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SEISMIC HAZARD OF EASTERN MEDITERRANEAN REGION

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ABSTRACT

In the present study, probabilistic seismic hazard assessment was conducted for the Eastern Mediterranean region based on several new results: (1) a new comprehensive earthquake catalog, (2) seismic source models developed based on new geological, seismicity and geodetic data; and (3) new ground motion prediction equations (GMPEs). As the number of available regional ground motion records is not adequate to develop successful local GMPEs, the data in hand was employed for determining the most representative GMPEs that were developed for similar tectonic environments. Based on different earthquake recurrence models, seismic source models, and GMPEs used in the analyses, sensitivity of seismic hazard results was investigated with the application of logic tree approach. Results indicate higher peak ground acceleration values for the Cyprus island than those suggested by Eurocode 8.

Introduction

Seismic hazard of the Eastern Mediterranean Region, more specifically that of the island of Cyprus, has been studied by several researchers up to now. Their work can be categorized under two main headings: (1) those that made use of the maximum observed shaking approach (i.e. Ergunay and Yurdatapan, 1973; Republic of Cyprus Geological Survey Department (CGSD), 1992; CGSD, 2007 – the latter two has been used between 1992-2007 and 2007-present respectively as the official seismic zonation maps in the southern part of the island) and (2) those that are based on the probabilistic seismic hazard assessment approach (i.e. Erdik et al., 1997; Can, 1997; Erdik et al., 1999 as part of the Global Seismic Hazard Assessment Program - GSHAP; Jimenez et al., 2001 as part of the Seismotectonics and Seismic Hazard Assessment of the Mediterranean Basin project –SESAME; Rogers and Algermissen, 2005 and Cagnan and Tanircan, 2009). The seismic hazard estimates of these studies vary considerably; for example for the southwestern city of Paphos, the peak ground acceleration (PGA) values vary between 0.1g-0.4g.

One of the main reasons for this considerable variability is the absence of local GMPEs and more importantly absence of local strong motion records that would guide the researchers in quantitative ranking of GMPE's, which were developed for similar tectonic environments, according to their suitability. This is partly due to the fact that modern strong motion network operation did not start on the island until late 1990s with the

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number of instruments still being very limited and partly, due to current network operators' not opening the available data to public. However, recently the database of CGSD became accessible through Kyriakides (2007). *In the present study, main emphasis is given to quantitative selection of suitable GMPEs for the Eastern Mediterranean Region based on this new local strong motion database, in addition to recently compiled Turkish (Akkar et al 2009) and European strong motion databases (Akkar and Bommer, 2007).* The findings were then applied to the seismic source models of Cagnan and Tanircan (2009) to obtain improved seismic hazard estimates for the region.

Quantitative Comparison of Available GMPEs

Strong Motion Data of Cyprus

A total of 28 strong motion instruments have been deployed on Cyprus since 1997; 24 (owned by CGSD) of these being in the southern part of the island and 4 (owned by METU-NCC) of them in the northern part of the island. For the temporary period of 1996-2005, Kandilli Observatory and Earthquake Research Institute (KOERI) also recorded data through 6 instruments in the northern part of the island. The events, of which strong motion records were obtained on the island by CGSD, METU-NCC and KOERI are listed in Table 1.

Table 1. List of events and corresponding number of records in the strong motion database of Cyprus (SS: strike slip, N: normal, R: reverse and U: unknown faulting mechanism)

Epicenter	Network	Rec. #	Date	Time	R_{epi}	M_w	Mech.
34.41N-32.12E	KOERI/CGSD	3	09/10/96	13:10:52	95-183	6.8	SS
34.27N-32.37E	CGSD	3	13/01/97	10:19:26	53-76	5.7	SS
34.49N-32.30E	CGSD	4	25/05/99	17:15:29	57-97	5.5	N
34.63N-32.86E	CGSD	1	11/08/99	20:00:12	9	4.0	R
34.74N-32.88E	CGSD	1	11/08/99	04:43:25	9	4.1	R
34.75N-33.00E	CGSD	1	11/08/99	01:28:38	9	4.2	R
34.64N-32.85E	CGSD	2	11/08/99	04:27:33	5-9	4.8	R
34.75N-33.03E	CGSD	3	11/08/99	04:40:20	5-9	5.6	R
34.79N-33.00E	CGSD	3	12/08/99	18:57:36	10-13	4.2	R
34.81N-32.98E	CGSD	4	13/08/99	15:31:40	17	4.2	R
34.79N-33.02E	CGSD	1	17/08/99	15:06:20	13	4.6	R
34.78N-33.01E	CGSD	1	23/08/99	15:02:23	13	4.0	R
34.83N-32.99E	CGSD	1	26/08/99	01:48:50	18	4.4	R
34.67N-33.29E	CGSD	1	23/04/00	04:56:39	15	4.0	U
34.27N-33.32E	CGSD	5	16/12/00	14:27:20	51-63	4.4	U
34.87N-33.75E	CGSD	1	01/09/01	19:22:46	77	4.2	U
34.94N-32.51E	CGSD	2	10/11/01	02:23:57	20-28	4.3	U
35.16N-32.72E	CGSD	1	25/04/02	22:34:52	51	4.0	U
34.75N-33.16E	CGSD	2	20/06/02	02:55:48	14-15	4.1	U
34.70N-33.12E	METU-NCC	2	16/09/09	17:09:40	56-88	4.9	U
34.52N-32.13E	KOERI	2	09/10/96	14:19:38	133-178	5.4	U
36.88N-35.37E	KOERI	4	27/06/98	13:55:52	234-285	6.2	SS

The metadata for these records were developed by applying the same hierarchical procedure that was used in the preparation of Turkish strong motion database (Akkar et al., 2009). The full waveforms of the CGSD data were not available to us hence the accurate processing technique of Boore and Akkar (2003), which was also used in the cases of Turkish and European databases, could only be applied to the data from northern part of the island. The PGA values given in Kryiakides (2007) are the maximum PGA (PGA_{MAX}) values. In this study, the corresponding geometric mean PGAs (PGA_{GM}) were estimated by using the PGA_{MAX} - PGA_{GM} relationships suggested by Beyer and Bommer (2006). The data in hand is far from having uniform magnitude and distance distributions: 60% of the records in the strong motion database of Cyprus have M_w values less than 5.0, 50% have epicentral distance (R_{epi}) values less than 30 km. As a result of this, in the quantitative analysis of GMPEs, we decided to consider also the recently compiled Turkish strong motion database (Akkar et al., 2009) in addition to the European strong motion database (Akkar and Bommer, 2007). Only the European database records from Greece, Uzbekistan, Armenia, Iran, Georgia, Albania in addition to Turkey (except from the ones that already present in the Turkish strong motion database) were considered in this study; as these counties are situated on the same subplate as Cyprus (Jackson, 1988). For most of the records of the European database and all of Cypriot database, the station site condition information is based on surface geology in the form of rock, stiff and soft soil classes. In this study, for the rock, stiff and soft soil conditions V_{s30} ranges of $760 \leq V_{s30} \leq 1080$, $360 \leq V_{s30} \leq 760$ and $180 \leq V_{s30} \leq 360$ m/s assumed to be applicable. For entries with unknown V_{s30} values of these databases, arithmetic means of these ranges were employed as the corresponding V_{s30} parameter. For the Turkish strong motion database, this was not an issue as V_{s30} measurements are available for each record.

Comparison of GMPEs with Observed Data

In the previous seismic hazard studies carried out for the East Mediterranean region, GMPEs such as Boore et al. (1997) (in Erdik et al., 1997), Campbell and Bozorgnia (1994) (in Rogers and Algermissen, 2005), Akkar and Bommer (2007) and Boore and Atkinson (2008) (in Cagnan and Tanircan, 2009) were employed. In addition to these, it was our intension to test recently derived GMPEs for Cyprus, Greece, Turkey and Europe (Kyriakides, 2007; Darciu and Tselentis, 2007; Akkar and Cagnan, 2009; Kalkan and Gulkan, 2004 and Bommer et al. (2007), respectively) for their goodness-of-fit with the observed regional ground motion data. However parameter compatibility between the databases in hand and the GMPEs to be tested is a key issue in these kinds of studies. The distance parameter in Campbell and Bozorgnia (1994) is the distance to seismogenic rupture. Unfortunately, the metadata of the databases considered are not adequate to correctly calculate this distance parameter hence Campbell and Bozorgnia (1994) model is excluded from our quantitative comparisons. The strong motion data in hand from intermediate depth events was not adequate in number to make similar quantitative comparisons for intermediate depth GMPEs. Therefore, we limited the scope of this goodness-of-fit analysis to shallow events and GMPEs developed for crustal earthquakes.

In Scherbaum et al. (2004), a number of statistical measures of the goodness-of-fit of a model to a sample of observed data are described that enables quantitative comparisons possible. In the present study, the likelihood-based scoring system of Scherbaum et al. (2004) is preferred as with this method effects associated with the fit of the median values as well as the shape of the underlying distribution of total model residuals can be captured. In this method, the performance of the GMPEs is assessed by considering both the distributions of the normalized total model residuals (expected to follow standard normal distribution) and the distribution of likelihood values (expected to follow uniform distribution between zero and one). In the case of unbalanced databases (i.e. with certain events providing large numbers of records) however, disagreement of total normalized residuals with standard normal distribution can very well be due to dissimilar numbers of records from each event rather than systematic difference between the observed values and model estimates. In order to correct this deficiency, Stafford et al. (2008) modified the likelihood method of Scherbaum et al. (2004) so that rather than total model residuals, inter-event and intra-event residuals can be considered in the analysis which remain normally distributed even in the case of unbalanced databases. Hence after applying the original likelihood based scoring system of Scherbaum et al. (2004) to all the GMPEs, the Stafford et al. (2008)'s modified method was employed as well enabling observation of degree of improvement in results with the latter method.

Table 2. GMPE rankings of Akkar and Bommer (2007)- AB, Boore and Atkinson (2008)- BA, Kyriakides (2007)- KR, Boore et al. (1997)- JB, Bommer et al. (2007)- BO, Darciu and Tselentis (2007)- DT, Kalkan and Gulkan (2004)- KG and Akkar and Cagnan (2009)- AC for the Turkish, Cypriot and European Strong Motion Databases. Ranking parameters are: the median, mean and standard deviation of the total normalized residuals (median, mean, Std) and median likelihood values (LH).

	Turkish Database				**Cyprus Database**				**European Database**			
	Median	**Mean**	**Std**	**LH**	**Median**	**Mean**	**Std**	**LH**	**Median**	**Mean**	**Std**	**LH**
AB	-0.93	-0.94	1.19	0.29	-1.00	-0.80	1.03	0.28	-0.12	-0.31	1.27	0.39
BA	-1.93	-1.97	1.63	0.05	-1.19	-1.34	1.31	0.22	-0.31	-0.32	1.25	0.43
KR	-0.71	-0.59	2.43	0.11	0.19	-0.01	2.48	0.05	-2.01	-2.11	1.96	0.05
JB	-4.35	-4.18	2.09	0.00	-3.43	-3.32	1.68	0.00	-1.26	-1.31	1.90	0.16
BO	-0.70	-0.71	1.08	0.36	-0.54	-0.49	0.91	0.46	-0.07	-0.26	1.33	0.39
DT	-1.34	-1.38	1.38	0.16	-0.76	-0.82	0.97	0.40	-0.40	-0.44	1.21	0.44
KG	-2.65	-2.47	1.89	0.01	-1.73	-1.73	1.17	0.08	-0.66	-0.70	1.42	0.40
AC	0.07	0.09	1.00	0.49	0.32	0.39	0.87	0.52	0.88	0.73	0.97	0.33

In Table 2, the total model residual based results for all GMPEs considered in this study are summarized. Based on the classification scheme of Scherbaum et al. (2004), some of the GMPEs are classified as inappropriate for use in the seismic hazard assessment of Eastern Mediterranean region (indicated with grey color in Table 2). Since in the case of European and Cypriot strong motion databases, the V_{s30} parameters are estimated from surface geology, and in the case of Cypriot strong motion database same processing technique could not be applied to the records as in the European and Turkish strong motion databases; the combined data could not have been considered as a homogenous one. Hence, the results are presented separately for each database in Table 2 to enable observation of effects of these aforementioned heterogeneities on the results. Akkar and Cagnan (2009), Bommer et al. (2007) and Akkar and Bommer (2007) yield satisfactory results in case of all three databases. Kyriakides (2007) and Boore et al. (1997), on the other hand, are found to be unsuitable for the Eastern Mediterranean region with all three databases. This is particularly interesting in the case of Kyriakides (2007) model as it is merely based on the events in the Cypriot strong motion database. Boore et al. (1997) model was used in previous seismic hazard assessment studies carried out for Cyprus and Turkey, although results indicate very low degree of agreement between the estimated PGA values and observed PGA values, estimated PGA values being considerably larger than observed values. Majority of the data in the Turkish and Cypriot strong motion databases belong to $4.0 \leq M_w < 5.0$ range. In order to observe the effects of this on the results, the analyses repeated with databases only including $5.0 \leq M_w$ records. This modification to databases mostly improved the results for Darciu and Tselentis (2007) and Boore and Atkinson (2008) models. Therefore it can be concluded that these two models are inappropriate for small magnitude earthquakes ($M_w < 5.0$) in the region of interest. However even in the absence of $M_w < 5.0$ events, the Boore and Atkinson (2008) model was observed to have the tendency to considerably overestimate PGAs in the case of Turkish strong motion database.

The Stafford et al. (2008)'s likelihood method based on inter-event and intra-event residuals was applied to GMPEs for which inter-event and intra-event variances are provided (i.e. Akkar and Bommer, 2007; Boore and Atkinson, 2008; Bommer et al., 2007; Darciu and Tselentis, 2007 and Akkar and Cagnan, 2009 except from Boore et al., 1997 as it gave very poor results with total model residuals). Results indicate that Akkar and Bommer (2007), Bommer et al. (2007) and Akkar and Cagnan (2009) models yield satisfactory predictions in case of all three databases considered. As Akkar and Bommer (2007) and Bommer et al. (2007) have the same functional form and use essentially the same database, we decided to use only one of them in the seismic hazard analysis that is Bommer et al. (2007) as it has wider applicability. The Darciu and Tselentis (2007) model also shows satisfactory degree of agreement with observed data in the case of Cypriot and European databases, the comparatively poor behavior in the case of Turkish database is due to dominance of $Mw<5.0$ events in this database as range of applicability of this model does not fully include these small events. For Akkar and Cagnan (2009), Bommer et al. (2007) and Darciu and Tselentis (2007), results are summarized graphically in Figures 1 and 2 for intra-event and inter-event residuals, respectively. In this study, the degree of improvement introduced to the results by considering intra-event residuals rather than total model residuals was observed to be insignificant. In the light of these detailed quantitative comparisons, Akkar and Cagnan (2009), Bommer et al. (2007) and Darciu and Tselentis (2007) GMPEs were found to be the most suitable for the Eastern Mediterranean region.

Seismic Hazard Assessment

The catalog developed for the region bounded by 28^o-39^o E longitudes and 31^o-39^o N latitudes was obtained by merging data from international databases (Harvard CMT, Preliminary Determination of Epicenters, and International Seismological Summary), regional network catalogues (KOERI, CGSD, TUBITAK, NOA, GIT), as well as from various sources that exists in the literature (Cagnan and Tanircan, 2009). The catalog used in this study, spans the time period 2150 BC – 2008 AD. Two different seismic source zonation models were used: Model 1 is based on the seismic source zonation models proposed by Papaioannou (2001) for shallow and intermediate depth earthquakes; Model 2 is based on the seismic source zonation model proposed by Demircioglu et al. (2007). Once the time periods, for which the earthquake data is complete, were identified by Stepp (1972)'s method, the complete part of the catalogue was used to obtain earthquake recurrence relationships including corresponding uncertainties for each seismic source zone considered by employing Weichert's maximum likelihood approach (Weichert, 1980).

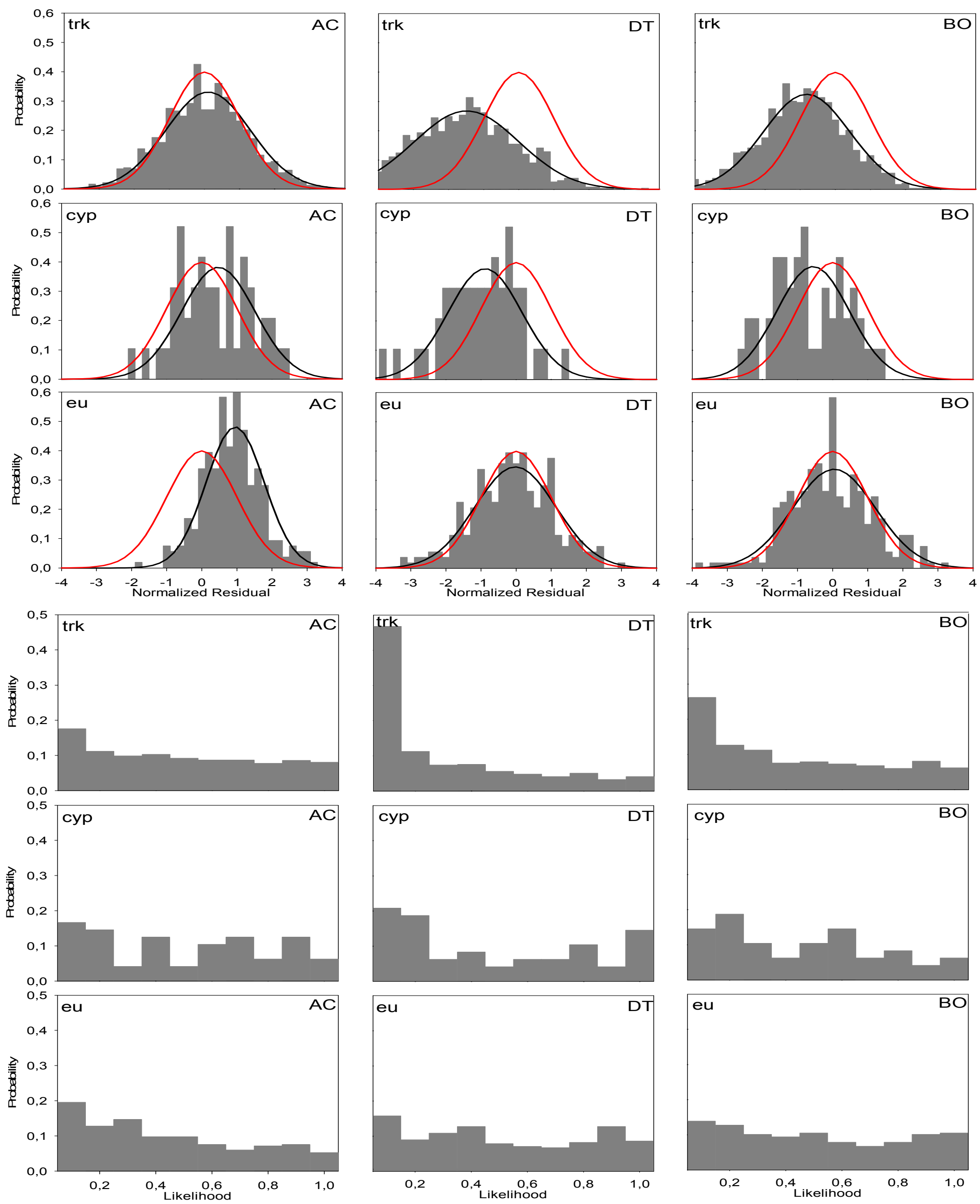

Figure 1. Histograms of the normalized intra event model residuals and likelihood values for Akkar and Cagnan (2009) (AC), Darciu and Tselentis (2007) (DT) and Bommer et al. (2007) (BO). Three different databases: Turkish (trk), Cypriot (cyp) and European (eu) are considered. The plots of the normalized intra event residuals also include the standard normal distribution (*solid red line*) and the normal distribution fitted to the residuals (*solid black line*).

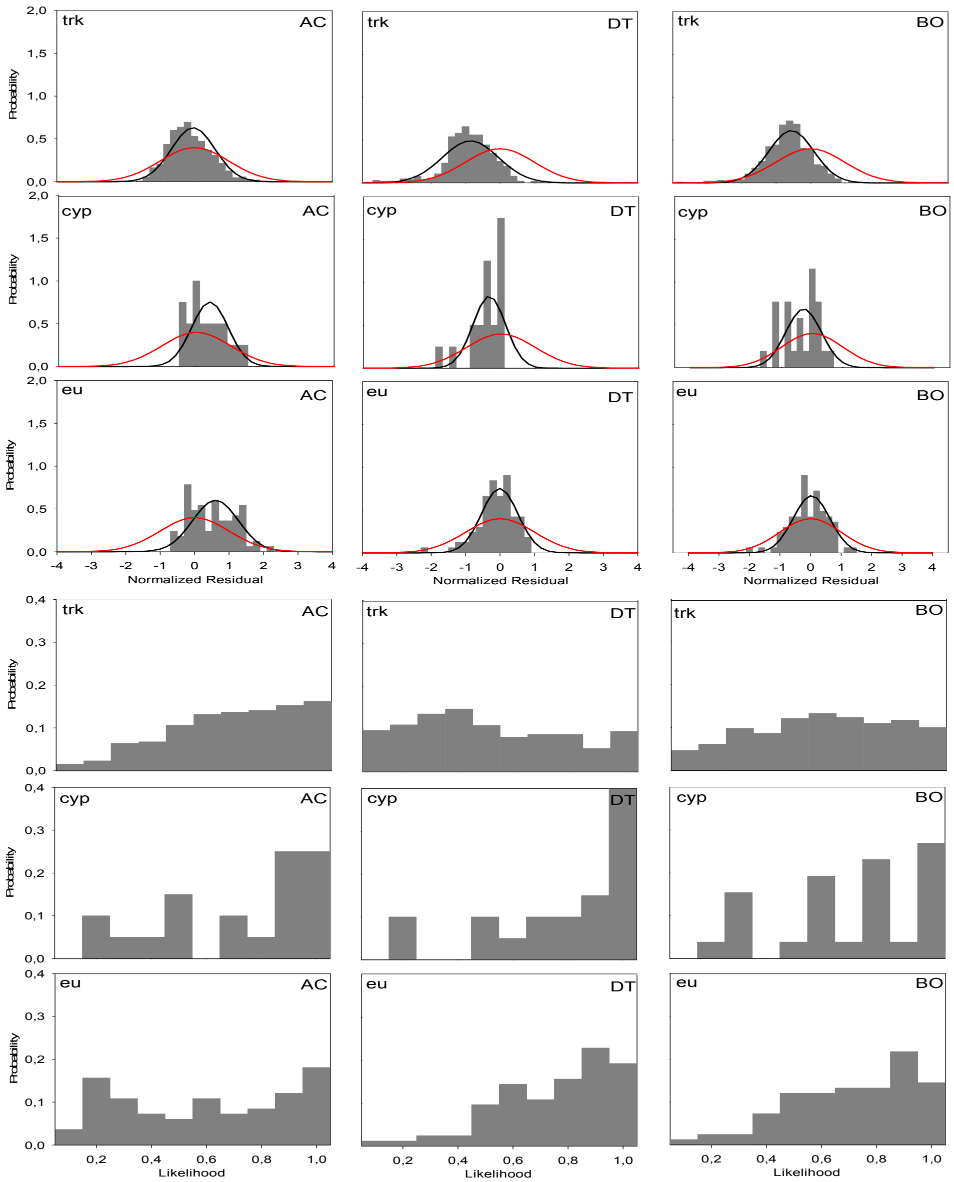

Figure 2. Histograms of the normalized inter event model residuals and likelihood values for Akkar and Cagnan (2009) (AC), Darciu and Tselentis (2007) (DT) and Bommer et al. (2007) (BO). The plots of the normalized inter event residuals also include the standard normal distribution (*solid red line*) and the normal distribution fitted to the residuals (*solid black line*).

In this study, the software EZ-FRISK was used to compute the seismic hazard over a $0.05^{\circ} \times 0.05^{\circ}$ uniform grid for the region of interest. The computations were conducted to obtain PGA values for the return period of 475 years and rock site conditions. The logic tree approach was employed to combine results obtained with seismic source zonation models 1 and 2, mean recurrence coefficients (a and b) as well as upper and lower bound recurrence coefficients (a_{upper}, b_{upper} and a_{lower}, b_{lower}, respectively) and GMPEs of Akkar and Cagnan (2009), Bommer et al. (2007), Darciu and Tselintis (2007), Atkinson and Boore (2003), and Youngs et al. (1997) (Figure 3). In case of model 2 and shallow depth source zones of model 1, the GMPEs of Akkar and Cagnan (2009), Bommer et al. (2007), Darciu and Tselintis (2007) were used with the weights of 0.4, 0.4, and 0.2, respectively. Higher weights were assigned to Akkar and Cagnan (2009), Bommer et al. (2007) relationships, as they indicate better goodness-of-fit with regional data and have wider range of applicability (both magnitude and distance vise). In case of intermediate depth source zones of model 1, the GMPEs of Atkinson and Boore (2003) and Youngs et al. (1997) were used. In Figure 4a-b, the PGA distribution for Cyprus and corresponding coefficient of variance (COV) distribution that indicates overall variability of results due to seismic source model uncertainty, earthquake recurrence model uncertainty and ground motion prediction model uncertainty are given, respectively.

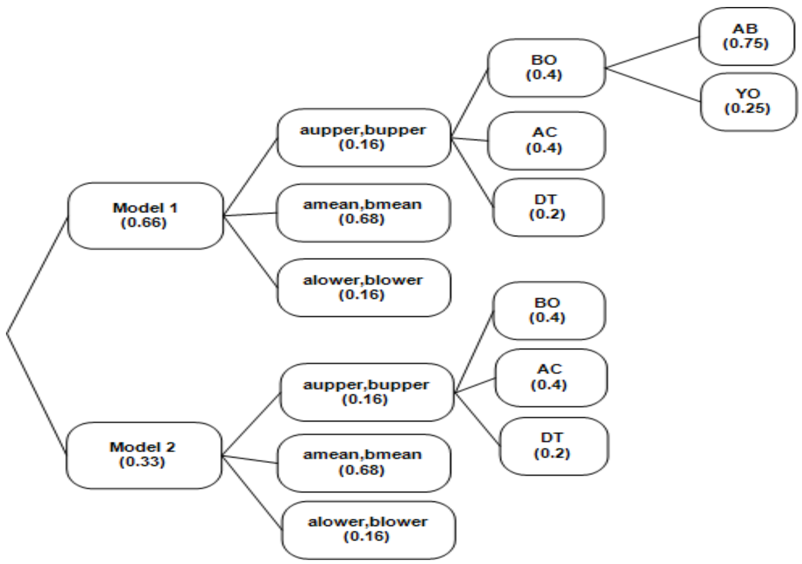

Figure 3. Logic tree including the applied weights (Bommer et al., 2008 – BO, Akkar and Cagnan, 2009 – AC, Darciu and Tselentis, 2007 – DT, Atkinson and Boore, 2003 –AB, Youngs et al. 1997 – YO).

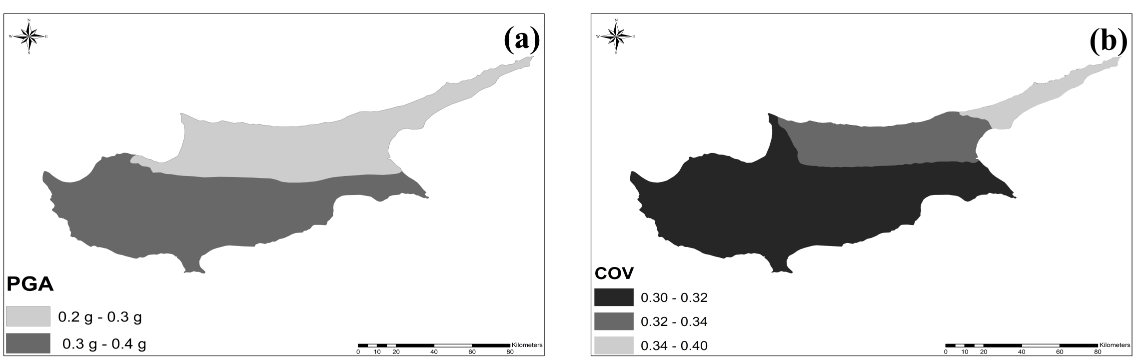

Figure 4. (a) PGA distribution for the return period of 475 years and (b) associated uncertainty.

Conclusions

In this study, local GMPEs with very limited underlying databases and functional forms (i.e. Kyriakides, 2007) are once again proved to be inadequate in accurately modeling ground motion attenuations even for intended localities. For the Eastern Mediterranean region, goodness-of-fit of Akkar and Cagnan (2009), Bommer et al. (2007) and Darciu and Tselintis (2007) models to the 1478 observed regional data was found to be acceptable. This study marks the first occasion of employing quantitative goodness-of-fit assessment methods for identification of suitable GMPEs for the Eastern Mediterranean region. Together with an extensive earthquake catalogue spanning the period 2150 B.C.-2008 A.D. and recent seismic source models developed based on new geological, seismicity and geodetic data, the identified GMPEs were used in the seismic hazard assessment of Eastern Mediterranean region. Final results for the island of Cyprus indicate a high hazard along the southern coastline, reaching a peak at Paphos region. Rest of the island is characterized by moderate PGA values. These results suggest higher PGA values than those suggested by Eurocode 8. The Eurocode 8 suggested map is based on observed maximum regional earthquake intensities unlike the probabilistic hazard assessment employed in this study.

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