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PROBABILISTIC SEISMIC HAZARD ASSESSMENT BASED ON MONTE CARLO SIMULATIONS FOR MARMARA REGION, TURKEY

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Abstract: *This study presents an approach for predicting the Seismic Hazard at macro level as a part of a novel Earthquake Risk Assessment and Management framework. Developing countries are considered as the main application area for the framework, where limited data regarding seismicity, soil conditions, building stock and population are available. A Probabilistic Seismic Hazard Analysis (PSHA) methodology based on Monte-Carlo (MC) approach is employed to calculate earthquake hazard. In this approach, synthetic earthquake catalogues are generated by randomizing parameters obtained from historic and instrumental past earthquake data in a controlled way to represent the seismicity of an area. Fault segmentation and background seismicity model is used for the definition of seismic sources. Particular attention is paid to the definition of areal background source zones. In addition to Poissonian model, time-dependent model is adopted in hazard calculations to quantify the effect of temporal dependencies between seismic events. The Marmara Region in Turkey is selected as a case study area to apply the developed procedure. Results of this work showed that seismic hazard predictions for the case study area are in line with those obtained by the existing studies (such as SHARE, AFAD RED) and with those given in the recently updated Turkish Seismic Code. This indicates that PSHA based on MC simulations can be an attractive alternative to the conventional method due to its flexibility in treating uncertainties.*

Introduction

Earthquakes are still a major threat to communities, particularly in the developing countries where the majority of the existing structures are substandard due to improper seismic design, inadequate detailing during construction and poor material quality. The society will benefit from modern seismic code provisions for only newly constructed buildings. Existing building stock constructed according to older versions of seismic design codes will still remain substandard according to new seismic design provisions. Economic losses and causalities following a future earthquake can be substantially reduced by developing a better understanding of seismic risk to structures.

This work presents initial results for an Earthquake Risk Assessment (ERA) and management framework for substandard buildings in developing countries. An early version of the framework has been successfully applied by Kythreoti (2002) to Cyprus and by Khan et al. (2018) to Pakistan. In the updated version of the framework, a probabilistic Monte-Carlo (MC) approach based on Poissonian and time-dependent hazard models is developed to generate synthetic earthquake catalogues that are representing possible future seismicity in the area of application (Musson, 2000). In MC based PSHA, the key parameters are randomized based on distribution functions with means and standard deviations to generate synthetic catalogues. This can be considered as an advantage over conventional PSHA which requires the use of discrete branches of the logic tree with the assignment of subjective weights (Musson, 2000). Therefore, MC based PSHA is expected to offer more flexible solutions over the conventional PSHA in treating uncertainty.

In this study, a computer code is developed to perform seismic hazard assessment using MC simulations. The employed hazard assessment methodology combines seismic source zoning, earthquake magnitude-recurrence relationships and ground motion prediction equations (GMPEs) to produce hazard maps in terms of the desired probability of exceedance of ground

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motion. Marmara region (Turkey) is selected as a case study area to validate the developed hazard module of the ERA framework. The study area is one of the most seismically active zones in the world and has produced many large earthquakes with strike-slip faulting mechanism. Moreover, it is expected to have an earthquake with M≥7.0 in the vicinity of Istanbul, one of the most populated and industrialized parts of Turkey. Economic losses and causalities following a future earthquake can be substantially reduced by developing a better understanding of future earthquake risks and by adopting appropriate seismic risk mitigation planning.

PSHA using MC Simulations

The conventional approach for the PSHA proposed by Cornell (1968) is based on total probability theorem and is widely accepted in practice. However, Monte-Carlo (MC) simulations can be an efficient and flexible alternative against conventional PSHA when more complicated factors (e.g. spatial correlation of ground shaking) are involved (Akkar and Cheng, 2015). In the MC based PSHA procedure, an earthquake in a region is considered as random event, with variations in space and time. The controlled use of random numbers can be applied in the model to develop synthetic earthquake catalogues using a MC process. Events in the existing historical and instrumental catalogues can be associated with either fault source zones (FSZs) and background source zones (BSZs). For BSZs, random values are generated to determine occurrence of earthquakes for every BSZ for each year of the catalogue. The location and depth of the epicenter are determined randomly in MC simulations within the source zone. Finally, the magnitude value is assigned randomly against the magnitude-frequency relationship for that BSZ. Each synthetic catalogue represents one of the possible outcomes of future seismicity in that region, that would be in line with past behavior. The general procedure for synthetic catalogue generation for BSZ in MC process is shown schematically in Figure 1.

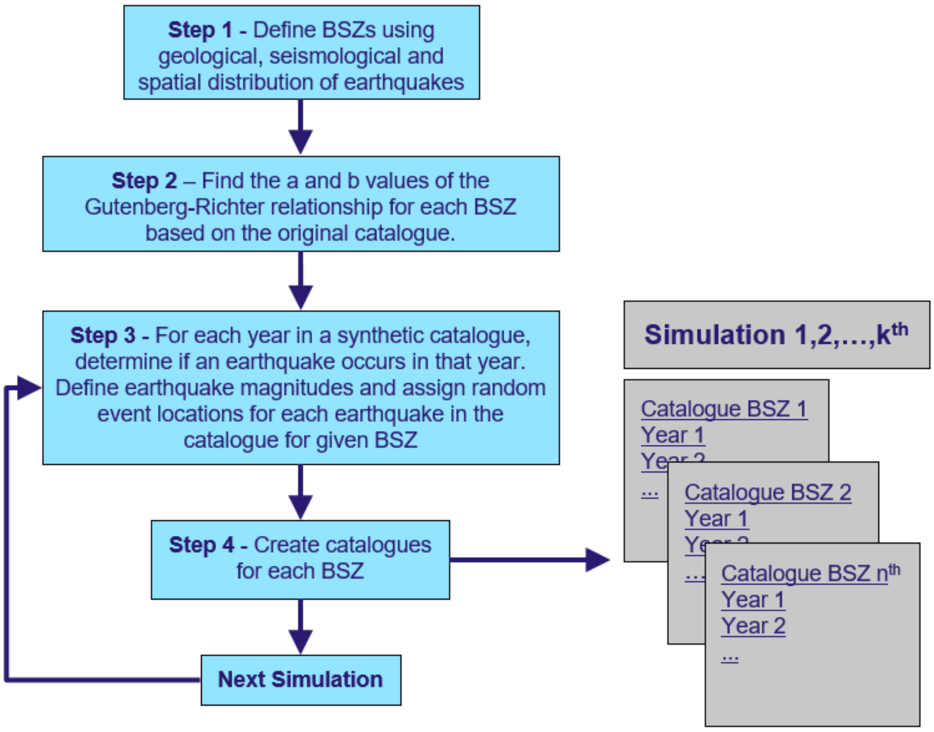

Figure 1. Flowchart for generation of MC earthquake catalogues for BSZs.

The algorithm of generation of a synthetic catalogue for a FSZ is similar to that for a BSZ. Instead of recurrence relationship used for BSZ, the characteristic magnitude M_{char} with associated annual occurrence rate is utilized to generate the events for FSZs. Empirical relationships proposed by Wells and Coppersmith (1994) and Youngs and Coppersmith (1985) can be employed to define M_{char} and associated recurrence intervals using fault geometry and slip rate. The simplified procedure for synthetic catalogue generation for FSZ in MC process is given in Figure 2. The simplified procedure for synthetic catalogue generation for FSZ in MC process is given in Figure 2. For more detailed procedure on the determination of earthquake occurrence in BSZs and FSZs, readers are referred to paper written by Crowley and Bommer (2006) or Sianko et al. (2019). For each earthquake generated, the Ground Motion Prediction Equations (GMPEs) can be employed to calculate the ground shaking at a site.

As a final step, the worst case of ground shaking at the site is selected among all source zones per catalogue year and these are sorted in decreasing severity. Desired level of probability of exceedance can be calculated by picking a value in the sorted list that is exceeding a critical value as described in Musson (2000).

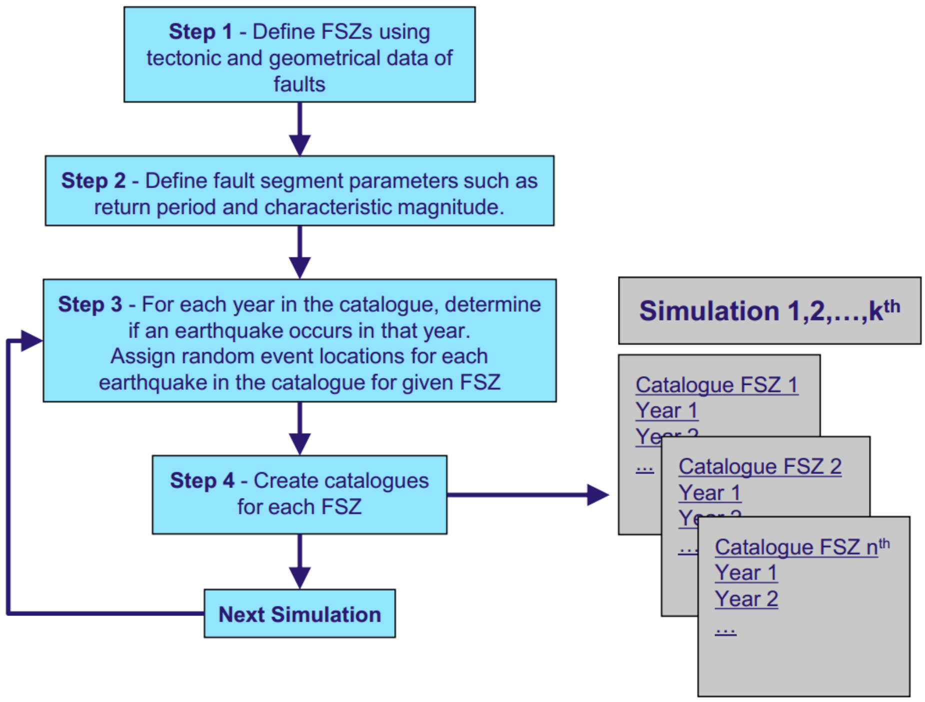

Figure 2. Flowchart for generation of MC earthquake catalogues for FSZs.

The Case Study: Marmara Region

The Marmara region, Turkey is selected as a case study area to verify the developed hazard assessment procedure. The North Anatolian Fault (NAF) extends across northern Turkey for more than 1500 km, and moves about 25 mm/year in right-lateral slip between Anatolia and Eurasian plate (Straub et al., 1997). The western part of the NAF has greatest impact on the tectonic regime of the Marmara Sea area: the NAF continues as a single fault line east of 31.5°E, whereas to the west the NAF splits into a complex fault system (Fig. 3). Three main braches of this system can be identified as northern NAF (NNAF), central NAF (CNAF) and southern NAF (SNAF) branches. Various slip rates can be observed among branches with the northern one being the most active with slip rates ranging between 14-24 mm/year, while the central and southern branches are moving at only 2-8 mm/year (Murru et al., 2016). Both the Kocaeli (August 17, 1999) and Duzce (November 12, 1999) earthquakes are the last major events occurred in the Marmara region.

In this study, the GMPEs proposed by Akkar et al. (2014) and Boore and Atkinson (2008) are employed to estimate earthquake hazard in terms of PGA. The logic tree is used to treat epistemic uncertainty with two braches representing each of the attenuation equations. The weights to the branches are assigned as follows: 0.7 to GMPE proposed by Akkar et al. (2014) and 0.3 to GMPE by Boore and Atkinson (2008). The bigger weight value is given to GMPE proposed by Akkar et al. (2014) as the data used for a developing of this GMPE is mainly based on the earthquake records from the Turkey.

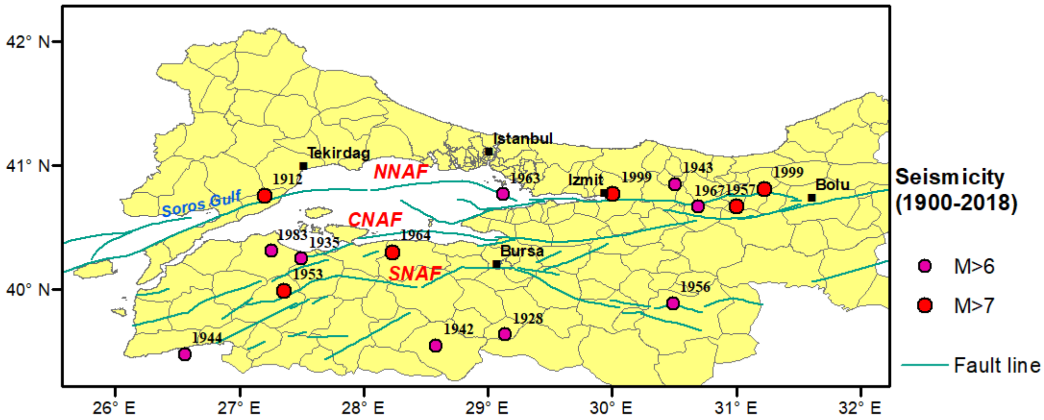

Figure 3. Study area with illustrated faults system and epicentral location of major earthquakes occurred between 1900 and 2018.

Earthquake Data

The AFAD catalogue (http://www.deprem.gov.tr/en/eventcatalogue) is used to represent the instrumental seismicity in the study area. The catalogue consists of events of $M_w \geq 4.0$. The historical events from the catalogue prepared by Ambraseys and Jackson (2000) are merged into instrumental catalogue. A catalogue homogenisation is carried out by converting different magnitude scales to the moment magnitude, M_w, using conversion relationships derived by Kadirioğlu and Kartal (2016).

After the homogenisation of the catalogue, the earthquake data needs to be re-processed for the removal of the fore and after-shocks (declustering). Most of the PSHA studies are based on Poissonian assumption, that all events occurring are independent from each other in terms of space and time. Therefore, all dependent events (foreshocks and aftershocks) need to be removed from the catalogue to satisfy Poissonian assumption. In this study, the methods developed by Gardner and Knopoff (1974) and Knopoff (2000) modified by Aldama-Bustos (2009) are utilized for catalogue declustering. Table 1 summarizes the outcomes of each of the procedure.

Algorithm	Mainshocks	Removed events	Identified clusters	Total events in catalogue
Gardner and Knopoff (1974)	417	432	110	849
Modified Knopoff (2000)	524	325	91	849

Table 1. Summary of dependent events removed for final catalogue using different algorithms.

Earthquake recurrence (Gutenberg-Richter) relationship requires a complete catalogue to define seismicity of the earthquake zones. Catalogue completeness periods for different magnitude ranges are determined using the procedure proposed by Stepp (1972).

Source Zones

The Marmara region is divided into 18 area BSZs as shown in Figure 4. Table 2 provides a summary of the seismicity parameters used for each of the BSZs including *a* and *b* values of the Gutenberg–Richter (G-R) relationship, and the minimum and maximum magnitudes, M_{min} and M_{max}, for each BSZ. A source zone number is assigned to each BSZ, which corresponds to the number shown in this figure. The procedure developed by Weichert, (1980) is utilised to calculate *b* parameter of the G-R relationship with completeness periods for each magnitude range. Also, *a* values are found depending on the activity rate of the BSZs. The chi-squared (X^2) statistical test proposed by Musson and Winter (2012) is utilised to compare the events in the synthetic catalogues with the events in the existing catalogues in terms of spatial and magnitude distribution of events. Synthetic catalogues developed for the BSZs given in Figure 4 are in good agreement with the observed seismicity of the area.

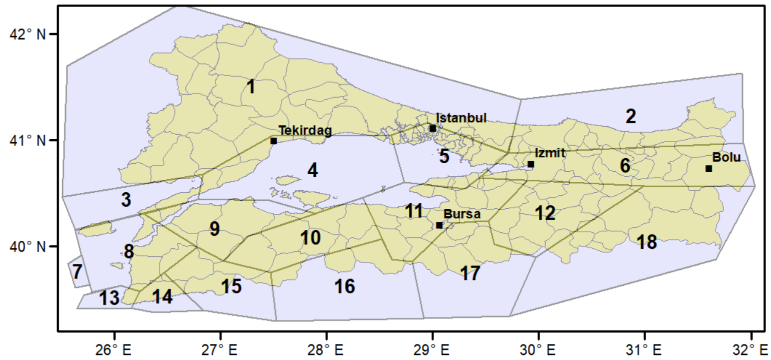

Figure 4. BSZs used to represent areal seismicity.

BSZ #	M_{min}	M_{max}	a	b	σ(b)
1	4.0	5.5	2.20	0.69	0.126
2	4.0	5.6	1.96	0.62	0.109
3	4.0	6.0	3.33	0.83	0.082
4	4.0	6.8	3.62	0.87	0.079
5	4.0	6.7	2.99	0.83	0.107
6	4.0	6.9	2.32	0.62	0.077
7	4.0	5.6	2.88	0.97	0.254
8	4.0	5.6	2.95	0.89	0.157
9	4.0	6.6	3.08	0.91	0.149
10	4.0	6.9	2.13	0.66	0.109
11	4.0	6.6	3.27	0.88	0.105
12	4.0	5.9	2.58	0.82	0.151
13	4.0	6.6	3.66	1.03	0.148
14	4.0	6.7	2.69	0.88	0.192
15	4.0	5.5	2.60	0.90	0.236
16	4.0	6.2	3.79	0.98	0.108
17	4.0	6.1	2.26	0.72	0.126
18	4.0	6.4	3.01	0.81	0.096

Table 2. Seismicity parameters for BSZs presented in this study.

All earthquakes of Mw ≥ 7 are assumed to occur on faults through characteristic earthquakes, and the fault segmentation model developed by Erdik et al. (2004) has been used to model the location of characteristic earthquakes (Figure 5). The data about fault segments is summarized in the Table 3, where various parameters assigned to each fault segment including Poissonian and Time-dependent annual rates.

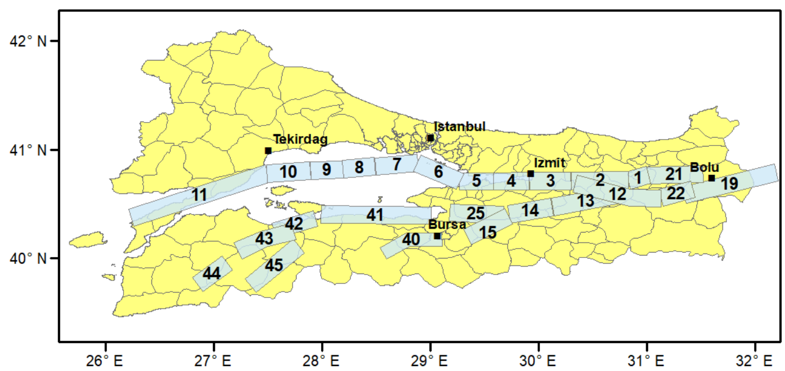

Figure 5. The adopted fault segmentation model proposed by Erdik et al. (2004)

Segment number	Char. Magnitude (Mw)	Poissonian Annual Rate	Mean recurrence time (years)	Time since last earthquake (years)	Time-dependent Annual rate
1	7.2	0.0071	140	17	0.0020
2	7.2	0.0071	140	17	0.0020
3	7.2	0.0071	140	17	0.0020
4	7.2	0.0071	140	17	0.0020
5	7.2	0.0057	175	125	0.0102
6	7.2	0.0048	210	265	0.0104
7	7.2	0.0040	250	253	0.0082
8	7.2	0.0040	250	253	0.0082
9	7.2	0.0050	200	463	0.0114
10	7.2	0.0050	200	1000	0.0110
11	7.5	0.0067	150	107	0.0121
12	7.2	0.0040	250	52	0.0010
13	7.2	0.0017	600	1000	0.0037
14	7.2	0.0017	600	1000	0.0037
15	7.2	0.0010	1000	1000	0.0020
19	7.5	0.0040	250	75	0.0022
21	7.2	0.0040	250	20	0.0001
22	7.2	0.0040	250	62	0.0015
25	7.5	0.0010	1000	1000	0.0020
40	7.2	0.0010	1000	164	0.0000
41	7.2	0.0010	1000	1000	0.0020
42	6.8	0.0010	1000	1000	0.0020
43	7.2	0.0010	1000	282	0.0002
44	7.2	0.0010	1000	1000	0.0020
45	7.2	0.0010	1000	66	0.0000

Table 3. Poissonian and Time-dependent annual rates for segments in the model, adopted from Erdik et al. (2004).

While the Poissonian process seems to be applicable in a global sense, extensive investigations on individual faults indicate a periodic occurrence of large (characteristic) magnitude earthquakes that implies the use of 'time-dependent' (or 'renewal') hazard models (Schwartz and Coppersmith, 1984). Marmara region has a well-defined fault system with a relatively good track of the big events occurring on the fault system since the 16th century. Therefore, the use of the time-dependent model for PSHA can provide a more accurate result, than a model based on the Poissonian process.

Results

The effectiveness of the proposed methodology is demonstrated by carrying out a PSHA study for the Marmara region, Turkey. Seismic hazard maps (Figures 6-9) are derived for the probability of exceedance (PE) of 2% and 10% in 50 years using Poissonian and time-dependent models. These maps are developed for rock soil conditions representing average shear wave velocity of 760 m/s in the top 30 m. From results obtained, the difference in PGA between time-dependent and Poissonian models for Istanbul area is noticeable. Time-dependent method predicts higher PGA due to the fact that the faults segments close to Istanbul have not experienced the characteristic earthquake for a long period; thus the probability of occurrence of an earthquake predicted by time-dependent model is higher than that predicted by the Poissonian model. On the other hand, for the eastern part of the Marmara region, the Poissonian model predicts lower PGA values than that of obtained by the time-dependent model, due to the occurrence of the Kocaeli and Duzce earthquakes in 1999.

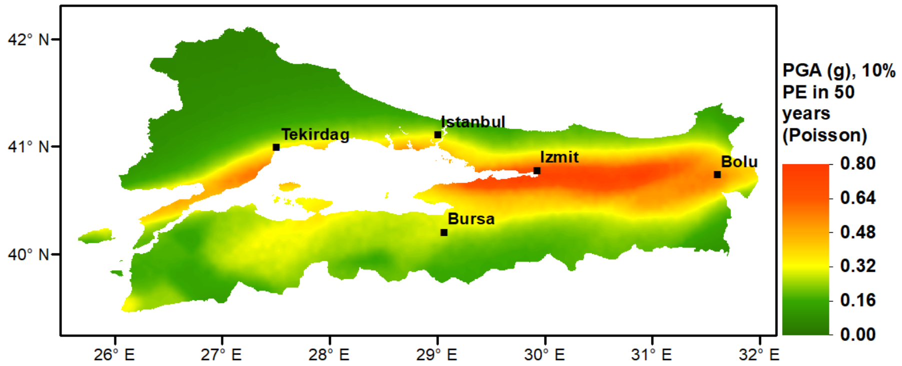

Figure 6. Seismic hazard map of Marmara region for PGA (g) considering 10% probability of exceedance in 50 years (the Poisson model).

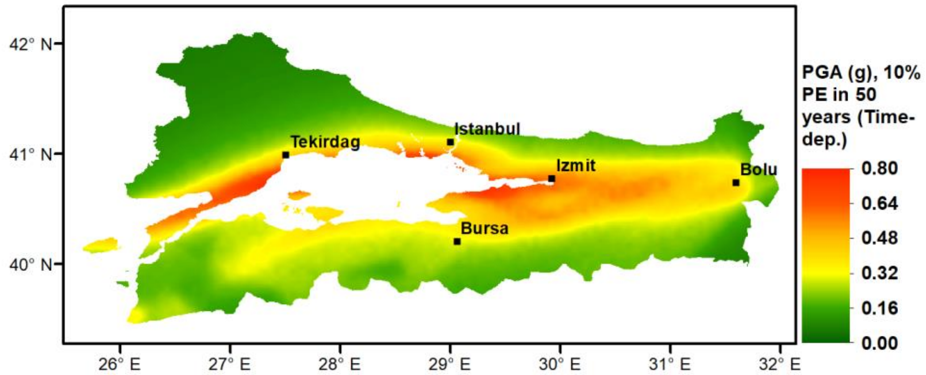

Figure 7. Seismic hazard map of Marmara region for PGA (g) considering 10% probability of exceedance in 50 years (Time-dependent model).

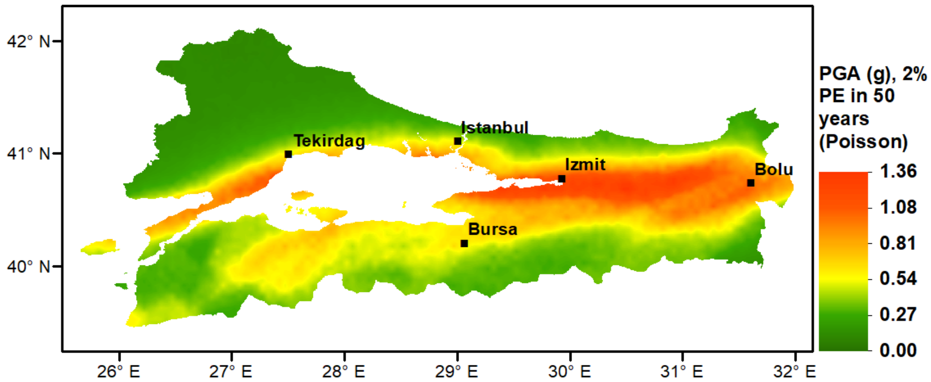

Figure 8. Seismic hazard map of Marmara region for PGA (g) considering 2% probability of exceedance in 50 years (the Poisson model).

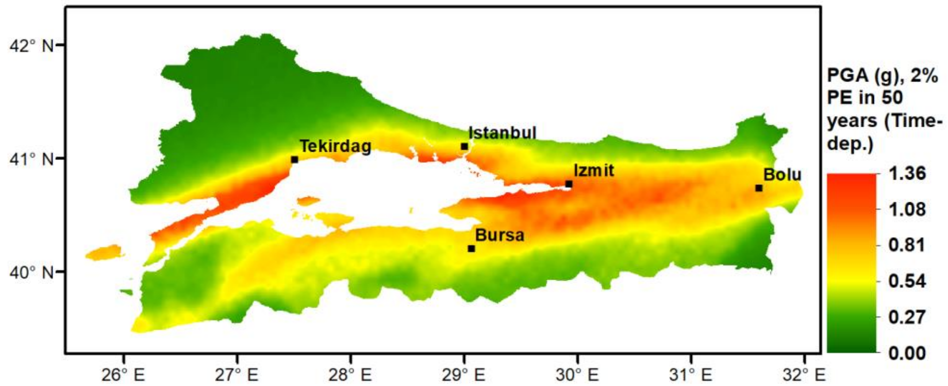

Figure 9. Seismic hazard map of Marmara region for PGA (g) considering 2% probability of exceedance in 50 years (Time-dependent model).

Results from Poissonian model for PE 10% in 50 years are compared with the existing hazard maps (see Table 4) developed in the SHARE project (Woessner et al., 2015) and developed by the Disaster and Emergency Management Presidency of Turkey (AFAD) (Figure 10). An absolute difference in terms of PGA (g) for hazard maps created in the SHARE project and in the current work is presented in a colour map format in Figure 11. It can be concluded that, in general, there is an agreement between the Poisson model results of this study and the hazard maps developed in reference studies. Therefore, proposed procedure can be used as a hazard estimate procedure for risk calculations in later stages of the ERA framework applied in developing countries.

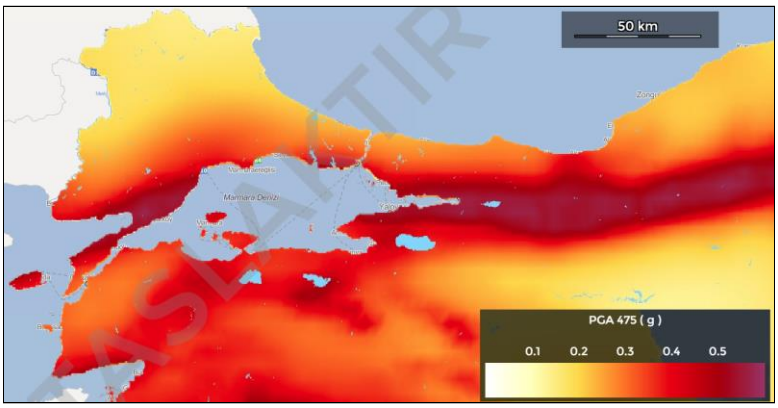

Figure 10. Seismic hazard map of Marmara region by AFAD for PGA (g) considering 10% probability of exceedance in 50 years (AFAD, 2018).

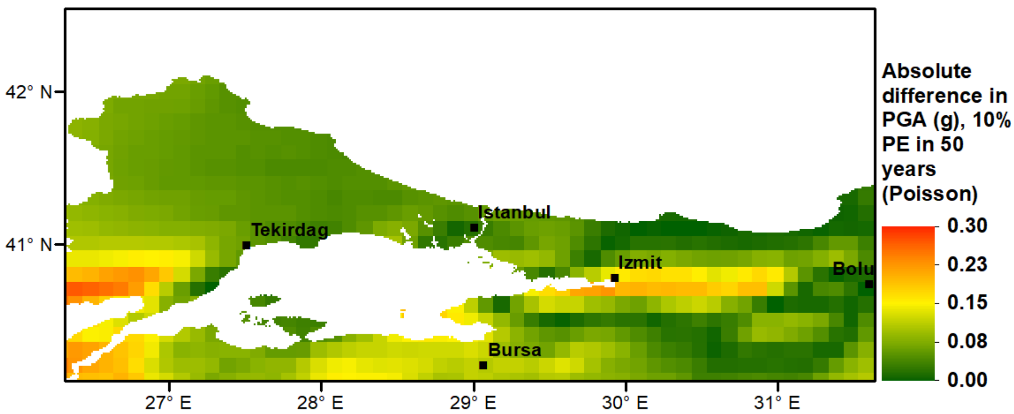

Figure 11. Comparison of results shown as absolute difference in PGA between results of this study and project SHARE considering 10% probability of exceedance in 50 years.

	Result from this study			
City	**Poisson (PGA)**	**Time-Dependent (PGA)**	**AFAD (PGA)**	**SHARE (PGA)**
Istanbul	0.27g	0.37g	0.32g	0.31g
Izmit	0.59g	0.75g	0.72g	0.47g
Bursa	0.29g	0.39g	0.35g	0.38g
Tekirdag	0.35g	0.37g	0.40g	0.37g
Bolu	0.48g	0.40g	0.63g	0.49g

Table 4. Comparison of PGA results with those from other studies for 475 years return period, major cities of Marmara region.

Conclusions

A practical PSHA methodology is proposed for an integration with a new Earthquake Risk Assessment (ERA) framework for countries where limited studies on tectonics and seismicity exist. This PHSA method is based on a non-conventional MC approach that generates synthetic catalogues with unknown parameters entered as distribution functions to represent the future seismicity of an area of interest. Poissonian and time-dependent (renewal) seismic hazard models are incorporated into the proposed methodology. Fault segmentation and background seismicity model is used for the definition of seismic sources. The Marmara region in Turkey is selected as a case study area. The proposed background zones are verified via test with associated seismicity parameters to check if the seismic zones can replicate the past seismicity. The PSHA hazard maps obtained in this work compare well with the results of the previous PSHA studies, which are based on conventional hazard assessment methods (e.g. AFAD maps and SHARE project outputs).

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