PROBABILISTIC SEISMIC HAZARD ASSESSMENT IN TERMS OF ENGINEERING PARAMETERS IN GREECE

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SUMMARY

The present study is a probabilistic seismic hazard assessment in terms of well known engineering parameters and is presented for the first time for the region of Greece. The following ground motion parameters have been investigated and mapped using the recently published attenuation relationships (predictive equations) of [Danciu & Tselentis, 2007], based on strong motion recordings of Greek earthquakes: peak ground acceleration (PGA), peak ground velocity (PGV), spectral velocity (S_v) and elastic input energy (VE_i) for 0.2 and 1 sec, Arias intensity (I_a), cumulated absolute velocity (CAV), CAV_5 and spectral intensity (SI).

The resulted maps portrait the spatial distribution of estimates of the engineering ground motion parameters that occur with a probability of 10% in 50 years (475 years return period).

INTRODUCTION

Conventionally, Probabilistic Seismic Hazard Analysis (PSHA) for a given site or region have been evaluated in terms of peak ground acceleration or spectral acceleration estimated at a specified period and damping. Although, these parameters are certainly convenient parameters for design of earthquake-resistant structures, some of the important characteristics associated to the ground motion, such as duration, frequency- and energy- content are not captured by their definitions. The importance of duration, frequency- and energy- content for non-linear response has been recognized, but these ground motion characteristics are still not used in the building design codes.

Many attempts have been done to employ ground motion characteristics into seismic design in the basis of the so-called energy-based seismic design methods [Housner, 1956; Uang & Bertero, 1988; Decanini & Mollaioli, 1998; Chai & Fajfar, 2000; Benavent-Climent *et al.*, 2002]. There is not a general established energy-based seismic design method yet; but the studies have advised the use of considering duration and energy parameters to describe the reliable design earthquake, as they adequately capture the destructive potential of the different type of time histories (impulsive, non-impulsive, periodic with long-duration pulses, etc) corresponding to an earthquake.

This study deals with PSHA in terms of engineering seismic parameters such as: peak ground acceleration (PGA), peak ground velocity (PGV), spectral velocity (S_v) and elastic input energy (VE_i) at selected frequencies and damping, Arias intensity (I_a), cumulated absolute velocity (CAV), CAV_5 and spectral intensity (SI). Work in progress will assess the effect that these models have on probabilistic seismic hazard analysis.

The broad area of Greece constitutes the overriding plate of the Africa-Eurasia convergent plate system, defining one of the most active plate tectonic regimes in the world and is characterized with high seismic hazard. Thus, the assessment of seismic hazard in Greece has been the subject of a growing number of studies during the last decades.

In Greece, the seismic hazard assessment, has been evaluated as the maximum expected intensity [Shebalin *et al.*, 1975; Papaioannou, 1984; Papazachos *et al.*, 1985; Papoulia & Slejko, 1997; Papaioannou & Papazachos, 2000] or as PGA, PGV and strong motion duration [Algermissen *et al.*, 1976; Papaioannou, 1984; Makropoulos & Burton, 1985; Papazachos *et al.*, 1990; Papazachos *et al.*, 1992; Theodulidis & Papazachos, 1992; Papazachos *et al.*, 1993; Koutrakis *et al.*, 2002; Burton *et al.*, 2003a; Tsapanos, 2003; Tsapanos *et al.*, 2003; Banitsiotou *et al.*, 2004; Mantyniemi *et al.*, 2004]

[Koutrakis *et al.*, 2002] assessed the PSHA for Greece in term of duration and PGA. The study proposed new predictive equations for bracketed duration of strong motion valid for the region under consideration;

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and the PSHA results are presented in the form of a map according to which Greece is classified in four different categories of equal seismic hazard.

Recently, [Tselentis *et al.*, 2005] have developed probabilistic seismic hazard maps in terms of I_a for Greece. The seismic hazard maps were proposed by authors using rock site conditions and for a period of 50 & 100 years with 90% probability of non-exceedance. These maps can be used additionally as a base for seismic hazard landslides mapping in the territory of Greece.

The major aim of this study was to incorporate the engineering ground motion parameters for the first time into PSHA analysis, based on the recently proposed predictive equations by [Danciu & Tselentis, 2007] valid for Greece.

The seismic hazard maps for the estimated engineering ground motion parameters and the results presented here are released for information and discussion and are not meant to be linked to any kind of regulation.

PROBABILISTIC SEISMIC HAZARD METHODOLOGY

The PSHA methodology was introduced more than forty years ago, in the landmark papers by [Cornell, 1968]and [McGuire, 1976]), since then it has become the most widely used approach to the problem of determining the characteristics of strong ground motion for engineering design [Bommer, 2002]. In essence, the PSHA is expressed in terms of exceedance probability per unit time period, of a given measure of ground motion intensity at a site by integrating the contributions of available geological, seismological and statistical information. The annual hazard curves are the result of the probabilistic hazard analysis for a site; for a given region the hazard maps can be obtained by simultaneously hazard analysis for many sites in the selected region and constructing iso-maps for specified ground motion levels corresponding to given return periods.

The analysis of seismic hazard at a site requires an approach for estimating the probability that various levels of ground motion will be exceeded at a selected location in some period of interest. A PSHA computational scheme involves the following constitutive models:

- Seismic sources
- Earthquake recurrence relationships
- Ground motion predictive equations (attenuation laws)
- Ground motion occurrence probability

The PSHA yields the annual frequency of exceedance of different ground motion levels for each of the selected engineering ground motion parameters. The result of PSHA at a given site is evaluated by this relationship ground motion level-annual frequency of exceedance, called ground-motion hazard curve. By performing simultaneously hazard analysis for a given region the hazard maps can be obtained by simultaneously hazard analysis for many sites in the selected region and constructing iso-maps for specified ground motion levels corresponding to given return periods. The procedure to develop seismic hazard maps based on engineering ground motion parameters is the same as for those based on PGA computations, but the predictive equations (attenuation lows) are different.

In the present study, we have retained the use of seismic source zones in the absence of detailed information about the activity rate of specific faults in Greece. In the present investigation we have adopted the most recent seismic source model regarding geographical distribution of seismo-tectonic zones in Greece, as has been proposed by [Papaioannou & Papazachos, 2000], the boundaries of which were chosen to reflect the seismicity adequately regarding tectonic units and lithospheric structure. Herein, a number of 67 shallow seismic source zones were used and the geographical distribution of these zones is presented on Figure 1.For the seismic zones considered, the slope (b-value) and the intercept (a-value) were reported in Table1 of [Papaioannou & Papazachos, 2000]. The set of predictive equations developed for engineering ground motion parameters and proposed by [Danciu & Tselentis, 2007] was selected herein. The selected predictive equations are based on strong motion data primary from Greek shallow earthquakes. Therefore we don't consider here the contribution of intermediate depth earthquakes that are present at the south Aegean area and probably we underestimate hazard for this region. The predictive equation model adopted to represent the attenuation of the ground motion has the following form:

$$\log_{10}(Y_{ij}) = a + bM_i - c\log_{10}\sqrt{R_{ij}^2 + h^2} + eS + fF + \varepsilon_{ij} \qquad (1)$$

where Y_{ij} is the response variable (the arithmetic average of the two horizontal components) from the jth record of the ith event, M_i is the moment magnitude of the ith event, R_{ij} is the epicentral distance from the ith

event to the location, h is the "fictitious" focal depth obtained from the regression analysis, and ε_{ij} is the error term for the jth records from the ith earthquake.
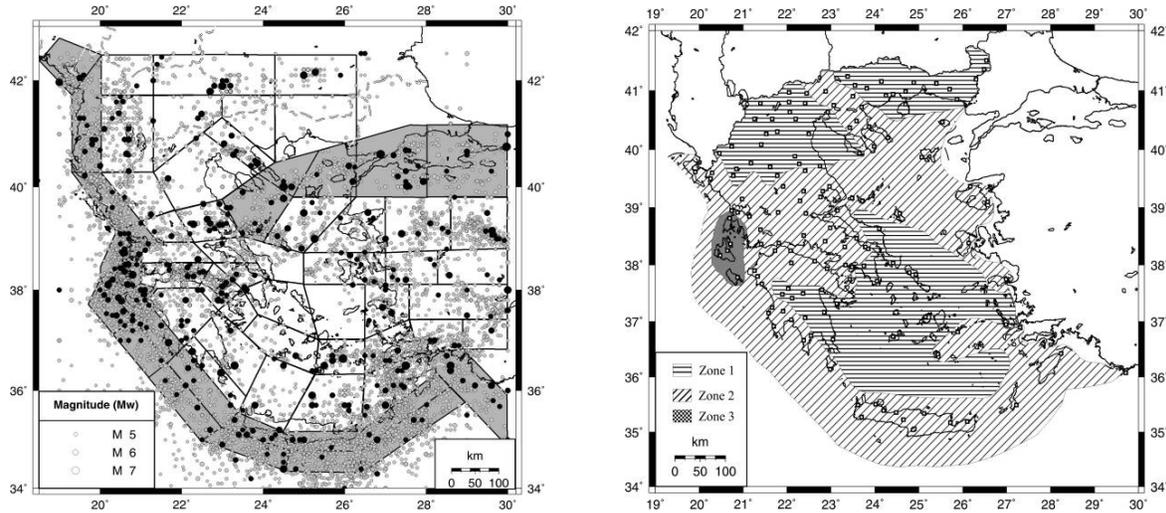

Figure 1: (*left*) Geographical distribution of the major shallow earthquakes ($M_w > 5$) and the seismogenic sources proposed by Papaioannou and Papazachos (2000). Grey filled sources correspond to thrust and strike slip faulting style. Figure 2: (*right*) The seismic hazard zonation of Greece according to the Greek Seismic Code EAK 2003

The proposed attenuation function are valid for earthquakes of moment magnitude (in the present study, referred as M_w) $M_w = 4.5$ to 7 and epicentral distance (in the present study, referred as R) up to 136 km. The Cornel-McGuire methodology incorporated in SEISRISK III [Bender & Perkins, 1987] computer code was adopted in the present analysis. The software allows for earthquake location uncertainty by considering location normally distributed with standard deviation; and ground motion variability is incorporated assuming a log-normal distribution about the mean, with a constant standard deviation σ^2. The mean probabilistic hazard is calculated for PGA, PGV, I_a, CAV, CAV_5, SI, S_v (0.2sec), S_v (1sec), VE_i (0.2sec), VE_i (1sec) for 475years return period. The selected engineering ground motion parameters are evaluated assuming an ideal "bedrock" ($V_s > 800$ m/s) local site conditions. Since the predictive equations take into account the fault mechanism, we performed hazard calculation in two steps. During the first step, hazard calculation was performed considering only normal fault mechanism, while on the second step the contribution of the thrust and strike slip faults was added. Therefore, we divided the seismogenic sources in two categories, as can be seen on the Figure 1, based on their seismotectonic characteristics and hazard results were overlapped. The geographical territory of Greece spanning the area 19°W - 30°East and 34°S to 42°N was divided into a mesh of points with an interval of 0.1° (about 10km) both in latitude and longitude.

PSHA RESULTS

An alternate approach of reporting the PSHA results is the representation of the estimated hazard parameters in the form of contours on maps. In the following the probabilistic seismic hazard maps of Greece based on the selected engineering ground motion parameters are presented. All of them reported for a mean return period of 475 years and assuming soil category rock for all the sites. The present maps are compared with the equal seismic hazard zones defined by [EAK, 2003] and plotted on Figure 2. A brief inspection of the hazard maps pointed out the primary difference produced by the different quantities that are mapped – different ground motion parameters. The reported maps identify the four regions in the Western, Southern and Northern Aegean (Hellenic trench) where the seismic hazard is relatively high compared with other. It is worth to mention here, that following hazard maps show the contours of the estimated ground motion parameters and the amount of interpolation depends upon the data points available thus, the maximum values may be located inside the contour.

PGA values shown in Figure 3 emphasize the three regions of high seismic hazard. The maximum PGA values are reached in the Western Hellenic Arc, predominant on the area of Levkas - Cephalonia – Zakinthos islands. The range of PGA values in this area is 0.45g to 0.65g. The Greek Seismic Code [EAK, 2003] places Levkas - Cephalonia – Zakinthos islands in the seismic hazard zone III, with a PGA value equal to 0.36g.   The larger values obtained here are due to the incorporation of the standard deviation on the ground motion predictive equations. The second region with high PGA values is located in the western on-shore end of the Northern Anatolia Fault – values reach in excess of 0.45g. The region is dominated by large magnitude events, such as the catastrophic earthquakes of 1999 August 17 and November 12 near Izmit and Duzce [Burton *et al.*, 2003b]. The third region where PGA exhibits high values is the Chalkidiki Peninsula, south of Thessaloniki. The PGA values are in the range 0.3 – 0.45g. The EAK 2003 map places this region into the hazard zone II and it can be observed that the estimated PGA values are higher than those from the EAK 2003 hazard zone II (PGA equal to 0.24g). The fourth zone of high PGA hazard is in the southern of Crete Island. Although, the values are high compared with those proposed by [EAK, 2003], it has to be mention here that the ground motion parameters estimated may be lower to respect to real ones since intermediate depth earthquakes which dominate these regions, were not taken into account given that only shallow events were considered herein. In addition to these four regions, the region including the Gulf of Corinth and the Patras Gulf also has relatively high values. In this region the PGA values range 0.25-0.3g and agree with the [EAK, 2003]zoning.

The map of PGV is shown in Figure 4. The general form of the maps in the first two figures is similar and the highest hazard occurs on the same regions, but they cover larger area in the case of PGV map. This difference may be associated with the fact that the coefficient for the magnitude from the predictive equation is greater for PGV then for PGA. Another explanation is that the velocity attenuates slower than acceleration and velocity is more sensitive to the high magnitudes [Papazachos *et al.*, 1993].

In Figure 5 Arias intensity is mapped. By mapping the I_a, the earthquake induced landslide and liquefaction potential can be estimated. [Keefer & Wilson, 1989] proposed three groups of slop instability based on the threshold values of Ia: 0.11 m/sec – falls, disrupted slides and avalanches; 0.32 m/sec – slumps, block slides and earth flows; and 0.54 m/sec – lateral spreads and flows. These threshold contours were plotted on the map and it appears that for some regions where high topographic relief is combined with the high Arias intensity estimated values there is significant slope instability potential. I_a values as high as 500 cm/sec2 were computed in the western Hellenic Arc and in the western on-shore end of the Northern Anatolia Fault. The latest region is dominated by large magnitude events.

Figures 6 and 7 summarize the maps of the estimated CAV and CAV_5 values. These maps have similar pattern with the previous maps, in sense that they have predict higher hazard for the same regions as the other parameters does. Moreover, by investigating the CAV map, the regions of high hazard can be clearly identified.

The hazard map associated to SI is presented in Figure 8. The SI increases the distribution of the regions with high hazard. The high SI values are presented starting from the western to the southern part of Hellenic Arc. The region is exhibit SI values larger than 60 cm. The same SI is observed in the northern Hellenic Arc and in Corinth Gulf. It should be noted that the SI map and PGV map are similar and mutually corroborative. Both maps exhibit extended hazard for the region spanned from the west to the southern Hellenic Arc. This region has been reported by [EAK, 2003] as zone II, but based on the SI results the region appears to expect higher hazard.

The period-dependent parameters S_v and VE_i for periods of 0.2 and 1.0 sec are shown in Figure 9a-b and Figure 10a-b. From the comparison of the four maps it becomes clear the regions with the high hazard are similar with the previous reported hazard maps. By studying the S_v and VE_i maps for short period of 0.2 sec it can be observed that the VE_i values are larger. This is due to the fact that for short periods the VE_i is asymptotic to the maximum spectral velocity, while the spectrum velocity approaches zero [Chapman, 1999]. Comparing the maps for S_v and VE_i computed at 1sec, can be observed that VE_i exhibit larger values. The geographical distribution of the hazard is slightly different; the regions with high seismic hazard are covering a larger area. This is due to the fact, that the influence of long-period is more evident into the case of the regions dominated by large magnitude earthquakes. These differences, between the geographical distributions of the period-dependent parameters infer that a single seismic hazard map for all periods may not be sufficient.
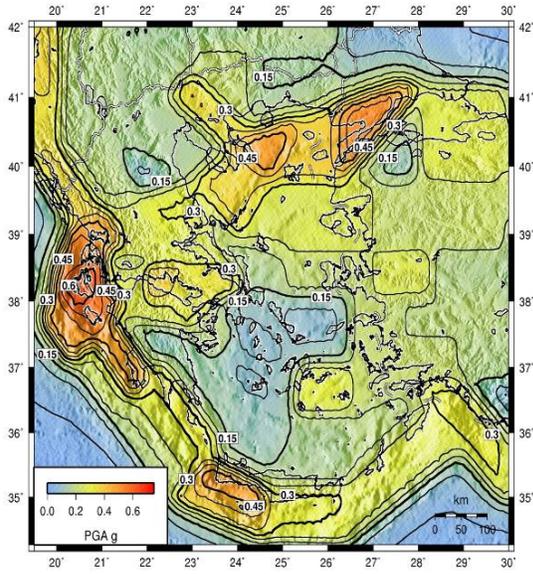
Figure 3: Seismic hazard map in term of PGA for Greece. Results are for an ideal bedrock soil condition estimated at mean return period of 475 years
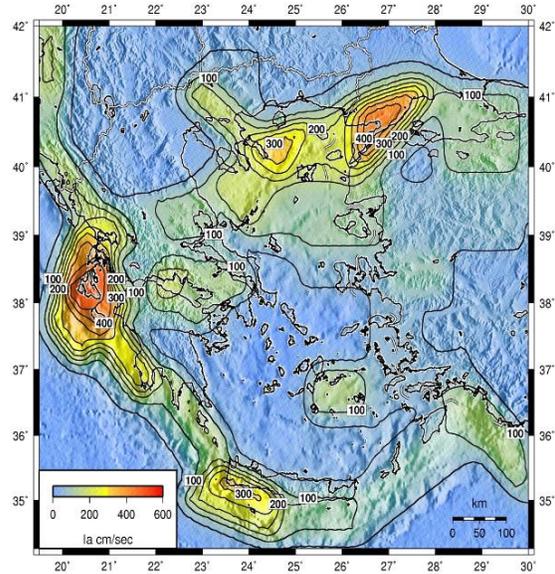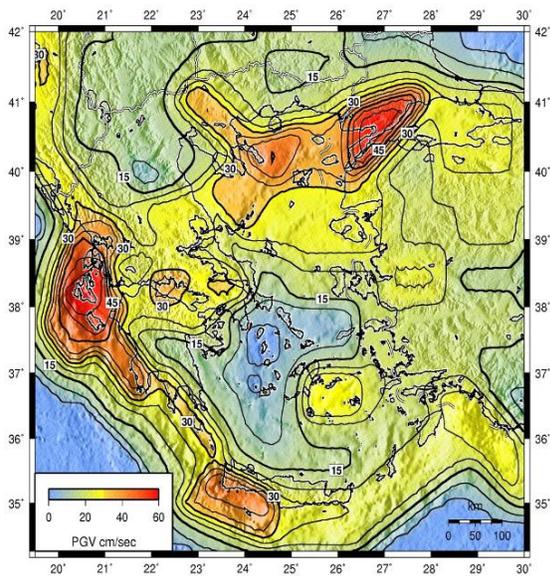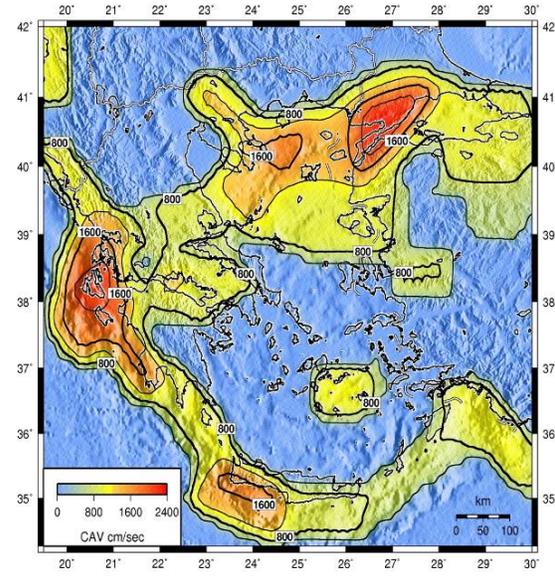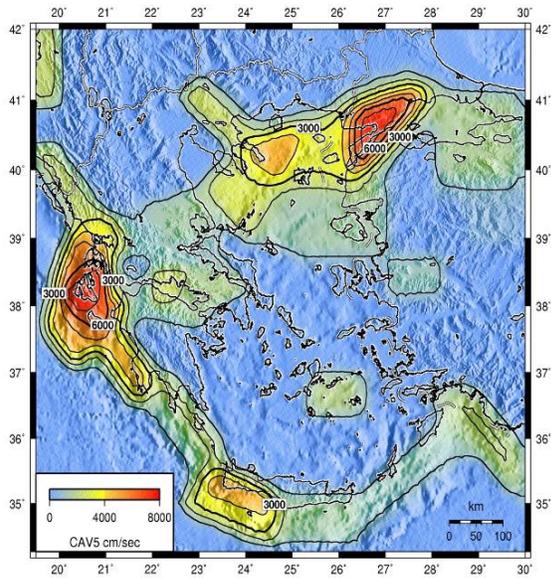

Figure 5: Seismic hazard map in term of I_a for Greece. Results are for an ideal bedrock soil condition estimated at mean return period of 475 years

Figure 4: Seismic hazard map in term of PGV for Greece. Results are for an ideal bedrock soil condition estimated at mean return period of 475 years

Figure 5: Seismic hazard map in term of CAV for Greece. Results are for an ideal bedrock soil condition estimated at mean return period of 475 years

Figure 7: Seismic hazard map in term of CAV_5 for Greece. Results are for an ideal bedrock soil condition estimated at mean return period of 475 years
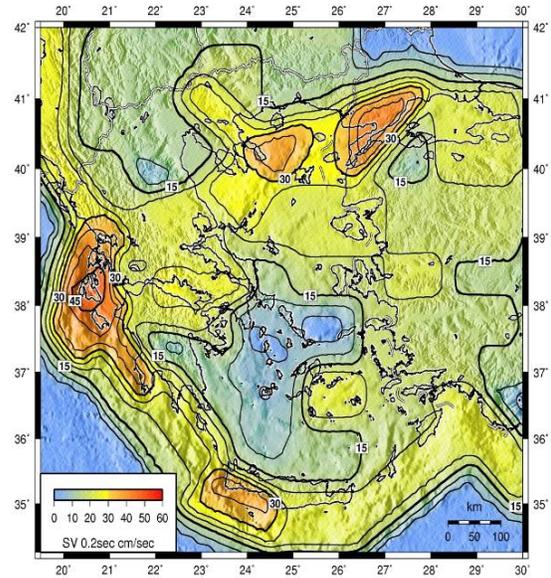

Figure 9a: Seismic hazard map in term of S_v (0.2sec) for Greece. Results are for an ideal bedrock soil condition estimated at mean return period of 475 years
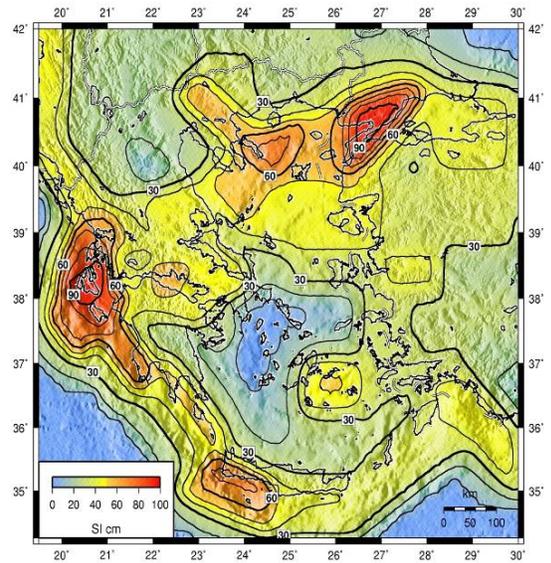

Figure 8: Seismic hazard map in term of SI for Greece. Results are for an ideal bedrock soil condition estimated at mean return period of 475 years
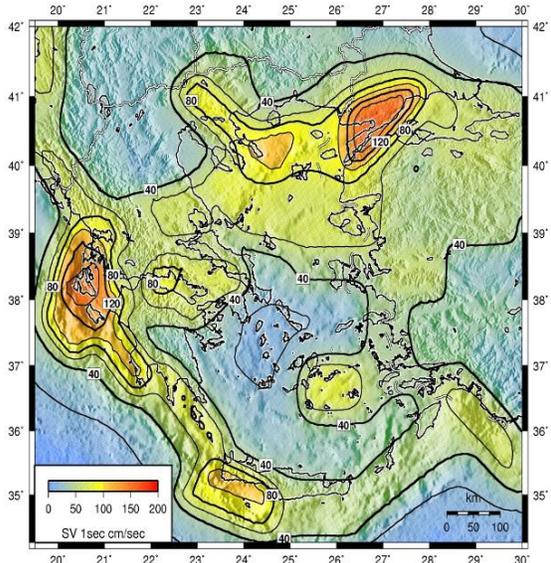

Figure 9b: Seismic hazard map in term of S_v (1 sec) for Greece. Results are for an ideal bedrock soil condition estimated at mean return period of 475 years

Figure 10a: Seismic hazard map in term of VE_i (0.2sec) for Greece. Results are for an ideal bedrock soil condition estimated at mean return period of 475 years
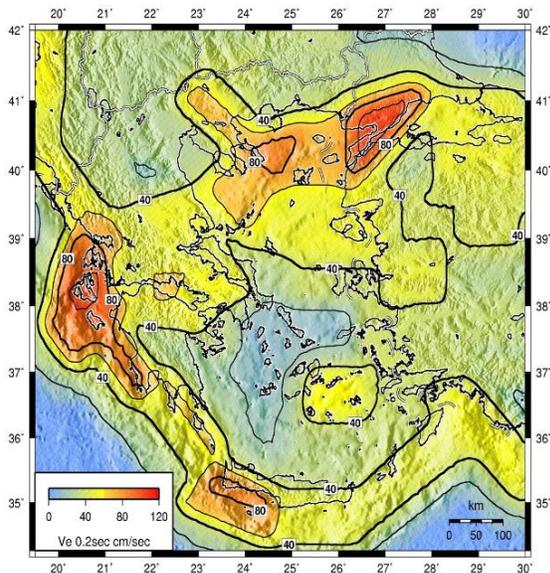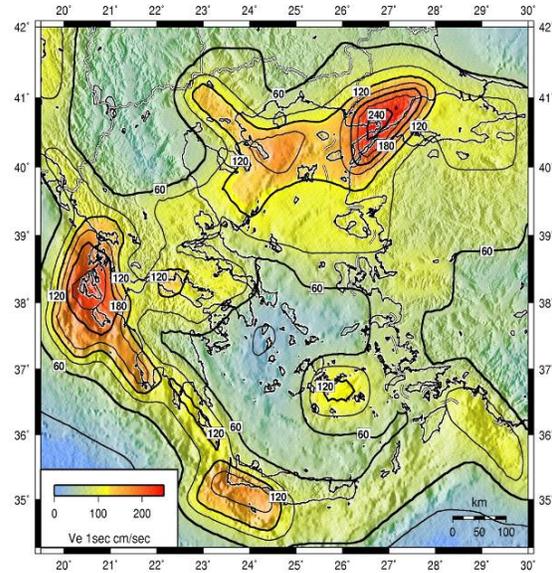
Figure 10b: Seismic hazard map in term of VE_i (1sec) for Greece. Results are for an ideal bedrock soil condition estimated at mean return period of 475 years

CONCLUSIONS

In this study we have developed new hazard maps for Greece, taking into account damage-related ground motion parameters which have the advantage to "capture" the effects of amplitude, frequency content and/or duration of a ground motion record. The contours of the estimated hazard for all the engineering ground motion parameters show a general agreement in identifying the high hazardous regions, but other areas of moderate to high values differ as frequency changes. This indicates the usefulness of representation of seismic hazard analysis based on more than one ground motion parameters. The hazard maps based on PGA or single spectral parameter is not able to represent the full description of the level of shaking expected at a given site. For a widespread region or territory, it is difficult to report the seismic hazard for complete spectra, thus by combination of short-period dependent parameters with long-period dependent parameters will better capture the earthquake damage destructiveness. The engineering ground motion parameters are expected to become more common in the future seismic hazard analyses. For hazard purpose, the engineering ground motion parameters would be mapped as an addition to the traditional seismic hazard maps, based on peak or spectral ground acceleration. For design purpose, this will support the selection of suitable earthquake scenarios, thus the selection of appropriate earthquake time histories.

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