First Draft

PROBABILISTIC SEISMIC HAZARD ASSESSMENT IN TERMS OF ENGINEERING PARAMETERS IN GREECE

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ABSTRACT

The present study is a probabilistic seismic hazard assessment in terms of well known engineering parameters, 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 and Tselentis (2007), based on strong motion recordings of Greek earthquakes: peak ground acceleration, peak ground velocity, spectral velocity, elastic input energy for 0.2 and 1 sec, Arias intensity, cumulated absolute velocity (CAV), CAV_5 and spectral intensity. A Poissonian model of earthquake occurrence is assumed and the corresponding hazard maps on the basis of the recommendations in EUROCODE8 (475 year return period) are evaluated.

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 (Benavent-Climent et al. 2002; Chai and Fajfar 2000; Decanini and Mollaioli 1998; Housner 1956; Uang and Bertero 1988). Although there is not a general established energy-based seismic design method yet; these investigations highlight the importance of using 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.

For performance-based design, the ground motions may need to be specified by acceleration time histories consistent with the expected earthquake scenarios. The acceleration time histories can be selected to reflect an earthquake scenario; scaled to match or exceed the controlling design earthquake over a period of interest; or generated on the basis of a model of the earthquake source. Therefore, in the view of seismic hazard, the ground motion characteristics are essential and the measures that reflect these characteristics should be considered in all seismic hazard assessment.

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. These engineering ground motion parameters are supposed to be objective measures of ground motion damage potential and have geotechnical and structural application.

In the framework of the PSHA, I_a has begun to be considered as one of the basic ground motions measures. Abdrakhmatov et al. (2003) have computed a probabilistic seismic hazard analysis in terms of I_a for the territory of Kyrgyzstan, and Peláez et al. (2005) for south-eastern Spain. Both studies have shown that I_a is a good landslide hazard descriptor.

Probabilistic seismic hazard maps, in terms of SI and considering local soil conditions were reported by Peruzza et al. (2000). The major findings of that study was that the SI, can well synthesise the overall information available from traditional probabilistic studies, but also suggests that soil condition is a first-order ingredient for effective seismic hazard mapping at national level.

Recently, the Electric Power Research Institute – (EPRI), have established a CAV criterion as an alternative to the classic conservative lower bound body wave magnitude cut-off value of 5.0 (approximate moment magnitude of 4.6) to integrate into the PSH. The application of a minimum CAV value significantly reduces the contribution of small magnitude earthquakes to the total hazard. The magnitude of the dominant earthquake is shown to increase from 5.25 to 5.8 by applying the minimum CAV as a filter. This example shows that the past PSHA studies that used a minimum moment magnitude of 4.6 can overestimate the hazard by including earthquakes that are not damaging but contribute significantly to the hazard when they are located at short distances from the site, (EPRI 2006).

Chapman (1999) studied the implication of VE_i in PSHA. The study concluded that if the PSH was assessed on the basis of VE_i, strong magnitude earthquakes contributed more to total hazard compared to a conventional elastic response spectrum-based hazard assessment. It should be mentioned here, that a similar conclusion is derived from a comparison between duration-based and acceleration-based seismic hazard assessments, (Koutrakis et al., 2002).

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 (Papaioannou 1984; Papaioannou and Papazachos 2000; Papazachos et al., 1985; Papoulia and Slejko 1997; Shebalin et al., 1975) or as PGA, PGV and strong motion duration (Algermissen et al., 1976; Banitsiotou et al., 2004; Burton et al., 2003a; Koutrakis et al., 2002; Makropoulos and Burton 1985; Mantyniemi et al., 2004; Papaioannou 1984; Papazachos et al., 1993; Papazachos et al., 1990; Papazachos et al., 1992; Theodulidis and Papazachos 1992; Tsapanos 2003; Tsapanos et al., 2003)

Papazachos et al. (1993) have reported seismic hazard maps for Greece based on PGA, PGV and macroseismic intensity. The results of the hazard analysis, i.e. the seismic hazard parameters versus the mean return period for T = 475 yr were fitted by log-linear equation, and based on these recurrence relationships, four zones of equal seismic hazard were reported for the territory of Greece.

Papaioannou and Papazachos (2000) have investigated seismic hazard in Greece using both time-independent and time-dependent models. They reported results for 144 broad sites and the major finding was the new seismic regionalization of the broader Aegean area. They have employed PGA, PGV and macroseismic intensity as hazard parameters; they fitted seismic hazard parameters versus the mean return period for T = 475 yr by log-linear equation; and reported the expected values for the 144 sites.

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; 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 reported I_a 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. The study considered the recently proposed predictive equations by Danciu and Tselentis (2007). Secondary aim of the present study was to investigate the relationship between estimated values of the engineering ground motion parameters and mean return period, assuming time-independent occurrence of earthquakes. The return periods derived for this relationship were fitted by linear regression and results were reported for 144 broad sites.

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.

GROUND MOTION PARAMETERS

The engineering ground motion parameters, selected to describe the earthquake destructiveness potential, can be classified as structure-independent or structure-dependent. The structure-independent parameters: PGV, I_a, CAV, CAV_5, are simple in definition, based only on the recorded acceleration time history and have general applications (Danciu and Tselentis 2007). Generally speaking, the independent-structure parameters would reflect the level of ground motion on the short-period structures.

Structure-dependent parameters: SI, VE_i, and S_v are based on recorded acceleration time history and physical characteristics of the structure. They request more computational effort than structure-independent parameters and are appropriate for structure specific analysis. Elastic input energy-E_i for PSHA is converted into elastic input energy-equivalent velocity - VE_i. The structure-dependent parameters SV and VE_i were computed for both short and long periods: 0.2 and 1.0 sec and at 5% damping ratio. Short period S_v (0.2s) and VE_i (0.2s) reflect the level of shaking that will have effects on short-period structures (one-to two story buildings). Long period S_v (1.0s) and VE_i (1.0s) reflect the level of shaking that will have effect on longer-period structures (10+ story buildings). Due, to its definition, SI would reflect the ground motion effects on the long period structures.

Therefore, by taking into account these ground motion parameters, herein referred as engineering ground motion parameters, into the seismic hazard analysis, a better distribution of the earthquake damage potential can be defined. This will support the selection of proper earthquake scenarios and proper characterization of the earthquake time histories for structural design. Moreover, by using consistent hazard parameters, the PSHA results would conduce to improved visualization of equal seismic hazard, improved regionalization of the hazard.

PROBABILISTIC SEISMIC HAZARD METHODOLOGY

The PSHA methodology was introduced more than forty years ago, in the landmark papers by Cornel (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 and 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) used in the present investigation are those reported in Table1 of Papaioannou and Papazachos (2000).

The set of predictive equations developed for engineering ground motion parameters and proposed by Danciu and 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 (Danciu and Tselentis 2007):

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

where Y_{ij} is the response variable (the arithmetic average of the two horizontal components) from the j^{th} record of the i^{th} event, M_i is the moment magnitude of the i^{th} event, R_{ij} is the epicentral distance from the i^{th} event to the location, h is the "fictitious" focal depth obtained from the regression analysis, and ε_{ij} is the error term for the j^{th} records from the i^{th} earthquake.

The error term in equation (1) is normally distributed with zero mean and standard deviation σ^2. The error term, accounts the ground motion variability and has an important contribution to the final results of the probabilistic seismic hazard analysis. Neglecting the ground motion variability would produce lower values on the PSHA results (Bender 1984; Bommer and Abrahamson 2006). The ground motion parameters are assumed to be log-normally distributed about the mean, with a constant standard deviation σ^2 for all magnitudes and distances. The coefficients of the predictive equations for each one of the considered engineering parameters are presented on the Table 1.

The dummy variables S, F refer to the site classification and fault mechanism, respectively. 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 and 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 eight different return periods: 25, 50, 75, 100, 150, 200, 475 and 950 years. 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.

Furthermore, 144 sites were selected to geographically cover the area of the seismic zones included in the Greek Seismic Code – EAK (2003). The updated version of EAK 2003 divides into three different zones of seismic hazard the country based on PGA and macroseismic intensity. The selected sites together with the equal seismic hazard zones defined by EAK 2003 are presented on the Figure 2.

For every site, the expected engineering ground motion parameters at the selected return periods were computed. Next, the sites were classified accordingly to the zonation presented in the EAK 2003; then for each zone the expected values were averaged and finally, the results were fitted with a simple linear regression of the form:

$$\log_{10} Y = a + b \log_{10} X \tag{1}$$

where Y is the estimated engineering ground motion parameter, X is the mean return period, and a, b are the intercept and the slope obtained by fitting the data. Following the aforementioned approach, one could obtain the engineering ground motion parameters for a given site and for a given return period.

PSHA RESULTS

The results of PSHA as mentioned previously have been generated in the form of hazard curves for the 144 selected sites that were distributed within the three equal seismic hazard zones. The recurrence relationships for the three zones, defined by the EAK 2003, are shown in Figure 3 to 4; and summarized in Table 2. The plots in Figure 3 depict the recurrence relationships for the three seismic zones based on PGA, PGV, I_a, CAV, CAV_5, SI and selected mean return periods. Figure 4 presents S_v and VE_i at the selected periods of 0.2s and 1.0s. It can be observed that the fitted lines corresponding to the three different zones of equal hazard tend to increase with increasing return period, achieving greater PGA values for the third seismic hazard zone.

Following the results summarized in Table 2 estimated ground motion parameters, for different return periods and different seismic zones can be assessed. For comparison, a mean return period of 475 years is selected and for the three seismic hazard zones the engineering parameters estimated are compared with the estimated parameters defined by EAK 2003. The results are shown on Table 3, and in addition, the table has been completed with the values corresponding PGA, PGV, macroseismic intensity and bracketed duration reported elsewhere (Koutrakis et al., 2002; Papaioannou and Papazachos 2000). The aforementioned studies have reported the PSHA results for the old Greek Seismic Code –NEAK, which consider four equal seismic hazard zones.

The updated version - EAK 2003 incorporates the first two seismic zones defined in NEAK as being one seismic hazard zone with a lower acceleration level equal to 0.16g. Comparing the estimated PGA values on the Table 3 it can be observed that the PGA values estimated in the present study exhibit higher values for all seismic hazard zones. This difference can be explained by the fact that the present study considers the uncertainty in the ground motion estimates. We have investigated the sensitivity of accounting the standard deviation of the PGA predictive equations for the selected seismic hazard zones. The results are reported on the same table, and as it can be seen an increase of almost 15% in PGA is obtained for all equal seismic hazard zones.

Furthermore, the relationship between macroseismic intensity and engineering parameters estimated at the selected sites (144) has been investigated. For all these sites, the estimated engineering parameters accompanied by the macroseismic intensity reported by Papaioannou and Papazachos (2000) for a return period of 475 years are reported on Table 4. It can be observed that the maximum predicted values of the intensity and engineering parameters does not occur at the same sites.

The higher estimated intensity values occur at the sites surrounding the Southern Aegean while the maximum engineering parameters values arise into the Western Aegean. This discrepancy can be explained by the fact that the Southern Aegean region is dominated by intermediate depth earthquakes. These intermediate seismic zones have not been considered into the present analysis, thus the PSHA results in these region are underestimated.

Another remark can be done, by comparing the results of the sites nr 7 – Alexandroupolis and nr 77 – Kyparissia. For both sites the value of reported intensity (at the mean return period of 475years) is the same 7.55. The values of the estimated engineering parameters differ, and it can be observed that the estimated values at the site nr 77 – Kyparissia are larger that those presented at the site nr 7 – Alexandroupolis. The sites are located on different seismogenic zones, described by different annual rates. The site nr.7 – Alexandroupolis is located in the zone with an annual rate of earthquakes with magnitude greater than 5.0 equal to 0.158. The annual rate of earthquakes with magnitude greater than 5.0 for the site nr.77 – Kyparissia is equal to 0.960.

Therefore, the engineering parameters reports improved contribution to the hazard of frequent earthquakes, while the intensity does not. To convert the hazard from engineering parameters to intensity, we have fitted the results form Table 4 by a simple linear regression of the form of Eq. 1, where Y is the macroseismic intensity and X the engineering parameters. The equations, the associated coefficient of the determination R^2 (R-sqrt) and fitted lines for all the parameters are plotted in the Figures 5 and 6. The probabilistic seismic hazard, for a return period of 475 years, at any of these sites can be assessed in terms of macroseismic intensity by converting the estimated engineering parameters into intensity.

An alternate approach of reporting the PSHA results is the representation of the estimated hazard parameters in the form of contour maps. In the following the probabilistic seismic hazard maps of Greece based on the selected engineering ground motion parameters are presented. We assume a mean return period of 475 years and 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 the presented 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 contours.

PGA values shown in Figure 7 emphasize the three regions of high seismic hazard. The maximum PGA values are reached in the Western Hellenic Arc, and specially on the area of Levkas - Cephalonia – Zakinthos islands. The range of PGA values in this area is 0.45g to 0.65g. The EAK 2003 map in Figure 7 places Lefkas - Cephalonia – Zakinthos islands in the hazard zone III, with a PGA value equal to 0.36g (Table 4). 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 mentioned here that the ground motion parameters estimated may be lower since intermediate depth earthquakes which dominate these regions, were not taken into account and only shallow events were considered.

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 8. Ia shows a similar variation as that of PGA (Fig.7) with the highest hazard occurring on the same regions, but covering a larger area than in the case of PGA. This difference may be associated with the fact that the coefficient for the magnitude from the predictive equation is greater for PGV than 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 9, Ia is mapped. By mapping the I_a, the earthquake induced landslide and liquefaction potential can be estimated. Keefer and 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

Figure 10 and 11 summarize the maps of the estimated CAV and CAV_5 values. These maps have similar pattern with the previous maps, in sense that they 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 12. 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 the Hellenic Arc. The region exhibits 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 Figures13a-b and Figures 14a-b respectivelly. From the comparison of the four maps it becomes clear that 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, it 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.

CONCLUSIONS

Seismic hazard analyses implementing engineering ground motion parameters related to the seismic response of various kinds of structures to ground shaking has a great importance in all mitigation policies of seismic risk.

In this investigation 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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TABLES

	$\log_{10}(Y_{ij}) = a + bM_i + c\log_{10}\sqrt{R_{ij}{}^2 + h^2} + eS_o + fF_o + \varepsilon_{ij}$								

Table 1: Coefficients of the predictive equations (attenuation laws) selected for the present study.

Table 2: Regression coefficients of the recurrence relationships between estimated ground motion parameters and different mean return periods for the three zones defined by EAK 2003

PGA

PGV

I_a

CAV

CAV_5

SI

S_a(0.2 sec)

S_a(1 sec)

VE_i(0.2 sec)

VE_i(1 sec)

Macroseis

PGA

PGA

(Papaioannou an

PGV

(Papaioannou an

Bracketed Duration

of acc

(Koutrakis

PGA

PGA (%g) withou

PGA (%g) with

PGV

Ia (c

CAV

Table 4: Mean values for engineering parameters estimated for Mean-return Period of 475 Years and for all the seismic hazard zones considered in the two Greek Seismic Code: NEAK (1993) and EAK (2003)

			Long
			22.748
			24.785
			25.719
			21.396
			23.432
			22.08
			25.87
			22.764
			21.329
			24.651
			21.145
			22.381
			25.887
			21.262
			21.896
			24.935
			22.381
18	ARGOSTOLION	[illegible]	20.477
19	ARIDAIA	40.97	22.047
20	ARNAIA	40.486	23.583
21	ARTA	39.15	20.978
22	ASPROVALTA	40.72	23.699
23	ATALANTI	38.649	22.982

Table 5: Estimated engineering parameters and intensity (475 years) for the 144 selected sites

Table 5: *(continued)*

			Long
			22.915
			27.306
			21.779
			24.1
			21.663
			22.982
			23.065
			22.431
			22.414
			24.05
			20.694
			22.848
			22.865
			22.114
			23.332
			21.412
89	MESSINI	37.18	21.913
90	METSOVON	39.768	21.178
91	MILOS	36.729	24.417
92	MITHYMNA	39.367	26.17
93	MOIRAI	35.043	24.868

FIGURES

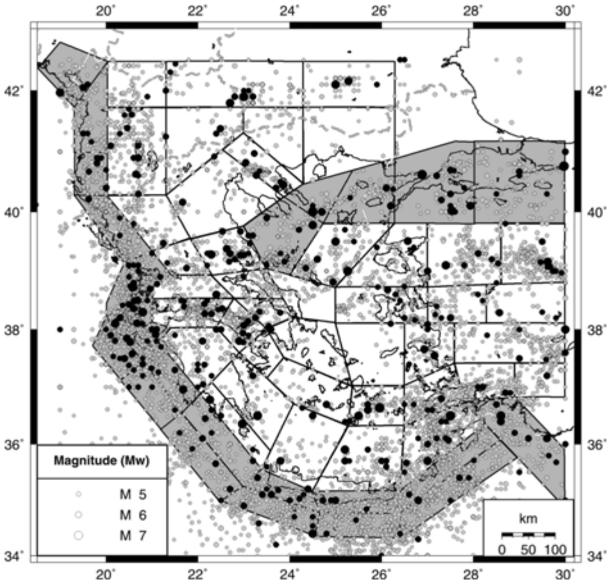

Figure 1: Geographical distribution of the major shallow earthquakes (M_w> 5) and the seismogenic sources proposed by Papaioannou and Papazachos (2000). Grey filled sources correspond to thrust and strike slip faulting style.

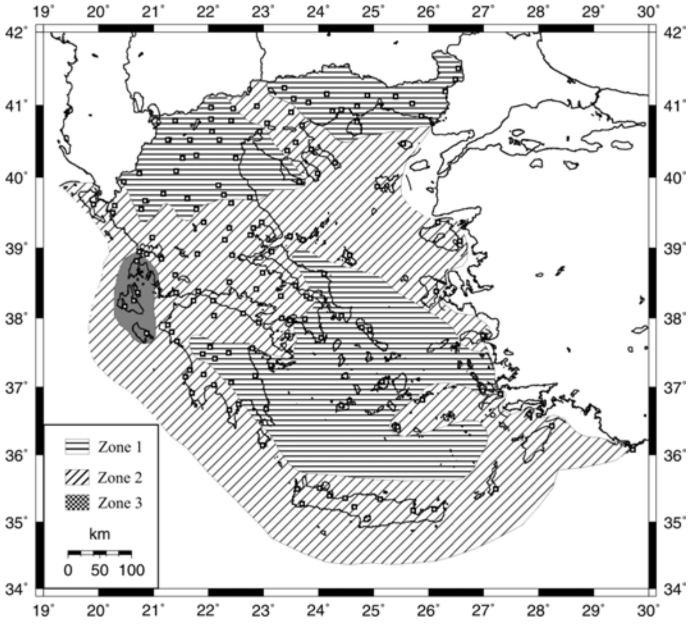

Figure 2: The seismic hazard zonation of Greece according to the Greek Seismic Code – EAK 2003

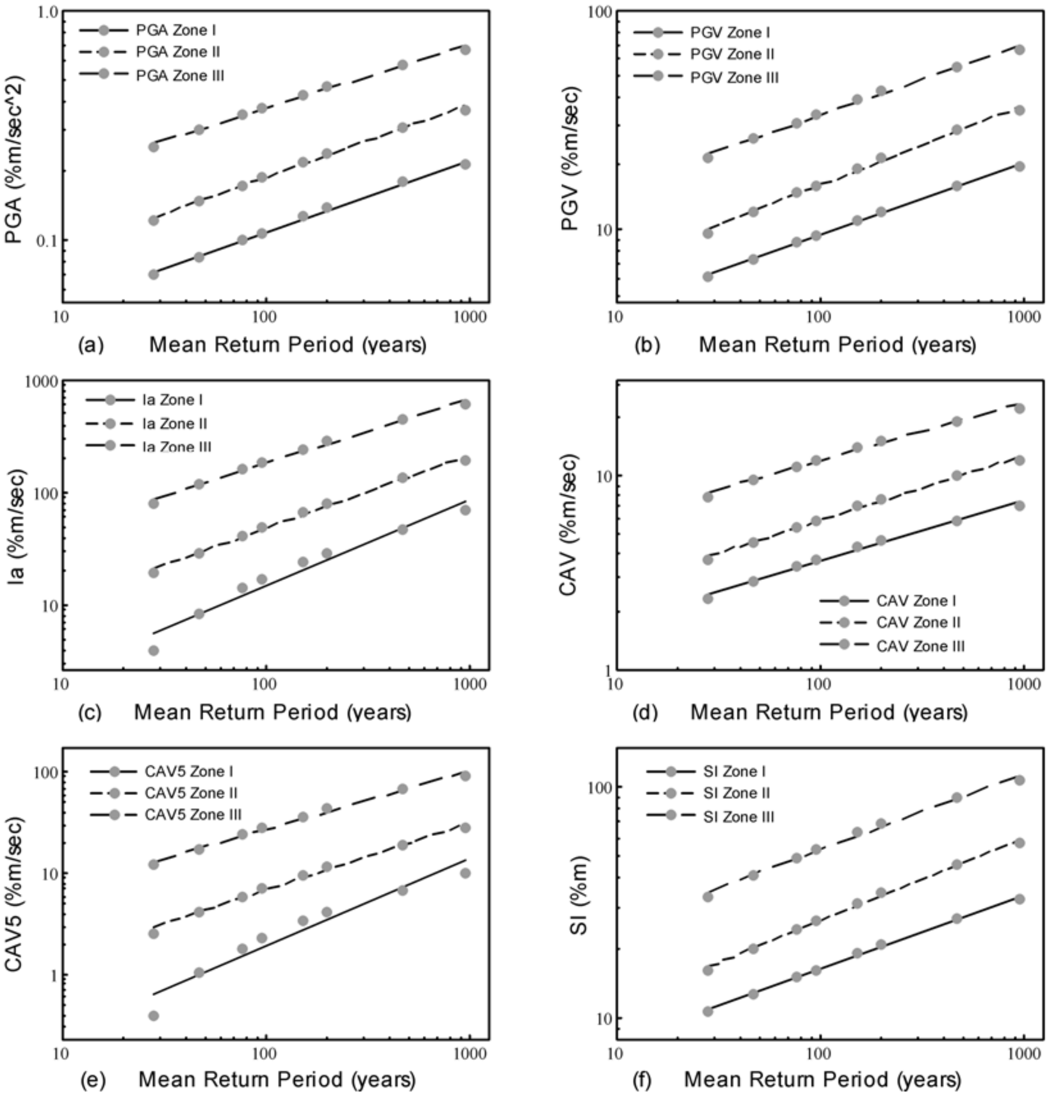

Figure 3: Recurrence relationships of mean ground motion parameters and different mean return periods for the three zones defined by EAK 2003: (a) PGA, (b) PGV, (c) I_a, (d) CAV, (e) CAV_5 and (f) SI.

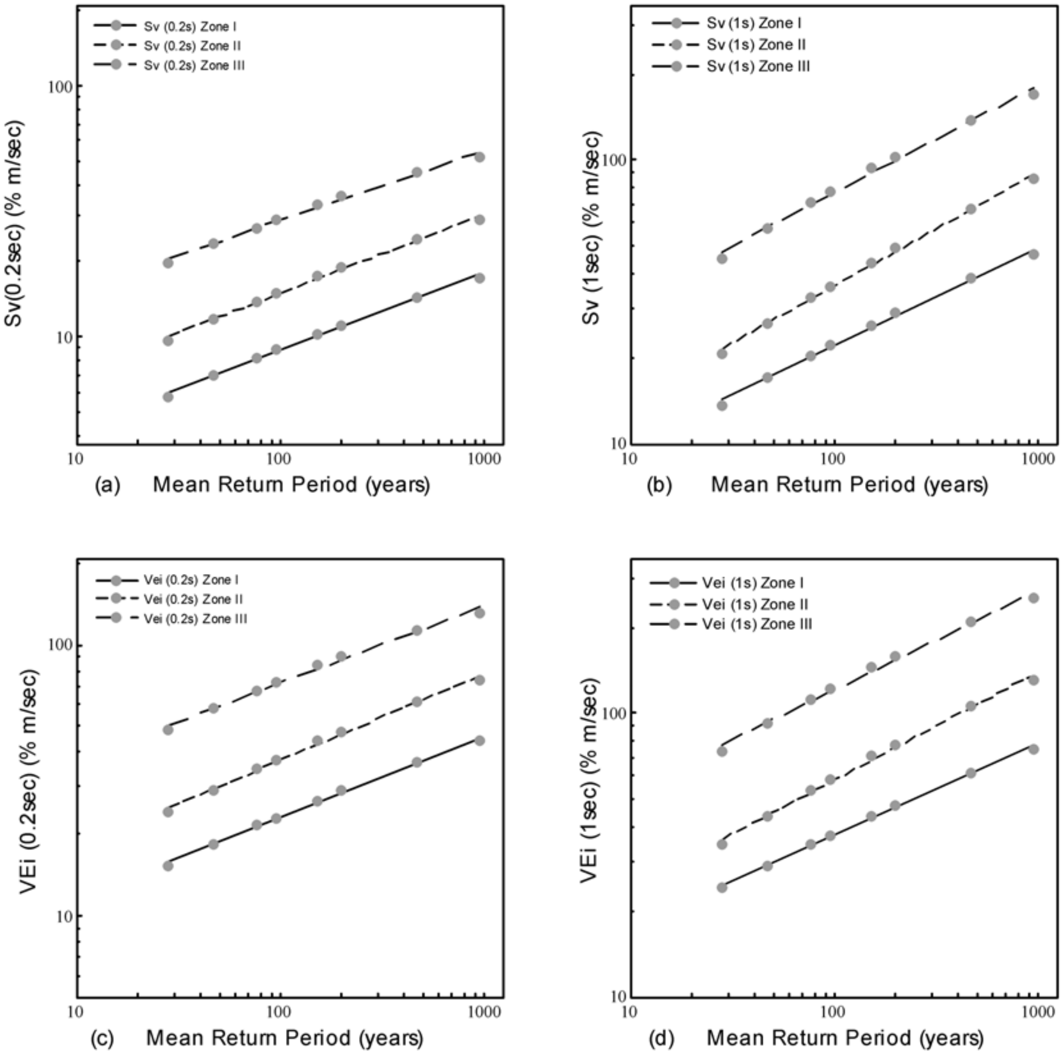

Figure 4: Recurrence relationships of mean ground motion parameters and different mean return periods for the three zones defined by EAK 2003: (a) S_v (0.2 sec), (b) S_v (1 sec), (c) VE_i (0.2 sec) and (d) VE_i (1 sec).

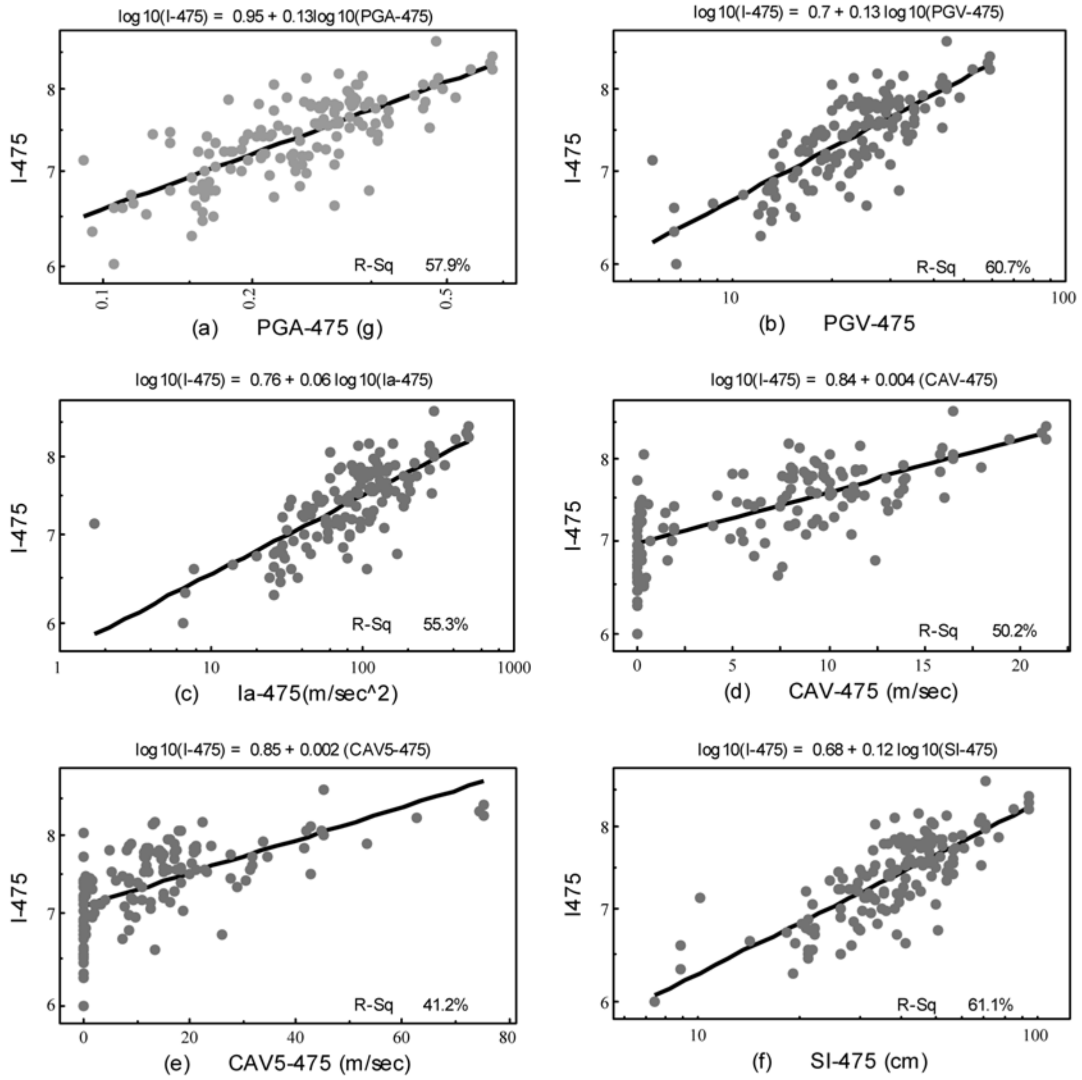

Figure 5: Fitted line results for (a) PGA, (b) PGV, (c) I_a, (d) CAV, (e) CAV_5 and (f) SI vs. macroseismic intensity estimated for the 144 sites at a constant mean return period of 475 years.

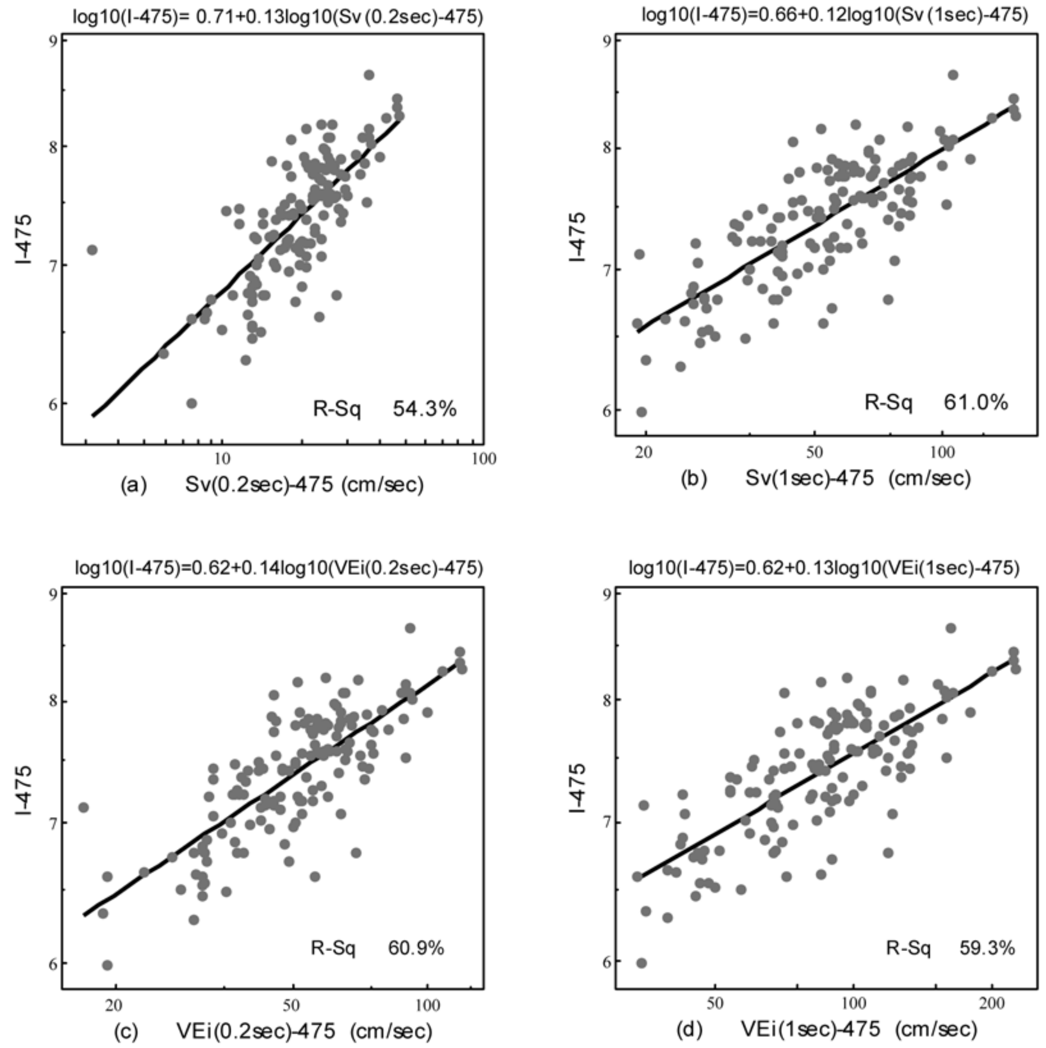

Figure 6: Fitted line results for ((a) S_v (0.2 sec), (b) S_v (1 sec), (c) VE_i (0.2 sec) and (d) VE_i (1 sec).vs. macroseismic intensity estimated for the 144 sites at a constant mean return period of 475 years.

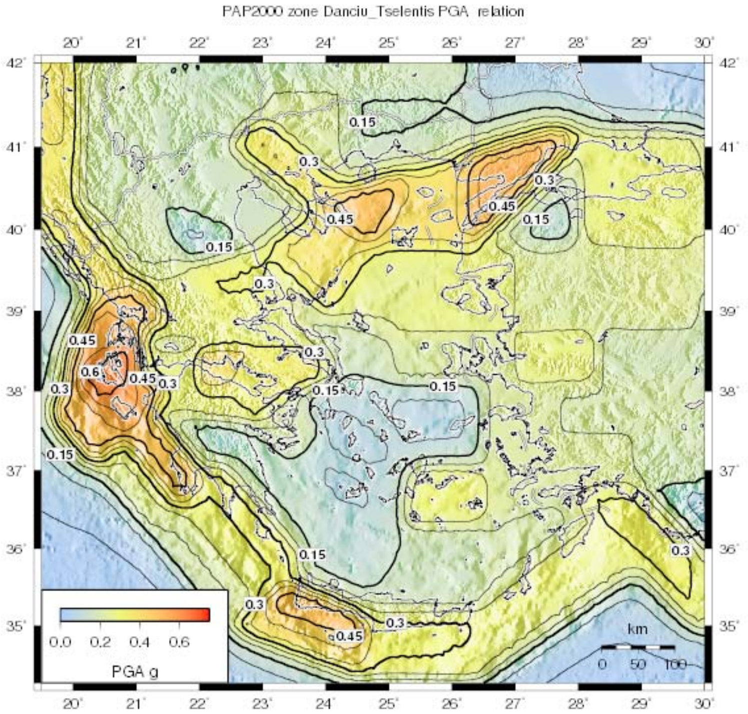

Figure 7: Seismic hazard map in term of PGA for Greece. Results are for an ideal bedrock soil condition estimated at mean return period of 475 years

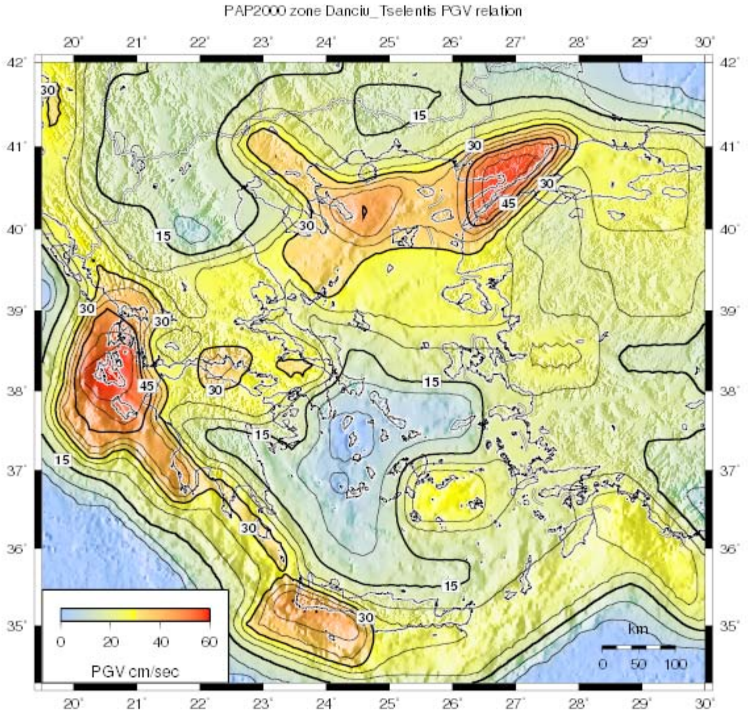

Figure 8: Seismic hazard map in term of PGV for Greece. Results are for an ideal bedrock soil condition estimated at mean return period of 475 years

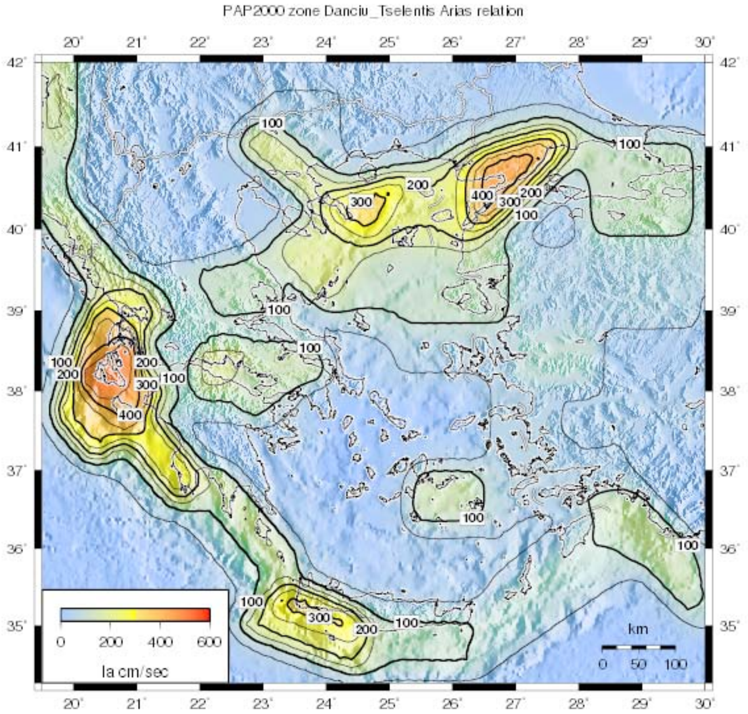

Figure 9: Seismic hazard map in term of I_a for Greece. Results are for an ideal bedrock soil condition estimated at mean return period of 475 years

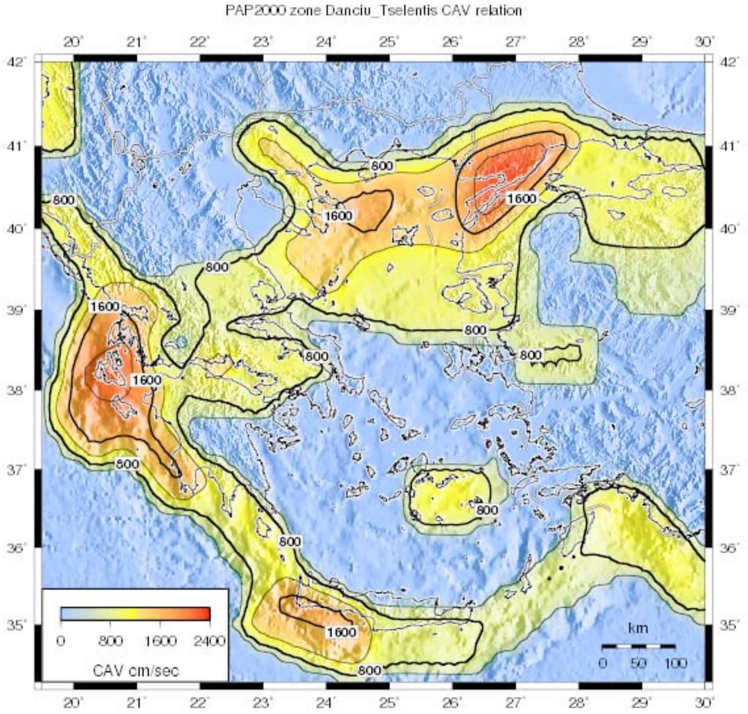

Figure 10: Seismic hazard map in term of CAV for Greece. Results are for an ideal bedrock soil condition estimated at mean return period of 475 years

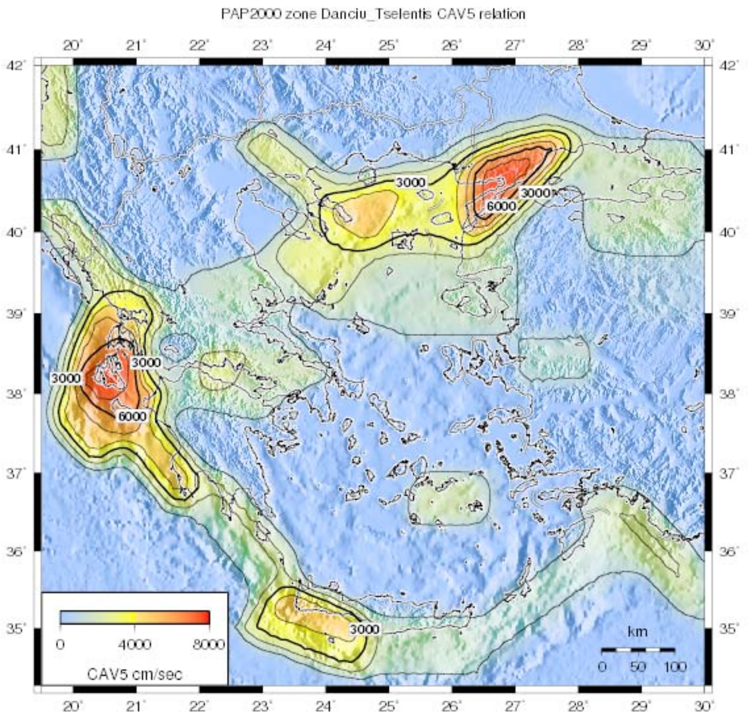

Figure 11: Seismic hazard map in term of CAV_5 for Greece. Results are for an ideal bedrock soil condition estimated at mean return period of 475 years

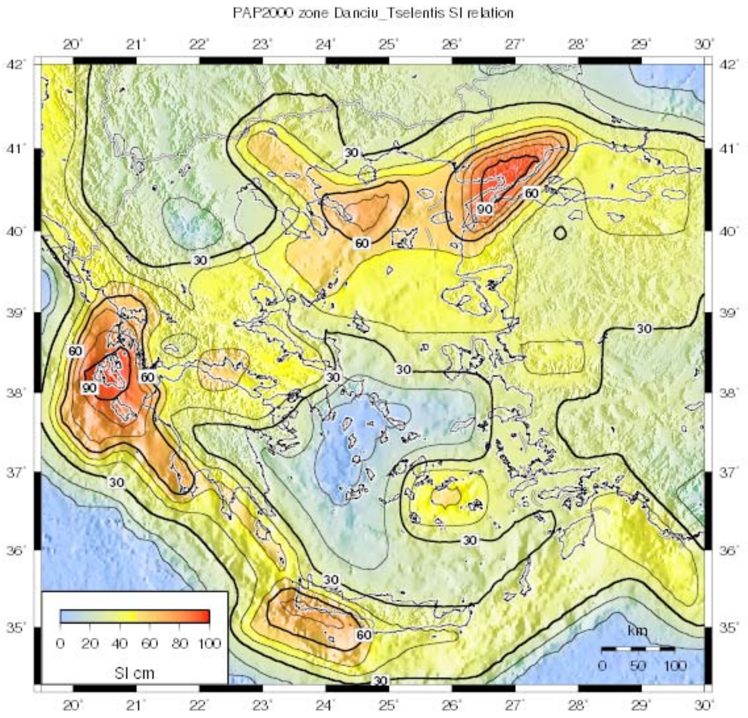

Figure 12: Seismic hazard map in term of SI for Greece. Results are for an ideal bedrock soil condition estimated at mean return period of 475 years

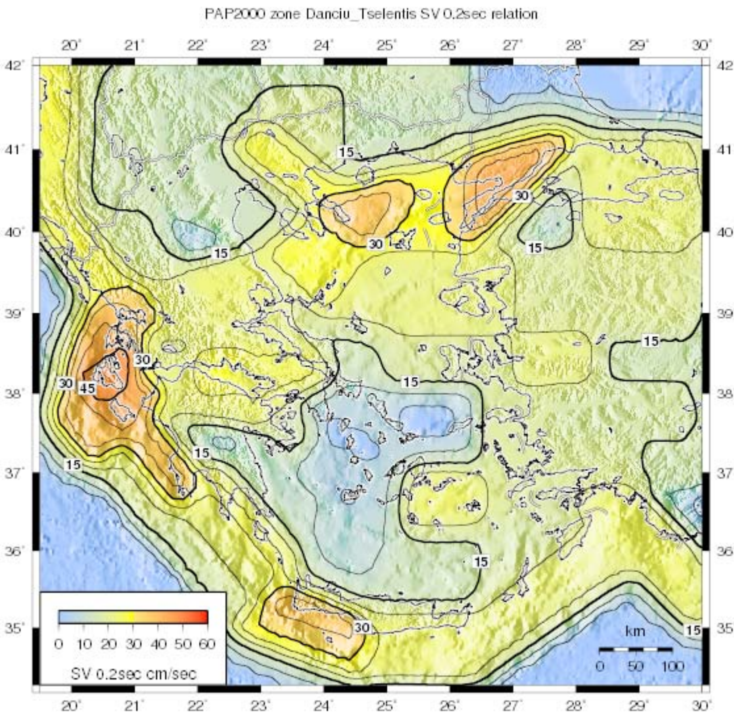

Figure 13a: Seismic hazard map in term of S_v (0.2sec) for Greece. Results are for an ideal bedrock soil condition estimated at mean return period of 475 years

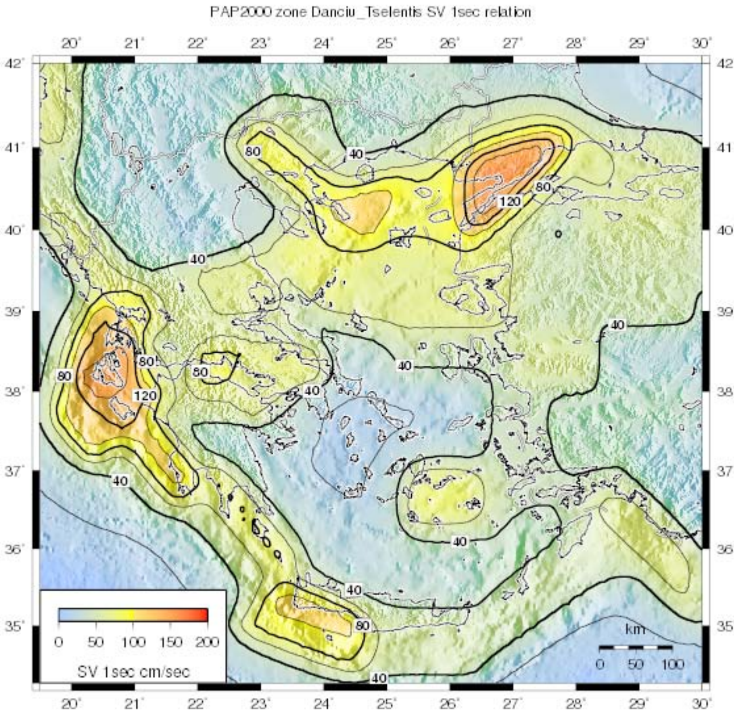

Figure 13b: Seismic hazard map in term of S_v (1 sec) for Greece. Results are for an ideal bedrock soil condition estimated at mean return period of 475 years

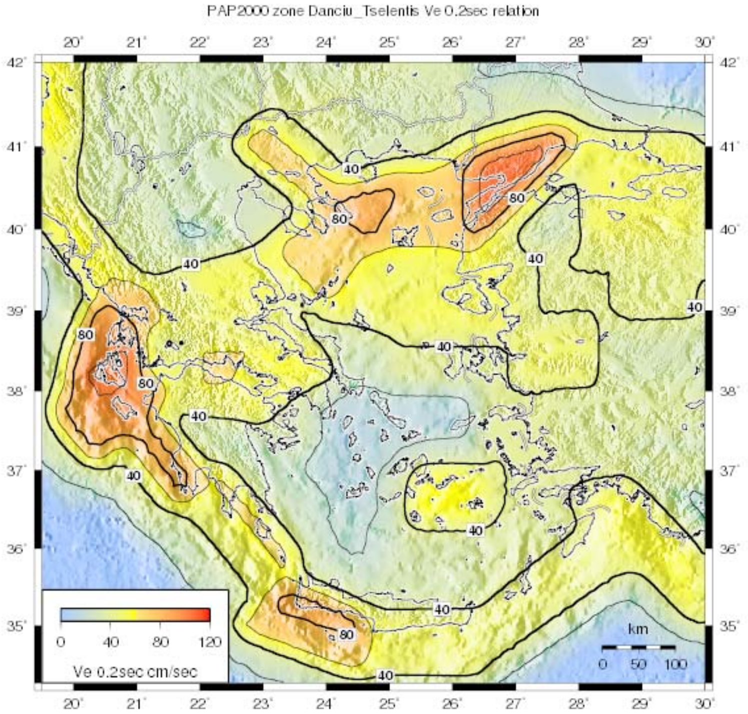

Figure 14a: Seismic hazard map in term of VE$_i$ (0.2sec) for Greece. Results are for an ideal bedrock soil condition estimated at mean return period of 475 years

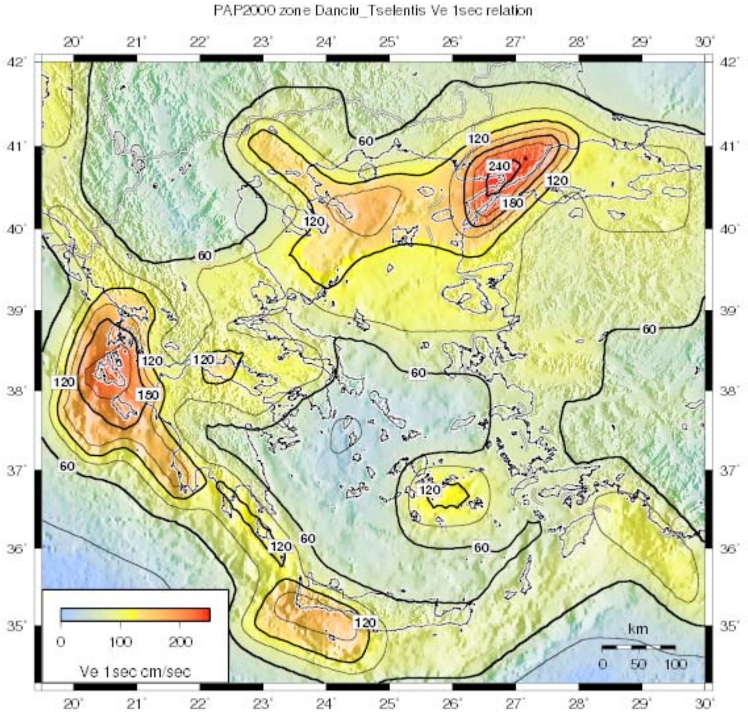

Figure 14b: : Seismic hazard map in term of VE$_i$ (1sec) for Greece. Results are for an ideal bedrock soil condition estimated at mean return period of 475 years