PRELIMINARY SEISMIC HAZARD ASSESSMENT FOR THE PYLOS REGION (SW HELLENIC ARC)

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Introduction. Greece is the most seismically active country in Europe, accounting for more than half of the continent’s seismic energy release and exhibits the highest seismic activity in the whole Mediterranean area. On the average, a M=6.3 earthquake occurs every year in the broader Aegean area. This high seismicity is usually attributed to the convergence of the Aegean lithosphere (front part of Eurasian lithospheric plate) and the eastern Mediterranean lithosphere (front part of the African lithospheric plate) in an about N-S direction, along a Benioff zone, which was identified through the accurate location of intermediate-depth (60-180 km) earthquakes, in southern Greece (Papazachos et al., 2000). The Hellenic arc is an ocean-continent type of interaction that occurs on a curved surface, which is defined by the shallow branch (20-100 km) of the Wadati-Benioff zone. The intersection of this zone with the Earth’s surface is a curve which follows the convex (outer) side of the sedimentary arc (western Peloponnnesus - west of Cythera - south coast of Crete - east coast of Rhodes) and dips at low angle (~30°) to the Aegean sea. The extension of the Wadati-Benioff zone reaches a depth of 150 km under the volcanic arc in the southern Aegean. Some earthquakes are located even deeper, up to focal depth of about 180 km. This deeper part (100-180 km) has a dip angle of about 45°. The existing scattering of the intermediate depth seismicity does not allow the determination of these dip angles with high accuracy (less than 5-10°). The shallow branch (20-100 km) defines the area of coupling between the Aegean and the Mediterranean lithospheres. This is strongly supported by the fact that all big intermediate depth earthquakes with magnitude up to 8.2 occur in this branch (Papazachos et al., 2000). The subduction occurs in a domain that is spatially confined laterally, between the continental foreland of Apulia with the Albanides and Dinarides to the NW, and in the east, by the fast westward lateral
extrusion of Anatolia, under the northward push of Arabia at its eastern edge since the middle Miocene (Sachpazi et al., 2000). According to Ambraseys and Jackson (1990), a 100 years’ data set of earthquakes in central Greece is inadequate for either a reasonable assessment of seismic hazard or for a confident estimation of maximum magnitude. Nevertheless, it is probable that the maximum magnitude is restricted by the maximum length of fault segments, which appears to be around 15-20 km. The earthquakes of $M_s \geq 5.8$ during 1890-1988 can account for a N-S displacement of around 45-70 cm (with maximum and minimum estimates a factor of two greater and smaller than this) across part of a 1890-1900 triangulation network in central Greece that was resurveyed in 1988. Considering that the contribution of smaller events may increase this displacement by about 50%, this cumulative seismic displacement is similar to that estimated from the geodetic work (about 100 cm). A recent study (Nur and Cline, 2000) of earthquakes occurring in the Aegean and Eastern Mediterranean region during the 20th century has showed that this area is criss-crossed with major faults and that numerous large earthquakes often occur in groups, known as “sequences” or “storms”, in which one large quake is followed days, months, or even years later by others elsewhere on the now-weakened fault line. When a map of the areas in the Aegean and Eastern Mediterranean region affected by 20th century earthquakes of magnitude 6.5 and greater is overlaid on Robert Drews’ map of sites destroyed in these same regions during the so-called “Catastrophe” near the end of the Late Bronze Age (among which Pylos), it is evident that all these sites lie within the high-shaking areas. Based on these data, Nur and Cline (2000) suggest that an “earthquake storm” may have occurred in the Late Bronze Age Aegean and Eastern Mediterranean during the years 1225–1175 BC. The western part of the Hellenic Arc between Pirgos and Pylos, western Peloponnesus, is one of the most seismically active areas in the whole Mediterranean. This area has been repeatedly affected by large magnitude earthquakes that have caused severe destruction and human loss (i.e. 1886 Philiatra M7.3, 1893 Zante-Keri M6.5, 1899 Kiparissia M6.5, 1947 Pylos M7.0, and 1997 Gargaliani M6.6). Some of the largest regional tsunamis in the Mediterranean Sea have also been observed in association with large earthquakes (i.e. 1630 and 1866, southwestern Hellenic Arc), affecting near-field as well as remote coastal segments in western Peloponnesus, Crete, and as far as Alexandria (Egypt), Adriatic Sea and east Sicily. Also many earthquakes have caused local but strong tsunami waves.

**Preliminary seismic hazard assessment of the Pylos region.** The tectonic situation of the Hellenic arc requires that also deep seismogenic structures are taken into account in seismic hazard assessment. The most suitable computer code for modelling seismogenic sources of different deep geometry is CRISIS (Ordaz et al., 1999), which allows the use of subduction planes. A preliminary application of this code was performed taking the input parameters from literature. More precisely, Papaioannou and Papazachos (2000) considered surficial, intermediate, and deep seismogenic zones for their seismic hazard assessment of Greece. We defined a dipping plane according to the information available in literature (Papazachos et al., 2000) and schematized it by three sources: two are intermediate and one is deep (see Fig. 1b). In conclusion, 21 seismogenic zones were used for the hazard computation: 18 are shallow, 2 are intermediate, and one is deep.

All the parameters needed for the PSHA (seismicity rates, maximum magnitude, etc.) were taken from Papaioannou and Papazachos (2000) and from Papazachos et al. (1993) and three attenuation relations were considered: the Ambraseys et al. (1996) model, calibrated on European earthquakes, the Theodulidis (1991) relation, calibrated on Greek events, and the Sabetta and Pugliese (1987) one, calibrated on Italian quakes. For the intermediate and deep sources, the Papazachos et al. (1993) relations have been applied. The hazard map obtained by averaging the results computed with the different attenuation relations is shown in Fig. 1c.

**Towards the final seismic hazard assessment of the Pylos region.** 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 the research, we
show the elaboration based on a new seismogenic zonation for the Pylos region, which will integrate the results obtained by the national zonation, reported in Fig. 1c.

The first historically documented information in Greece on an earthquake is related to Cicero, who wrote that a strong earthquake, occurred in 550 BC, ruined Sparta and that a section of the summit of Mt Taygetos broke off. No historic information on the effects of earthquakes before the 6th century BC exists. Up to the middle of the 19th century, information on the earthquakes comes mainly from macroseismic effects of large shocks. In 1911 the first seismometer was installed in Athens and since then modern seismometers were in continuous operation. Since the 1950s the first seismological stations of the permanent network were installed in the area of Greece, and in the following decades the first telemetric network of seismological stations and the network of the strong motion instruments were established (Papazachos and Papazachou, 1997).

All the main historical events of the catalogue were revised during this project. Special investigations were carried out for the strong earthquakes which occurred within a 300 km distance from Pylos town. Great attention was paid to the offshore seismicity, especially to the 365 earthquake, which is considered the largest in the area under investigation, with a magnitude of 8.3. This event destroyed nearly all the towns in Crete and was followed by a tsunami which devastated the Nile delta. The 365 event was also probably responsible for reported or observed destruction in ancient towns of west Cyprus and Libya.

Also the instrumental seismicity was revised, and a lot of events were relocated, especially for the last decade. The catalogue contains magnitude according to the $M_L$ scale. From about 1911 to the 1963 magnitude were calculated in the National Observatory of Athens (NOA) from Maikna and Wiechert instruments which are of intermediate period (~6-8 s) and therefore they provided directly magnitude equivalent to $M_S$. After 1963 local magnitudes $M_L$ were determined from maximum amplitudes recorded by real Wood-Anderson instrument. The empirical formula $M_S = M_L + 0.5$.
Papadopoulos, pers. comm.) has been used to transform $M_l$ to $M_s$. This analysis implies that the catalogue is not absolutely homogeneous in its entire length but it is on a different way for the two intervals: pre-1963 and post-1963.

The catalogue used in the present study derives from 3 data files: the historical earthquake catalogue of Greece, which covers the period 550 BC to 1963 (Papazachos and Papazachou, 1997), the instrumental earthquake catalogue of Greece, which covers the period 1964 to 2006, and the recent earthquake locations from 2007 to April 2008. All these 3 files were compiled at NOA and benefit of the most updated revisions.

The catalogue so constructed consists of 70644 events which occurred from 550 BC to April 2008. The minimum magnitude in the catalogue is $M_s$ 1.7, but the catalogue is extremely poor of events before 1400 (Fig. 2a) and almost only earthquakes with magnitude larger than 6 are reported before 1800. An improvement of the data acquisition from 1900 is evident (Fig. 2b), but low magnitude events are reported only after 1964. The quality of location improved also with time and acceptable depth estimates seem available only in the last decades.

The first operation requested for an earthquake catalogue in view of its application for seismic hazard assessment according to the Cornell (1968) approach is the elimination of 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).

The completeness of the catalogue has been evaluated for each magnitude class, according to the chosen 0.5 step, by the Stepp (1972) graphs, where the cumulative numbers of events of the investigated magnitude class vs. time from present is analyzed. The change of the slope from a linear trend identifies the dates when the catalogue starts to be worse documented. In this way, the completeness of the catalogue for the different magnitude classes remains identified. Correctly, it

Fig. 2 – Distribution in time of the events of the earthquake catalogue used in the present project: a) from 550 BC to 1900; b) from 1900 to 2008.
should be stated that the periods identified represent periods 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. A separate analysis has interested the surficial events from the intermediate and deep ones. This separate analysis is motivated by the fact that surficial, intermediate, and deep earthquakes are all present in the study region and, consequently, seismogenic zones (SZs) with specific different depth will be designed for PSHA. As the quality of the depth estimates is acceptable only for the very last years (due also to the large number of off-shore earthquakes), a simple separation between surficial and non-surficial earthquakes has been considered. This separation has been placed at the depth of 20 km. The complete periods were suggested by Papadopoulos (personal communication) for the surficial seismicity, while they were taken from Skarlatoudis et al. (2004a) for the deep events. 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.

On the basis of a comprehensive analysis on the Greek seismicity and considering the geophysical information available for the region, a seismogenic zonation has been designed. It is completely new for the Pylos region (compare Figs. 1a and 3a), while outside it is modified from Papaioannou and Papazachos (2000) for the surficial zones. The intermediate and deep SZs are modified (Fig. 3b) from those of Papaioannou and Papazachos (2000). 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 Papaioannou and Papazachos (2000) have been modified in agreement with the geometry of the subduction plane proposed by Papazachos et al. (2000) and the accepted evidence of a dip of about 35° for the subduction plane. Two intermediate SZs have been designed between 20 and 60 km depth, and two deep SZs from 60 km depth downwards (Fig. 3b). The general trend reflecting the geometry of the Hellenic arc, clearly evident in the national zonation (Fig. 1a), is still present in the surficial zonation (Fig. 3a) but two transverse SZs are now introduced for modelling the major dextral transcurrent fault systems of the region: the Cephalonia fault and the Andravida one. The rest of the zonation reflects the national zonation with the needed modifications.

The agreement between the hypocentral distribution and the zonation is illustrated in Fig. 3. Surficial earthquakes occurred in the whole of the study region, and this aspect justifies the presence of the surficial SZs in almost all the region.

For the seismic hazard assessment according to the Cornell (1968) approach, the seismicity of each SZ is described by the the \( a \)- and \( b \)-values of the Gutenberg – Richter relation and by the value
of the maximum magnitude. The 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 changing point around 6.4 (Reiter, 1990). This fact affects the $b$-value estimates when $M_S$ is considered instead of the moment magnitude $M_W$. Anyway, the shift should be very limited (Ambraseys, 2003) and can be, then, 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 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 MLM 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: the maximum observed magnitude, the threshold magnitude considered complete in the catalogue, the average error in the magnitude estimates (fixed in our case arbitrarily at 0.2), the $b$-value of the G-R relation and its standard deviation, the annual rate (i.e.: the number of earthquakes with magnitude greater than, or equal to, the threshold magnitude) and the catalogue time span which is considered complete. This last parameter was set at 300 years as the HNH method used for the seismicity rate computation scans the whole catalogue and chooses the period which is most seismic in agreement with the return period of each magnitude class, a priori estimated. The KIJ approach considers four formulations for $M_{max}$ computation: the most robust Bayesian Kijko-Sellevol formula has been applied here.

Several attenuation relations have been proposed for Greece (Theodulidis and Papazachos, 1992; Papazachos et al., 1993; Theodulidis and Papazachos, 1994; Papaioannou, and Papazachos, 2000; Margaris et al., 2002; Skarlatoudis et al., 2003, 2004b); in the preliminary hazard assessment relations were applied: one of European relevance, one of Italian relevance and one calibrated on Greek data (Theodulidis, 1991). In the present application, the Papazachos et al. (1993) relations have been applied. More precisely, in the Papazachos et al. (1993) paper, different relations are reported and have been associated to surficial, intermediate, and deep SZs. The relation for surficial

![Fig. 4 – Seismic hazard of Pylos: a) PGA with a 475-year return period computed considering the standard deviation of the attenuation relations; b) complete seismic hazard curve for Pylos.](image-url)
events is almost equal to that proposed by Theodulidis and Papazachos (1992), while the others derive from it with some corrections based on macroseismic data. Unfortunately, the standard deviations of the Papazachos et al. (1993) relations are not reported, for all the value \( s_{ln} \) of 0.71 has been considered in agreement with Theodulidis and Papazachos (1992).

The computer code CRISIS (Ordaz et al., 1999) has been used for the hazard computation. The average depth of the surficial SZs has been set at 10 km, the intermediate SZs have a variable depth between 20 and 60 km, and the deep SZs have a variable depth between 60 and 180 km. Moreover, the program requests the minimum magnitude and its corresponding rate, the \( b \)-value, the maximum observed and the maximum computed magnitudes. The results here presented are in terms of horizontal peak ground acceleration (PGA) with a return period of 475 years, standard reference in seismic design (Fig. 4a). It can be seen that the highest ground shaking is reached in the Cephalonia and Lefkas islands (PGAs larger than 1 g). PGAs between 0.40 and 0.48 g interest the coast around Pylos with a little spot of higher hazard (between 0.48 and 0.56 g). Fig. 4b shows the complete seismic hazard curve for Pylos: the computed PGA for a 475-year return period is 0.6 g.

References


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