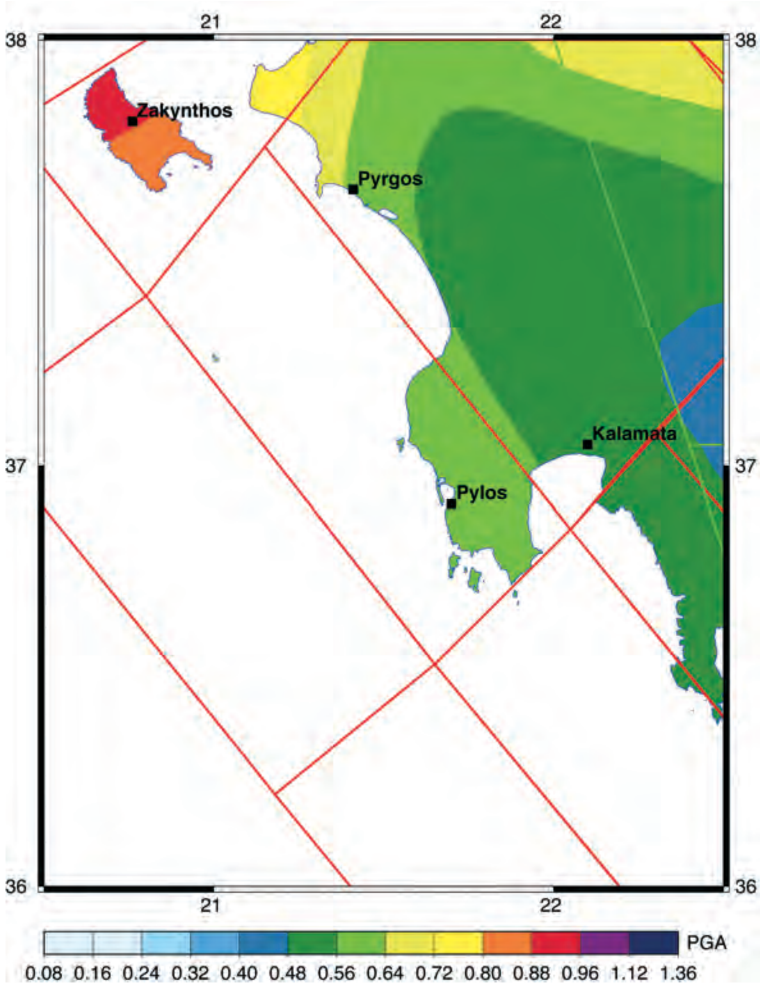

Fig. 3 - Rock seismic hazard of the Pylos broader region in terms of *PGA* with a 475-year return period computed with data from literature [Papazachos and Papazachou (1997) seismogenic zonation and Papaioannou and Papazachos (2000) seismicity parameters].

3 files were compiled at the National Observatory of Athens (NOA). All the main historical events from the catalogue were revised during the SEAHELLARC project by scientists from NOA. Special investigations were carried out for strong earthquakes which occurred within a 300 km distance from Pylos town.

The instrumental seismicity was also revised, and a lot of events were relocated, especially for the last decade. All events in the catalogue contain a magnitude estimate according to the M_S scale. From 1911 to 1963 the magnitude was calculated at NOA using Mainka and Wiechert instruments which belong to the intermediate period (~6-8 s) and therefore, provide a magnitude equivalent to M_S directly. After 1963, the local magnitude, M_L, was determined from maximum amplitudes recorded by real Wood-Anderson instruments. The empirical formula $M_S = M_L + 0.5$ (Papadopoulos, personal communication) has been used to transform M_L into M_S. We deduce that the catalogue is not homogeneous in the way that magnitude was estimated in the two periods:

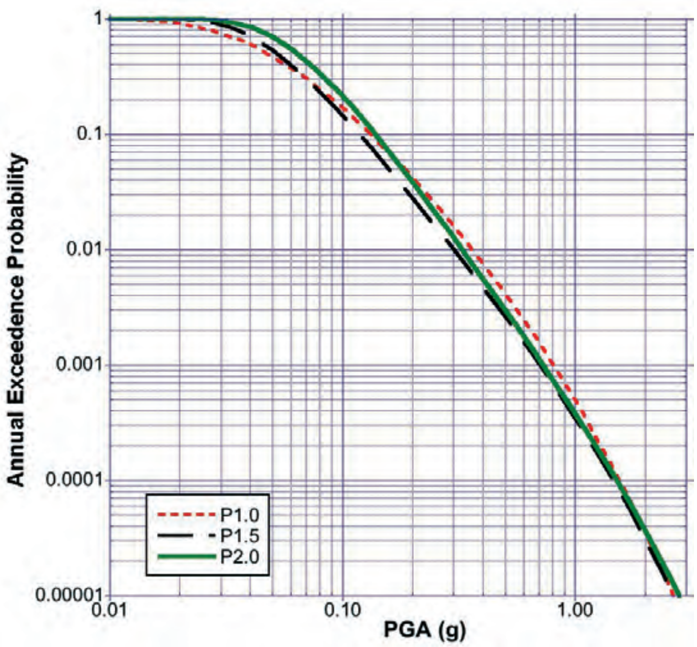

Fig. 4 - Seismic hazard curve for the town of Pylos. The short dashed line represents the results obtained through literature data (Papazachos and Papazachou, 1997; Papaioannou and Papazachos, 2000); the long dashed line shows the results with the SEAHELLARC earthquake catalogue and the Papazachos and Papazachou (1997) seismogenic zonation; the solid line indicates the results with the SEAHELLARC catalogue and zonation.

before 1963 and after 1963.

The resulting catalogue consists of 70,644 events that occurred from 550 BC to April 2008. The minimum magnitude in the catalogue is M_S 1.7, but the catalogue is extremely poor for events before 1400 (Fig. 5a), and almost only earthquakes characterized by a magnitude larger than 6 are reported before 1800. An improvement of the data acquisition from 1900 is evident (Fig. 5b), but low magnitude events are reported only after 1964. The quality of the location also improved with time and acceptable depth estimates seem to be available only for the last few decades.

The first step in compiling an earthquake catalogue, in view of its use for a seismic hazard assessment following Cornell's (1968) approach, is to eliminate foreshocks and aftershocks. In the present study, the removal of the dependent events was done according to the Gardner and Knopoff (1974) approach: i.e., by applying a space - time window calibrated on Greek seismic sequences (Latoussakis and Stavrakakis, 1992). In such a way, 31,518 dependent events were eliminated from the catalogue and the final data file used for hazard estimates (hereafter SEAHELLARC catalogue) include 39,126 events with an M_S larger than 1.7. A test has been performed to verify that the declustered catalogue obtained, follows a Poisson distribution. We have considered events with an M_W larger than, or equal to, 6.5, for which the catalogue had enough documentation covering the last 300 years. One-year intervals have been considered and the events in each interval have been counted. The resulting value of the χ^2-test [accepted test for binned distributions (Press *et al.*, 1992)] is equal to 0.77, corresponding to a significance level of 85% (Fig. 6b). The complete catalogue, conversely, failed to pass the same χ^2-test (Fig. 6a).

A separate analysis has interested the completeness of the surficial events in the SEAHELLARC catalogue as distinguished from the intermediate and deep ones. This distinct

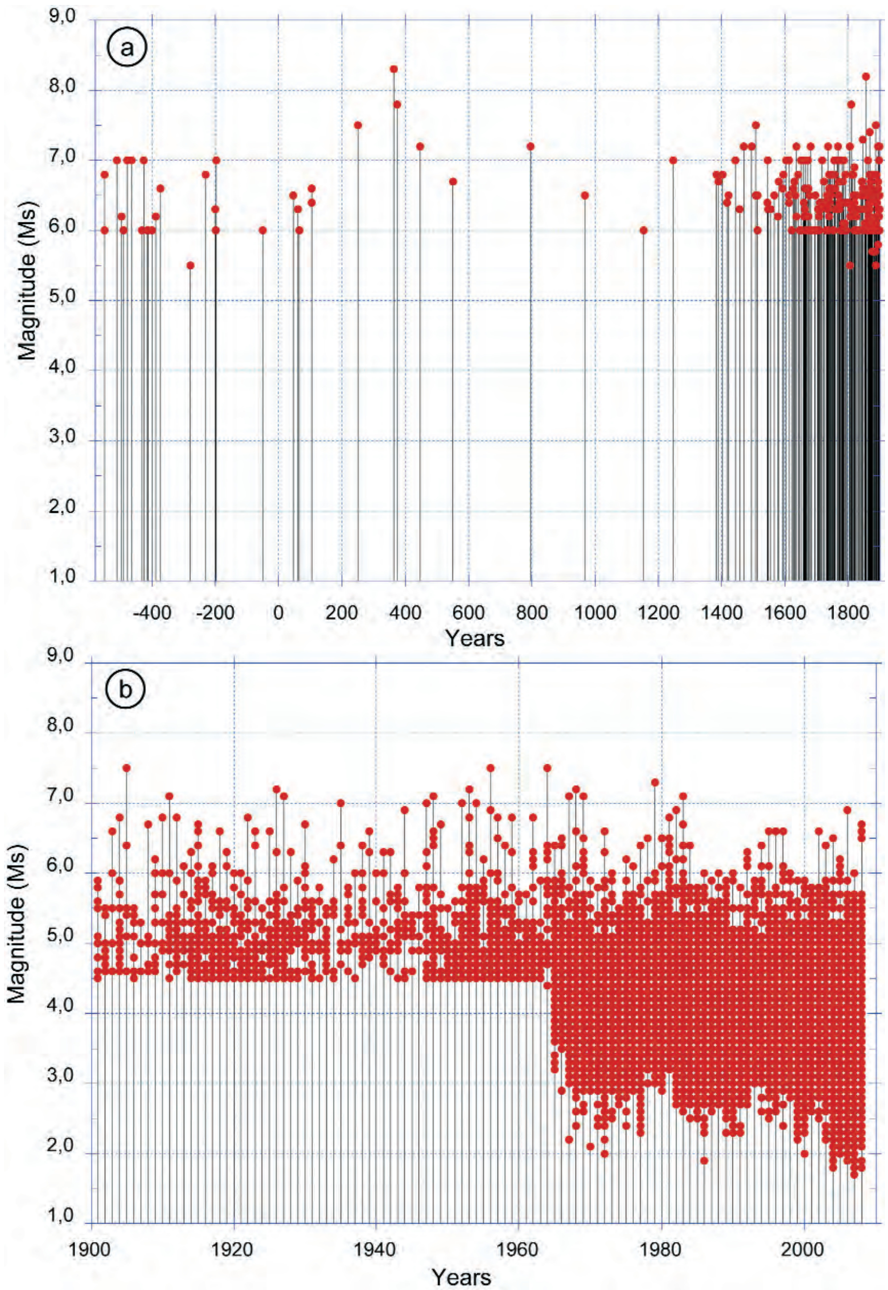

Fig. 5 - Distribution in time of the events of the SEAHELLARC earthquake catalogue: a) from 550 BC to 1900; b) from 1901 to 2008.

analysis is motivated by the fact that surficial, intermediate, and deep earthquakes are all present in the study area and, consequently, SZs with a specific different depth will be designed for the PSHA. As the quality of the depth estimates is good only for the very last few years (also as a consequence of the large number of offshore earthquakes), a simple separation between surficial and non-surficial earthquakes was taken into consideration. This separation has been set at a depth of 20 km. The complete periods were suggested by Papadopoulos (personal

Table 1 - Completeness periods of the SEAHELLARC catalogue.

M_S	Shallow events (h ≤20 km)	Int. & deep events (h >20 km)
3.0 – 3.4	1978	1978
3.5 – 3.9	1978	1978
4.0 – 4.4	1968	1978
4.5 – 4.9	1963	1978
5.0 – 5.4	1908	1968
5.5 – 5.9	1908	1968
6.0 – 6.4	1908	1908
6.5 – 6.9	1858	1908
7.0 – 7.4	1758	1848
7.5 – 8.0	1608	1808

communication) for the surficial seismicity, while they were taken from Skarlatoudis *et al.* (2004a) for the deep events. Both sets of completeness periods were checked by Stepp (1972) graphs. This check was done by analyzing the cumulative number of events in each magnitude class, according to the selected 0.5 step, vs. time from present. The change of the slope from a linear trend identifies the dates when the catalogue starts being documented in a worse way. So, the completeness of the catalogue for the different magnitude classes remains identified (Table 1). To be correct, it should be stated that the periods singled out represent intervals when the seismicity is stationary in time but the stationarity of the seismic process is a working hypothesis in PSHA and, consequently, stationarity and completeness can be considered equivalent. Long periods of completeness refer only to large magnitude classes (6.5 and larger) and the completeness of almost all the other classes is limited to the last century.

A second computation was then produced, considering again the Papazachos and Papazachou (1997) seismogenic zonation and the SEAHELLARC catalogue, instead of taking the seismicity parameters directly from Papaioannou and Papazachos (2000).

For the seismic hazard assessment [according to the Cornell (1968) approach], the seismicity of each SZ is described by the *a*- and *b*-values of the Gutenberg-Richter (G-R) relation and by the value of the maximum magnitude.

Individual seismicity rates have been computed following the "higher not highest" (HNH) method developed for the seismic hazard map of the Italian territory (Slejko *et al.*, 1998) in terms of M_S. The scaling law between magnitude M_S and moment M_0 is not linear from low to high values, and two linear branches have been proposed with a changing point around 6.4 (Reiter, 1990). This fact affects the *b*-value estimates when M_S is considered instead of M_W. Anyway, the shift should be very limited (Ambraseys, 2003) and so can be not taken into account in the *b*-value estimation.

Different methodologies for assessing the *b*-value of the G-R relation are available in literature. The least-squares method (LSM) is often used, although not formally suitable since

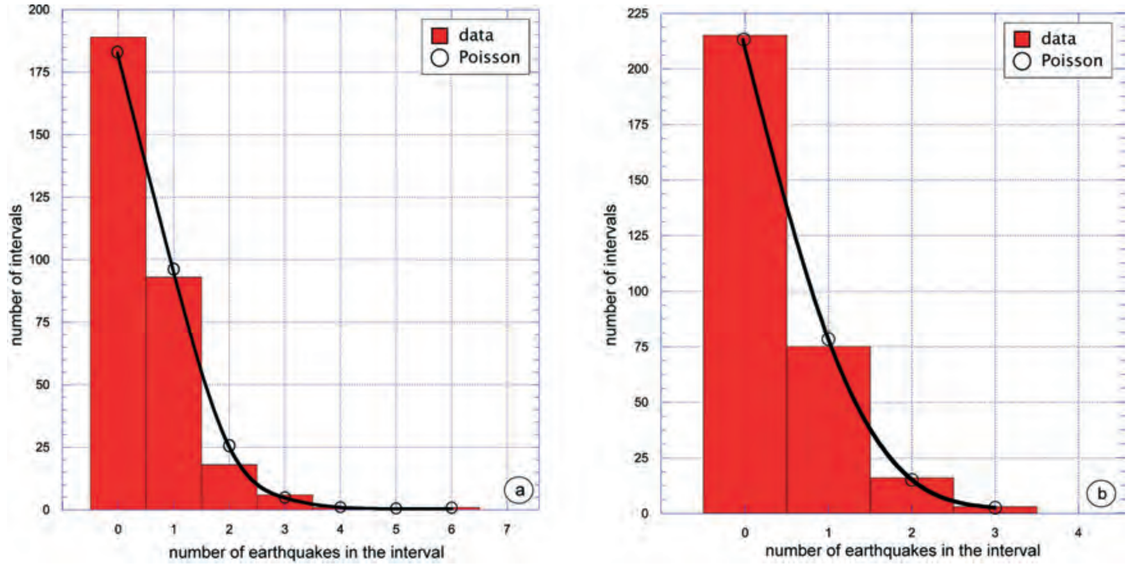

Fig. 6 - Test verifying the Poisson character of the SEAHELLARC catalogue: a) complete catalogue; b) de-clustered catalogue. Earthquakes with an $M_S \geq 6.5$ in the last 300 years have been considered and have been binned on a yearly basis.

magnitude is not error free, cumulative event counts are not independent, and the error distribution of the number of earthquake occurrences does not follow a Gaussian distribution. The maximum likelihood method (MLM) has been widely applied (Aki, 1965; Utsu, 1965): Weichert (1980) proposed a general routine suitable also for different completeness periods of the earthquake catalogue. For our purposes, the Weichert (1980) MLM with variable completeness periods has been applied.

The maximum magnitude M_{max} has been computed for each SZ according to the statistical approach proposed by Kijko and Graham (1998: KIJ). This approach computes M_{max} for a source on a statistical basis using as input data:

1) the maximum observed magnitude;
2) the threshold magnitude considered complete in the catalogue;
3) the average error in the magnitude estimates (fixed in our case arbitrarily at 0.2);
4) the *b*-value of the G-R relation and its standard deviation;
5) the annual rate (i.e., the number of earthquakes with magnitude greater than, or equal to, the threshold magnitude); and
6) the catalogue time span which is considered complete. This last parameter was set at 300 years since the HNH method used for the seismicity rate computation scans the whole catalogue and chooses the period which is most seismically in agreement with the return period of each magnitude class estimated a priori. The KIJ approach considers four formulations for the M_{max} computation: the most robust Bayesian Kijko-Sellevol formula has been applied here.

Table 2 displays the input parameters defined from the SEAHELLARC catalogue with respect to those defined by Papaioannou and Papazachos (2000). It can be seen that there is a notable

Table 2 - Seismicity parameters from Papaioannou and Papazachos (2000) and computed from the SEAHELLARC catalogue. λ_5 is the number of earthquakes with an M_S larger than, or equal to, 5.0. M_{max} is the maximum magnitude while M_{maxo} is the maximum observed magnitude. For the number of SZs refer to Fig. 2.

Zone	Papaioannou and Papazachos (2000)			From SEAHELLARC catalogue			
	λ_5	b	M_{max}	λ_5	b	M_{maxo}	M_{max}
5	0.922	0.96	6.9	0.333	1.05	6.5	6.5
6	1.286	0.99	7.1	0.731	0.89	6.7	6.7
7	2.697	0.99	7.3	1.126	0.95	7.4	7.4
8	1.258	0.99	7.1	1.018	0.97	6.8	6.8
9	0.960	0.98	7.2	0.778	1.09	7.5	7.7
10	0.476	0.97	7.1	0.377	1.32	7.0	7.2
11	1.200	1.02	7.1	0.972	0.97	6.6	6.7
12	0.282	1.00	6.4	0.482	1.30	6.5	6.5
13	0.451	0.99	6.3	0.684	1.28	6.2	6.2
24	0.522	0.95	6.9	0.617	1.18	7.0	7.1
25	0.602	0.96	7.2	0.241	1.14	7.2	7.3
26	0.184	0.95	6.8	0.187	1.28	6.5	6.6
38	0.503	0.93	6.8	0.153	1.25	6.5	6.7
39	0.464	0.94	7.0	0.234	1.29	7.0	7.2
42	0.560	0.96	6.8	0.498	1.12	6.8	6.8
43	1.076	0.94	7.0	0.362	1.15	6.8	6.8
44	0.953	0.92	7.0	0.336	0.98	6.8	6.8
45	0.271	0.92	6.5	0.061	1.05	6.3	6.8
D1	0.302	0.56	7.5	0.271	0.59	7.2	7.5
D2	0.100	0.56	7.5	0.052	0.63	6.9	7.3
D5	0.100	0.75	7.0	0.059	0.70	6.3	6.8

decrease in the seismicity rate for all SZs with the exception of SZs 12, 13, and 24. Conversely, the new b-values show a general increase for almost all SZs, even exceeding the value of 1.0 for several SZs. The new maximum magnitude M_{max} differs in almost all cases with respect to that of Papaioannou and Papazachos (2000), but no general tendency can be observed. As the method followed by Papaioannou and Papazachos (2000) is not declared, it is not possible to justify this difference.

As in the previous attempt (Fig. 3), the Theodulidis and Papazachos (1992) attenuation relation for surficial events has been applied to all (surficial, intermediate, and deep) SZs, considering the hypocentral distance.

Fig. 7 shows the seismic hazard obtained with these new seismicity data. The map shows lower values than the previous one (Fig. 3), and Pylos is now characterized by a *PGA* between 0.48 and 0.56 g. The largest ground motions are found, again, in Zakinthos Island with values larger than 0.64 g.

Considering the test site of Pylos, the complete seismic hazard curve (Fig. 4) displays an expected ground motion of 0.53 g for the 475-year return period (annual exceedence probability of 0.0021).

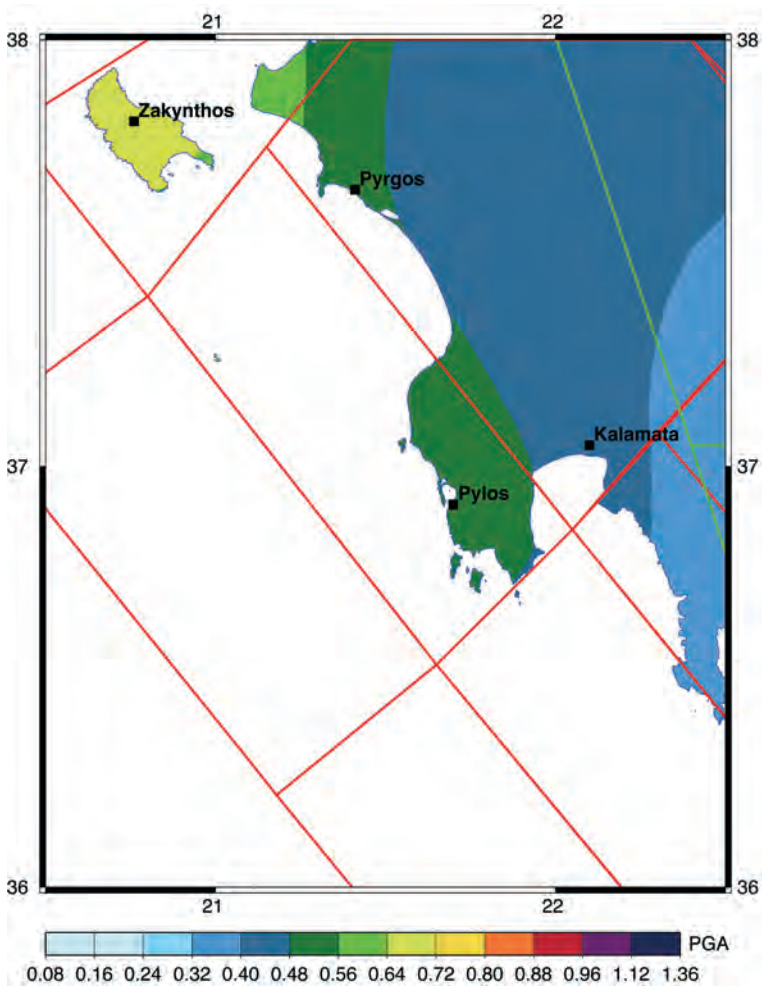

Fig. 7 - Rock seismic hazard of the Pylos broader region in terms of *PGA* with a 475-year return period computed with the Papazachos and Papazachou (1997) seismogenic zonation and the SEAHELLARC earthquake catalogue.

4.3. The third step: PSHA using a new seismogenic zonation and new seismicity data

The final seismic hazard assessment will consider different hypotheses for the seismogenic zonation, for maximum magnitude and seismic activity, and for the attenuation model. At the present stage of research, we show the result based on a new seismogenic zonation for the Pylos region, which integrates the results obtained by the national zonation (Fig. 7).

On the basis of a comprehensive analysis of Greek seismicity and considering the geophysical information available for the region, a new seismogenic zonation has been designed. This zonation is totally new for the Pylos region (compare Figs. 2a and 8a), while outside, it is only modified from Papazachos and Papazachou (1997) for the surficial zones. The intermediate and deep SZs are also modified (Fig. 8b) from those of Papazachos and Papazachou (1997). More precisely, it was decided to separate the surficial seismicity (depth less than or equal to 20 km) from the rest. The geometry of the intermediate and deep SZs of Papazachos and Papazachou

(1997) have been modified in agreement with the geometry of the subduction plane as proposed by Papazachos *et al.* (2000), whose western limb is located offshore the Peloponnese, and the accepted evidence of a dip of about 35° for this subduction plane (Papazachos *et al.*, 2000). Two intermediate SZs have been designed between a depth of 20 and 60 km, and two deep SZs from a 60 km depth downwards, as far as 160 km (Fig. 8b).

In short, 37 SZs were used for hazard computation: 33 are shallow (modelled by a horizontal plane at a 10 km depth), 2 are intermediate, and 2 are deep. The general trend reflecting the geometry of the Hellenic Arc, clearly evident in the national zonation (Fig. 2a), is still present in the surficial zonation (Fig. 8a) but two transverse SZs are introduced for the modelling of the major dextral transcurrent fault systems of the region: the Cephalonia and the Andravida faults [see also Slejko *et al.* (1999)]. The rest of the zonation reflects the national zonation with the required modifications. The agreement between the hypocentral distribution and the zonation is illustrated in Fig. 8. Surficial earthquakes occurred in the whole of the study region, and this justifies the presence of the surficial SZs in almost all the area.

The seismic hazard assessment has been performed in the same way as that of the previous attempt (Fig. 7), that is with the HNH method for seismicity rate computation in terms of M_S, the MLM for the *b*-value assessment, and the KIJ method for the M_{max} estimation (Table 3).

As in the previous runs (Figs. 3 and 7), the Theodulidis and Papazachos (1992) attenuation relation for surficial events has been applied to all (surficial, intermediate, and deep) SZs, considering the hypocentral distance for all the SZs.

Fig. 9 shows the hazard results as derived from this new seismogenic zonation. It can be observed that slightly higher ground motions than the previous elaboration (Fig. 7) are forecast almost everywhere, with the exception of the area of Kalamata (Fig. 7). The highest ground shaking is again reached on the Island of Zakinthos (*PGA* values larger than 0.96 g almost everywhere) and in the Kyllini peninsula (*PGA* values larger than 0.80 g in the westernmost strip). Ground motions between 0.56 and 0.64 g characterize the coast around Pylos.

In considering the test site of Pylos, the complete seismic hazard curve (Fig. 4) displays an expected ground motion of 0.56 g for a 475-year return period (annual exceedence probability of 0.0021).

The results of this last elaboration for the site of Pylos have been disaggregated (McGuire, 1995; Bazzurro and Cornell, 1999; Harmsen *et al.*, 1999; Harmsen and Frankel, 2001) to identify the origin of the main contribution to hazard. Fig. 10 clearly illustrates that only 4 SZs, of which SZ 86 has the largest impact, contribute with 94%. Although the seismicity of SZ 86 is not very high (see Table 3), this result is quite obvious since Pylos is located within SZ 86. Similar contributions, varying between 1% to 2%, are provided by SZs 13, 85, and 87. All these SZs are adjacent to SZ 86 and are similarly surficial. It is worth noting that only the SZs near Pylos contribute to its hazard, while the SZs situated far away, even if very active, such as SZ 81 Cephalonia, have no influence on the area.

5. Considerations on the preliminary seismic hazard assessments for the Pylos broader region

When comparing the three maps (Figs. 3, 7, and 9), one can see that there is an evident

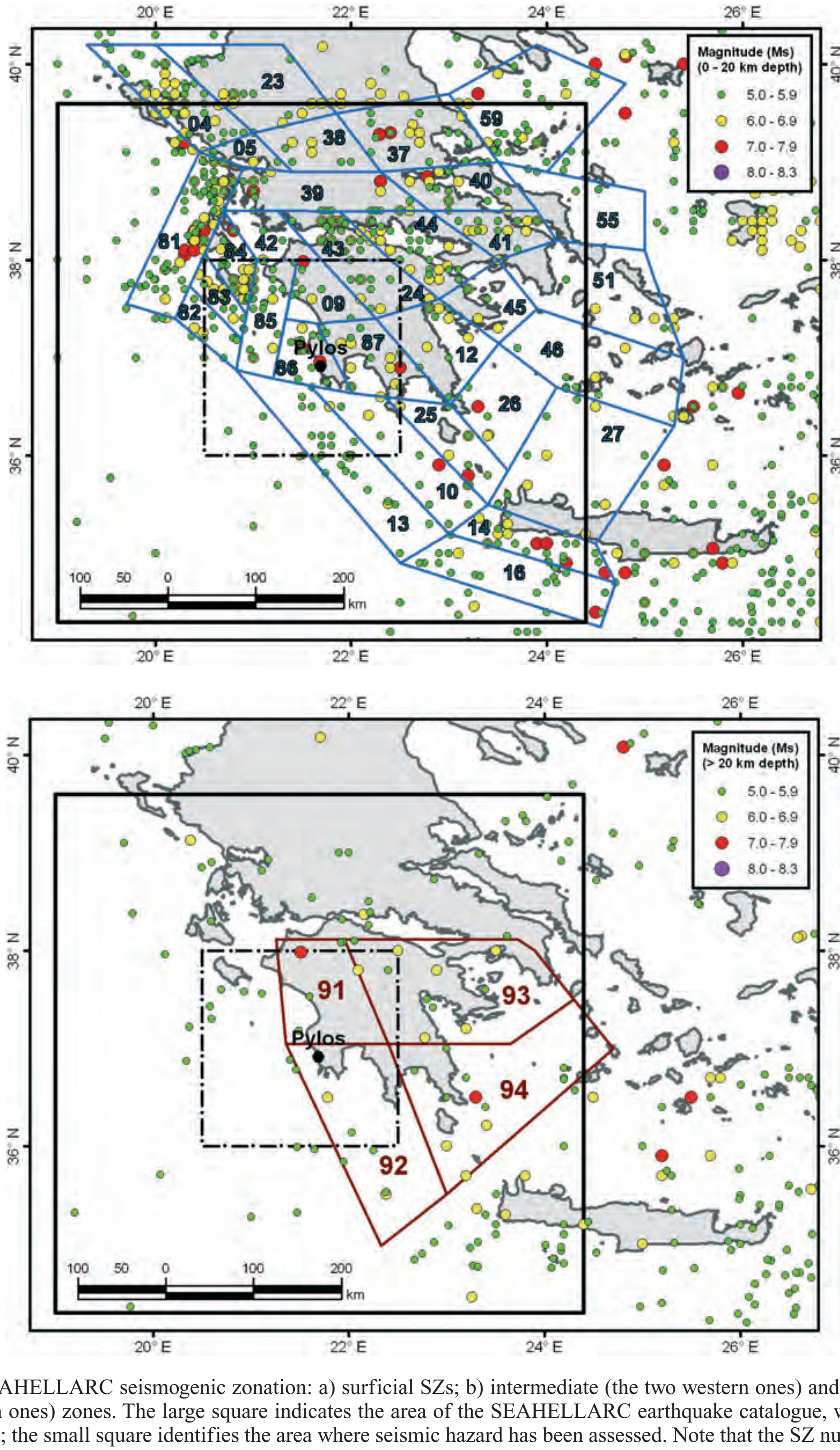

Fig. 8 - SEAHELLARC seismogenic zonation: a) surficial SZs; b) intermediate (the two western ones) and deep (the two eastern ones) zones. The large square indicates the area of the SEAHELLARC earthquake catalogue, where SZs are defined; the small square identifies the area where seismic hazard has been assessed. Note that the SZ numbers are different from those of Fig. 2.

Table 3 - Seismicity parameters for the SEAHELLARC zonation computed from the SEAHELLARC catalogue. λ_5 is the number of earthquakes with an M_S larger than, or equal to, 5.0. M_{max} is the maximum magnitude while M_{maxo} is the maximum observed magnitude. For the number of SZs refer to Fig. 8.

SZ	λ_5	b	M_{maxo}	M_{max}
SZ_04	0.97	0.91	5.8	5.9
SZ_05	0.08	1.00	6.1	6.1
SZ_09	0.12	1.49	5.8	5.8
SZ_10	0.39	1.28	6.1	6.1
SZ_12	0.08	1.26	5.5	5.6
SZ_13	0.60	1.25	6.0	6.2
SZ_14	0.30	1.07	6.3	6.3
SZ_16	0.45	0.90	7.0	7.0
SZ_23	0.34	1.06	6.1	6.1
SZ_24	0.13	1.11	6.5	6.
SZ_25	0.07	1.65	6.0	6.1
SZ_27	0.04	1.51	5.5	5.5
SZ_26	0.08	1.52	5.5	5.5
SZ_37	0.26	1.16	7.0	7.0
SZ_38	0.14	1.51	6.5	6.5
SZ_39	0.19	1.33	6.5	6.5
SZ_40	0.24	1.05	5.8	5.9
SZ_41	0.15	0.96	6.0	6.1
SZ_42	0.07	1.38	6.3	6.3
SZ_43	0.35	1.43	6.0	6.1
SZ_44	0.43	1.11	6.8	6.8
SZ_45	0.04	1.12	5.5	5.6
SZ_46	0.11	0.99	6.1	6.1
SZ_51	0.05	0.91	5.4	5.5
SZ_55	0.07	1.25	5.8	5.8
SZ_59	0.45	0.97	7.0	7.1
SZ_81	1.64	0.90	6.7	6.7
SZ_82	0.37	0.91	6.6	6.6
SZ_83	0.33	1.22	6.8	6.8
SZ_84	0.50	1.01	7.2	7.2
SZ_85	0.46	1.13	6.?	6.2
SZ_86	0.23	1.35	6.9	7.0
SZ_87	0.13	1.34	6.0	6.0
SZ_91	0.13	1.33	5.5	5.5
SZ_92	0.26	1.34	5.2	5.2
SZ_93	0.27	1.15	7.2	7.3
SZ_94	0.20	1.10	7.2	7.3

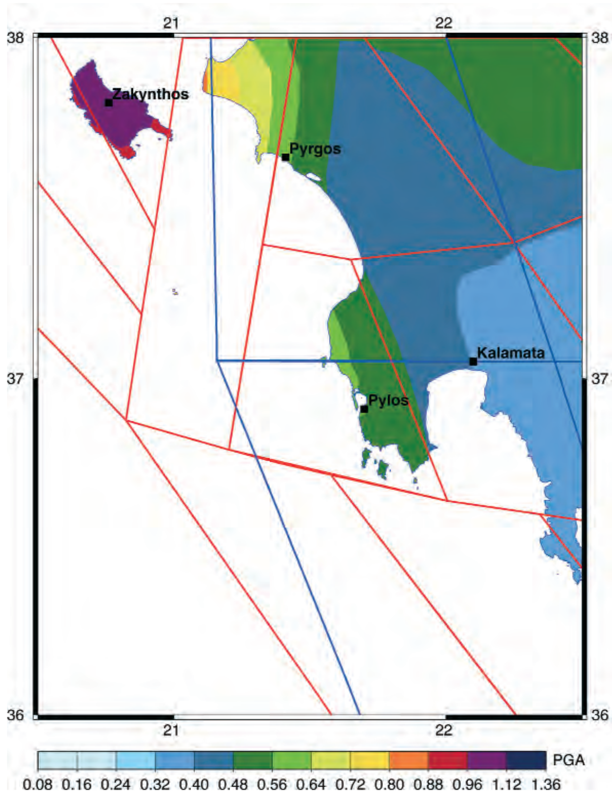

Fig. 9 - Rock seismic hazard of the Pylos broader region in terms of *PGA* with a 475-year return period computed with the SEAHELLARC seismogenic zonation and the SEAHELLARC earthquake catalogue

decrease of expected ground motion when re-computing the seismicity rates on the basis of the revised earthquake catalogue (compare Figs. 3 and 7). This is particularly evident for the Island of Zakinthos, where the *PGAs* are lower by about 0.16 g. A decrease of expected values can also be seen in the Pylos area, but it is limited to about 0.08 g only. For the Pylos area, this shaking does not change by introducing the new seismogenic zonation (compare Figs. 7 and 9), while it increases notably in Zakinthos (about 0.24 g) and, to a lesser extent, in the Kyllini peninsula (about 0.16 g).

The three seismic hazard curves calculated for Pylos (Fig. 4) are very similar to each other, while that obtained by using literature data is slightly higher than the other two for the probabilities of interest for the seismic zonation (annual exceedence probabilities between 0.02 and 0.0002, corresponding to return periods between 50 and 5000 years).

The results obtained for Pylos (0.56 g for a return period of 475 years) are remarkably higher than those available in literature [0.143 for Makropoulos and Burton (1985) and 0.29 for Papazachos *et al.* (1993)]. The former authors did not consider the aleatory uncertainty of the attenuation relation and it is not clear whether the latter ones introduced it, or not, in their computation (no standard deviation was indicated for the attenuation relations applied). Furthermore, the value given by Papazachos *et al.* (1993) is an average estimate because it refers to the entire south-western coast of

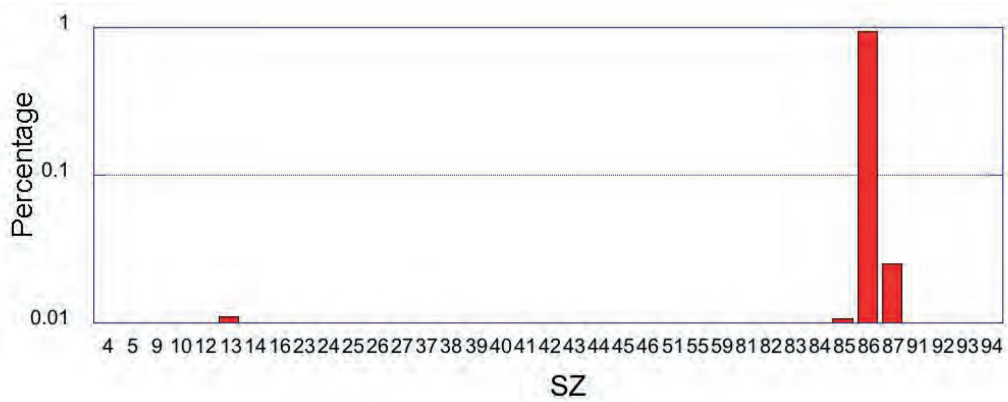

Fig. 10 - Deaggregation of the seismic hazard results in terms of *PGA* with a 475-year return period.

the Peloponnese. As indicated in the introduction, Papaioannou and Papazachos (2000) estimated an intensity of VII-VIII MM with a return period of 475 years for Pylos. Considering the scaling laws of Koliopoulos *et al.* (1998) and of Tselenis and Danciu (2008), we obtain mean values of 0.27 and 0.24 g, respectively. Again, it is not clear if the standard deviation of the attenuation relation was considered in these computations (we have not taken into account the uncertainty of intensity vs. *PGA* scaling laws cited above). Re-computing the expected ground motion in Pylos, according to the input data (zonation, seismicity rates, and attenuation model without standard deviation) provided by Papaioannou and Papazachos (2000), we obtained a value of 0.24 g for a return period of 475 years: such value is in full agreement with the literature results, suggesting that a fully probabilistic approach was not followed in the past.

6. Conclusions

Before producing, in the frame of the SEAHELLARC project, the final seismic hazard estimates for the Pylos broader region, preliminary models have been performed, aimed at verifying the influence of the geometry of the used seismogenic zonation and the estimation of the seismicity parameters (activity rates and M_{max}) on the ground motion results.

Considering the Pylos broader area (Figs. 3, 7, and 9), a general decrease of hazard is obtained by the computation of the seismicity parameters as deduced from the SEAHELLARC catalogue when compared to estimates based on literature. Conversely, a slight increase of hazard is obtained by considering the newly proposed seismogenic zonation on the mainland; this increase is remarkable for the Kyllini peninsula and for the Island of Zakinthos in particular.

Considering the test site of Pylos (Fig. 4), the variation of the expected ground motion, for a 475-year return period, appears very small and changes only from 0.63 g for the first elaboration to 0.56 g for the last one. The disaggregation of the results obtained with the SEAHELLARC catalogue data and the new seismogenic zonation (Fig. 10) indicate that the hazard of Pylos is only determined by the SZ where the town is located .

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