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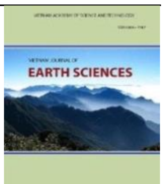

Probabilistic seismic hazard assessment for Hanoi city

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ABSTRACT

In this study, the methodology of probabilistic seismic hazard assessment proposed by Cornell and Esteva in 1968 was applied for Hanoi city, using an earthquake catalog updated until 2018 and a comprehensive seismotectonic model of the territory of Vietnam and adjacent sea areas. Statistical methods were applied for declustering the earthquake catalog, then the maximum likelihood method was used to estimate the parameters of the Gutenberg–Richter Law and the maximum magnitude for each seismic source zone. Two GMPEs proposed by Campbell & Bozorgnia (2008) and Akkar et al., (2014) were selected for use in hazard analysis. Results of PSHA for Hanoi city are presented in the form of probabilistic seismic hazard maps, depicting peak horizontal ground acceleration (PGA) as well as 5-hertz (0.2 sec period) and 1-hertz (1.0 sec. period) spectral accelerations (SA) with 5-percent damping on a uniform firm rock site condition, with 10%, 5%, 2% and 0,5% probability of exceedance in 50 years, corresponding to return times of 475; 975; 2,475 and 9,975 years, respectively. The results of PSHA show that, for the whole territory of Hanoi city, for all four return periods, the predicted PGA values correspond to the intensity of VII to IX degrees according to the MSK-64 scale. As for the SA maps, for all four return periods, the predicted SA values at 1.0 s period correspond to the intensity of VI to VII, while the predicted SA values at 0.2 s period correspond to the intensity of VIII to X according to the MSK-64 scale. This is the last updated version of the probabilistic seismic hazard maps of Hanoi city. The 2019 probabilistic seismic hazard maps of Hanoi city display earthquake ground motions for various probability levels and can be applied in seismic provisions of building codes, insurance rate structures, risk assessments, and other public policy.

Keywords: Probabilistic seismic hazard maps; Peak Ground Acceleration; Spectral Acceleration; Seismic source zones; Ground Motion Prediction Equations.

1. Introduction

Hanoi, the capital of Vietnam, is the political, administrative and cultural as well as science-technological center of the whole country. Hanoi at the same time is one of the economical, touristic, trading and service centers of the Asia-Pacific region. Since 2008, the city was enlarged and became the second largest city by population. As for the 2018 statistics, the city covers an area of 3.324,92 km², with 8,441,902 inhabitants.

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After expansion, the Hanoi metropolitan system consists of one central and five satelite urban areas and towns that linked together by a transportation framework in from of ring roads and radial axes with conection to the regional and national transportation networks.

Thus, with its great values and due to natural conditions, Hanoi city is vulnerable to many types of natural disaster. One of such disasters types that can harm the city is earthquake. As pointed out by scientists, Hanoi city is located in the seismic zone with MSK intensity of VII-VIII in the seismic zoning map of Vietnam (Nguyen Dinh Xuyen and Le Tu Son, 2009; Nguyen Hong Phuong and Pham The Truyen, 2015). With high density of population in the urban areas and fast development rate nowadays, Hanoi might subject to damage and losses if earthquakes occur.

Quantitative assessment of seismic hazard for Hanoi city has been started quite early. The first seismic micro-zonning map of the old Hanoi city was compiled in 1964 at the scale of 1:50,000 using seismic rigidity method and had been revised in 1973 and 1978 with update earthquake datasets. A more detail microzoning map of 1:25,000 scale for downtown areas of Hanoi was compiled in 1994 and revised in 2004 (Vietnam meteorological and hydrological administration, 1964; Institute for Natural Sciences, 1973; Center for Geophysical Research, 1978; Nguyen Dinh Xuyen et al., 1994; Nguyen Ngoc Thuy et al., 2004). It should be noted that for establishment of all above described maps, the deterministic approach had been used. Only since 2001, within framework of different scientific research projects, the probabilistic approach has been applied to compile seismic hazard maps of Hanoi city (Nguyen Hong Phuong, 2016; Nguyen Anh Duong et al., 2017).

As time goes by, with the development of the national seismic network and application of advanced technology, the knowledge on seismotectonics of Hanoi region becomes more and more accurate and reliable. There is growing need for detail assessment and frequent revision of probabilistic seismic hazard maps of Hanoi city in order to provide more precise input for seismic provisions of building codes, insurance rate structures, risk assessments, and other public policy.

This paper presents new results on probabilistic seismic hazard assessment for Hanoi city, using an updated until 2018 earthquake catalog and a comprehensive seismotectonic model of the territory of Northern Vietnam.

2. Theoretical background

In this paper, the classical PSHA methodology first proposed by Cornell and Esteva in 1968 is used (Cornell, 1968; Esteva, 1968). In the original Cornell-Esteva approach, if the study area can be divided into seismic sources according to geotectonic considerations, it can be assumed that, within a seismic source, an independent earthquake occurrence process is taking place and the magnitude exceedance rates, λ(M) can be estimated by means of statistical analysis of earthquake catalogs. These rates are the number of earthquakes, per unit time, in which magnitude M is exceeded, and they characterize the seismicity of the source.

The PSHA methodology also assumes that, within a seismic source, all points are equally likely to be an earthquake hypocenter. In this case, acceleration exceedance rates due to a single source, say, the i-th source, are computed using the following expression:

$$v_i(a) = \sum_j \mathrm{w}_{\mathrm{ij}} \int_{M_0}^{M_u} \left(-\frac{d\lambda_i(M)}{dM} \right) \Pr(A > a | M, R_{\mathrm{ij}}) \, dM \quad (1)$$

where M_0 and M_u are the smallest and largest magnitudes considered in the analysis respectively, Pr(A>a|M,R_{ij})) is the probability that acceleration exceeds the value a at the site, given that at distance R_{ij} an earthquake of magnitude M originates. R_{ij} are the distances between the site and the sub elements into which the source has been divided. A weight w_{ij} has been assigned to each sub-element, and the expression above assumes that $\Sigma w_{ij}=1$. Finally, the contributions of all N sources to earthquake hazard at the site are added:

$$v(a)=\sum_{i=1}^{N} v_i(a) \quad (2)$$

The seismicity model used in this paper is called the modified Gutenberg-Richter model, for which the earthquake magnitude exceedance rate is given by (Cornell and Vanmarcke, 1969):

$$\lambda(M)=\lambda_0\frac{e^{-\beta M}-e^{-\beta M_0}}{e^{-\beta M_0}-e^{-\beta M_u}}, M_0\le M\le M_u \quad (3)$$

where λ_0 is the exceedance rate of magnitude M_0, β is a parameter equivalent to the "b-value" for the source (except that it is given in terms of the natural logarithm) and M_u is the maximum magnitude for the source.

With the Poissonian assumption of earthquake occurrence within each seismic source, the probability density of the earthquake magnitude is given by:

$$p(M)=-\frac{d\lambda(M)}{dM}=\lambda_0\beta\frac{e^{-\beta M}}{e^{-\beta M_0}-e^{-\beta M_u}}, M_0\le M\le M_u \quad (4)$$

The procedure of probabilistic seismic hazard assessment for Hanoi city was carried out through the following steps:

(1) Determination of seismic sources in Hanoi region;

(2) Estimation of seismicity parameters for seismic source zones;

(3) Selection of ground motion prediction equations (GMPEs) for study region;

(4) Calculation hazard and compilation of probabilistic seismic hazard maps.

3. Seismotectonic framework

To incorporate all possible impacts from seismic sources to Hanoi city, the study area was enlarged to the whole Northern Vietnam territory. Fig. 1 shows the seismotectonic map of Hanoi city and surrounding areas, developed on the basis of up-to-date knowledge on seismically active faults and an earthquake catalog updated until 2018.

3.1. Active faults

The role of controlling the tectonic regime and seismic activity of the North Vietnam in general and the Hanoi region, in particular, the Red River Fault Zone (below referred to as RRFZ), also known as Ailao Shan-Red River shear zone. Originated from Tibet, China, the RRFZ spreads over 1000 kilometers along the NW-SE direction, crossing over the North Vietnam's territory until it reaches to the Bac Bo gulf (Fig. 1). The RRFZ is considered to be a boundary between the South China and the Indochina blocks. In the territory of Vietnam, the RRFZ is characterized by the Elephant Range (also known as Day Nui Con Voi) metamorphic massive, which is bounded by the Red River fault to the SW and the Chay river fault to the NE.

Results of detail geomorphologic investigation show that the Red River fault consists of two branches stretching along the two banks of the Red River. According to the geophysical data, the Red River fault is a deepseated fault that crosses through the Moho, with the average depth of more than 30 km (Bui Cong Que, 1983). Right lateral strike-slip offsets of these faults are determined by analyzing tributaries, stream channels, Quaternary alluvial fans and river valleys on Landsat and SPOT images, on detailed topographical maps, and by field observations. Geomorphology and topographical offsets suggest that these strike-slip movements are combined with normal slip (PhanTrong Trinh et al., 2012).

The Chay River fault is also identified as a deep-seated fault, stretching along the NE boundary of the Elephant Range metamorphic massive from Lao Cai to Viet Tri. The fault is clearly seen on the satellite Landsat and SPOT images. By analyzing the deviation across the fault of the stream network, Phan Trong Trinh et al. (2012) suggested that the offset of the right lateral displacement of the stream is 150–700 m; average offset is 150 m.

According to observed seismicity, the seismic active layer along the fault is determined within the depth from 20 to 25 km (Nguyen Dinh Xuyen 1987).

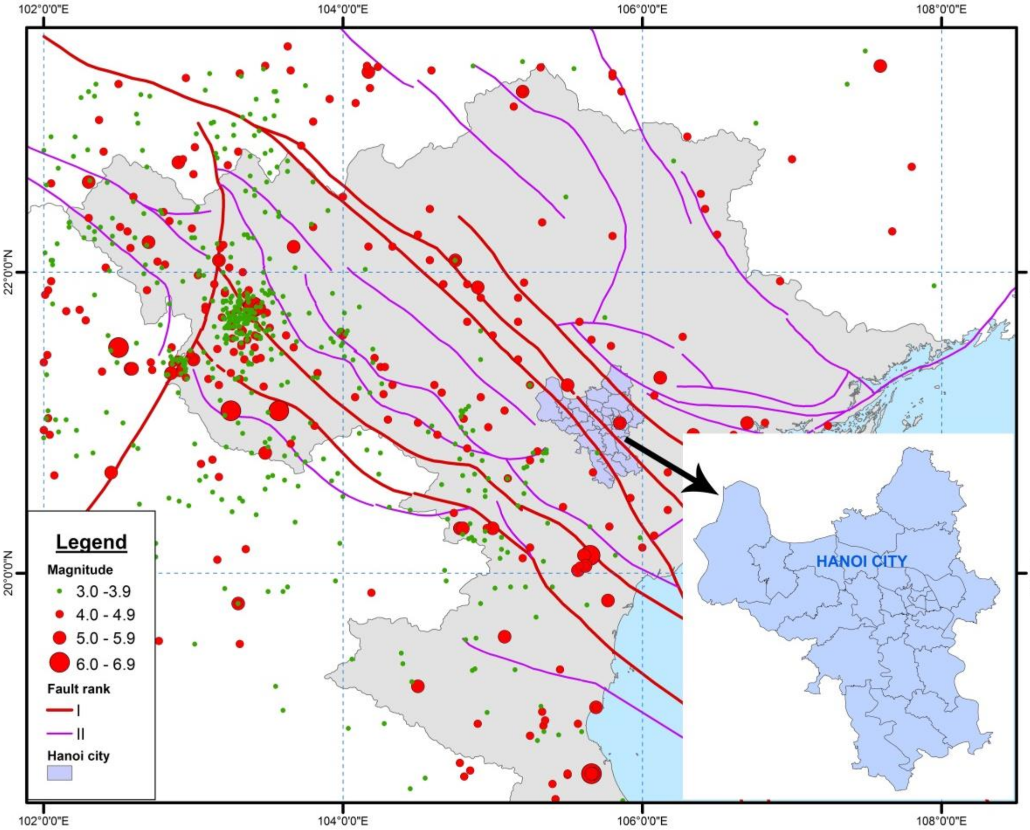

Figure 1. Seismotectonic map of the North Vietnam. The earthquake catalog used includes historical and instrumental data updated until 2018

Using the average length of offset channels and a minimum rate of 100-150 mm/yr for river propagation, Phan Trong Trinh et al., 2012 estimated the horizontal slip rates of 2.9±1.7 mm/yr for the Chay river fault, 2.3±1.5 mm/yr for the NE branch and 2.1± 1.5 mm/yr for the SW branch of the Red River fault.

Located in the NE and almost parallel to the RRFZ is the Lo river fault. According to the geological data, the fault appeared in Early Paleozoic. The fault is clearly seen on the satellite images, DEM maps from Tuyen Quang to Tam Dao and inferred to be continued until it reaches to the coast of the East Vietnam Sea if not be overshadowed by the sediments of the North Vietnam's delta. At Tuyen Quang, the fault is mainly identified as a right strikeslip, but along the SW side of Tam Dao mountain, it appears as a normal fault, dipping 70–80° to the SW direction. Some authors argue that the Lo river fault is a part of the RRFZ (Phan Trong Trinh et al., 2004; Cuong, N.Q. et al., 1999; 2001; Zuchiewicz et al., 2013; Ngo Van Liem et al., 2016).

Judging by size and role of controlling the regional tectonic activity, the Red River fault, the Chay River fault, and the Lo river fault are considered as the first rank of the seismically active faults which are capable of producing earthquakes in the territory of North Vietnam.

These three active faults are parallel and crossing the Hanoi's territory in the NW-SE direction.

Another active fault that crosses nearby Hanoi city is the Dong Trieu-Uong Bi fault, with the average depth of 30 km and dipping 60–80° to the NE direction. In the present time, the Dong Trieu-Uong Bi fault is assessed as left-lateral strike-slip, which is differing from the movement mechanism of the RRFZ. Regardless the fact that the Dong Trieu - Uong Bi fault belongs to a group of second-ranked active faults, its seismic impact to the Hanoi city has always been considered (Nguyen Hong Phuong, 2016).

3.2. Seismicity of Hanoi region

While the large earthquakes were not recorded in the Vietnamese part of the RRFZ, the events with medium magnitude occurred quite frequently (Fig. 1). During less than a century, from 1910 to 2005, 33 earthquakes with magnitude exceeding 4.0 have been instrumentally recorded within the zone. In addition, it is worth to mention the historical events, which might have occurred during the years 1277, 1278, 1285 and can be traced in the ancient annals. As described in literature, the first event "had caused a crack of 7 zhangs length (~24 meters) in the surface", while the second event was "a swam of three strong shakings during a day, and the third event "had made the gravestone in Bao Thien temple broken in two, and caused landslide in the Cao Son mountain" (Nguyen Dinh Xuyen, 2004). As evaluated by seismologists, the shakings of these historical earthquakes are comparable with intensity 7 or 7-8 on the MSK-64 intensity scale.

Among the earthquakes observed in the RRFZ, the largest events were concentrated along the Chay River fault. There were 3 events with magnitudes exceeding 5.0 instrumentally recorded along this fault, of which the epicenter of Yen Lac earthquake (M=5.3, occurred in 1958) is located within the territory of Hanoi city. The two other events have occurred in the territory of Yen Bai province, namely the Luc Yen earthquake (M=5.3, recorded in 1954) and the Yen Binh earthquake (M=5.2, recorded in 1961). It is also worth to note that three historical events described above (occurred right in the ancient city of Hanoi during 1277, 1278 and 1285) are assumed to be caused by the Chay River fault.

Seismic activity along the Red River fault is quite similar to that of the Chay River fault, but weaker in terms of frequency and magnitude. Three earthquakes with magnitudes M=5.0 were instrumentally recorded along the Vietnamese part of this fault. The nearest to Hanoi event is the Kim Boi earthquake (M=5.0, occurred in 1934). The two others events occurred further from Hanoi was the Yen Mo earthquake in Ninh Binh province (M=5.0, occurred in 1914) and the Ha Hoa earthquake in Phu Tho province (M=5.0, occurred in 1947).

Outside of the RRFZ, the Dong Trieu - Uong Bi fault, although is evaluated as the second-ranked active fault, had provoked a serial of strong earthquakes including the BacGiang earthquake (M=5.6, occurred in 1961), the Mao Khe earthquake (M=5.1, occurred in 1903), and the Dai Tu earthquake (M=5.0, occurred in 1967). The seismicity along the Lo River fault is weaker, where earthquakes of magnitudes not exceeding 4.8 have been recorded with sparse frequency.

4. Seismic source model

In this study, an areal source model is used, with asumption that an earthquake is caused by a source whose boundary encloses a zone of one or more seismically active faults, or a zone of concentrated seismicity (Budnitz et al., 1997). The seismic sources of Hanoi region were determined on the basis of known seismicity and seismotectonic characteristics. For this study, a seismic source zone is defined along seismically active faults by summing all the possible rupture zones caused by maximum earthquakes, which might occur within the given zone. In another word, this is the projection of tectonic fault plans counting from the lowest active layer to the Earth's surface. However, while delineating a seismic source zone boundary, this rule can be extended, depending on certain observed earthquake epicenter distribution, a set of faults in cases of scattered earthquake data. The acceptable boundary for a seismic source zone has to maintain all seismotectonic characteristics of the zone as a whole, namely the azimuthal location, direction of main geologic structures and cluster of earthquake epicenters.

The criterion on tectonic activity leads to the criterion on shaking attenuation from source to site. In practice, there are distances beyond which detailed source characterization is not necessary. It has been empirically proved that shaking attenuation in the region with stable tectonic regime is more gradual comparing with the attenuation in the region with active tectonic regime (e.g. Budnitz et al., 1997). For that reason, it is assumed that for application of PSHA to a certain region, a radius of 300 km from the site is appropriate for the study region in the active case, while a radius of 500 km is more appropriate in the stable case of tectonic activity. Based on all above-described arguments, the study region is defined as the area with radius of 500 km from the Hanoi city.

For delineation of seismic source zones in the study area, a pre-defined seismotectonic model developed for the territory of Vietnam and the East Vietnam sea was used (Nguyen Dinh Xuyen et al., 2004; Bui Cong Que et al., 2010; Nguyen Hong Phuong and Pham The Truyen, 2015). In total, 18 seismic source zones were delineated (Fig. 2). The names of seismic source zones are listed in Table 1.

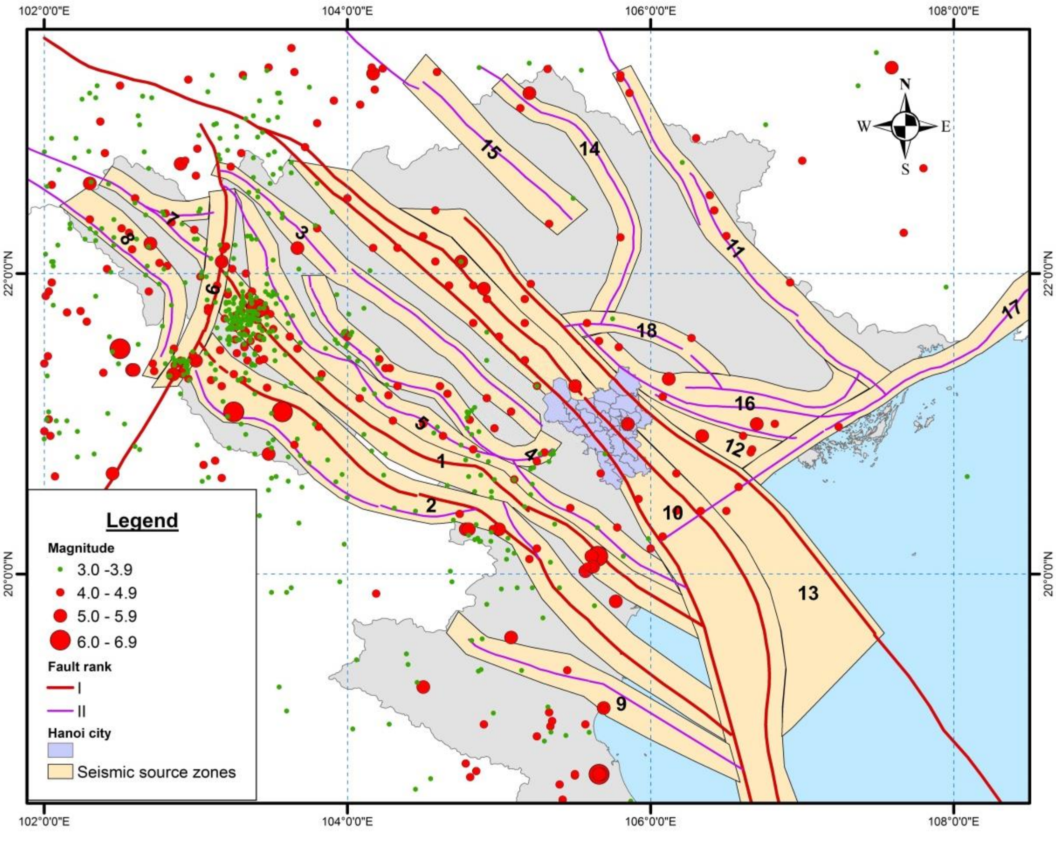

Figure 2. Map of the seismic source zones used in this study. The numbers in the map indicate the order numbers of seismic source zones listed in Table 1

Table 1. Seismic hazard parameter estimated for the seismic source zones of Hanoi region

No.	Seismic source zone	λ_0	N	M_0	M_{maxML}	M_{maxobs}	b_{ML}	Δb	H (km)
1	Son La	0.29	33	4.0	7.2	6.8	0.86	0.08	22
2	Ma river-Pumaytun	0.15	17	4.0	7.3	6.8	0.86	0.08	22
3	Phong Tho-Thanh Son	0.04	5	4.0	5.6	5.1	0.86	0.08	12
4	Muong La-Bac Yen	0.03	4	4.0	5.4	4.7	0.86	0.08	12
5	Da river	0.06	7	4.0	5.3	4.8	0.86	0.08	12
6	Lai Chau-Dien Bien	0.17	20	4.0	6.5	5.3	0.86	0.08	12
7	Muong Te	0.03	4	4.0	5.2	4.7	0.86	0.08	12
8	Muong Nhe	0.12	14	4.0	5.8	4.7	0.86	0.08	12
9	Song Hieu	0.02	1	4.0	8.7	5.2	0.86	0.08	12
10	Red river-Chay river	0.27	31	4.0	6.3	5.3	0.85	0.19	17
11	Cao Bang-Tien Yen	0.03	4	4.0	5.5	5.0	0.85	0.15	12
12	Northwestern Hanoi Depression	0.03	4	4.0	6.0	5.5	0.85	0.15	12
13	Lo river	0.04	5	4.0	5.3	4.5	0.85	0.15	12
14	Thai Nguyen-Bac Kan	0.03	4	4.0	5.7	5.2	0.85	0.15	12
15	Van Son-Ha Giang	0.02	2	4.0	5.1	4.6	0.85	0.15	12
16	Dong Trieu-Uong Bi	0.06	7	4.0	6.1	5.6	0.85	0.15	12
17	Cam Pha	0.02	1	4.0	5.5	4.7	0.85	0.15	12
18	13A national highway	0.03	3	4.0	5.3	4.8	0.85	0.15	12

Note: λ_0-annual exceedance rate corresponding to M_0; N-number of earthquakes within each source zone; $M_{max.obs.}$-observed maximum magnitude; M_{max_ML}-maximum earthquake value estimated by the maximum likelihood method; M_0-lower threshold of magnitude value used; b_{ML}-the b value (in the Gutenberg-Richter relationship) derived from the maximum likelihood results; H-thickness of the active layer of each source zone

5. Earthquake catalog

An earthquake catalog of Northern Vietnam was established based on the earthquake database of the Institute of Geophysics, Vietnam Academia of Science and Technology. The catalog includes all historical and macroseismic events (collected from 1311 to 1903) and instrumental events (recorded from 1903 to 2018) within a region bounded by φ=17.5-23.5°N; λ=102.0-108.5°E. All events of magnitude lower 4.0 then were removed from the catalog.

Data treatment plays important role in a seismic hazard assessment procedure, particularly in case of probabilistic application, as one of the basic requirement of the earthquake data to be used that they have to be statistically independent with each other. For this reason, a statistical procedures were applied to remove all forshocks and aftershocks from the catalog. Then, the catalog was grouped by the seismic source zones into subcatalogs prior to the hazard computation.

In this study, the window method proposed by (Gardner and Knopoff 1974) was chosen for declustering earthquakes catalog of Vietnam. For each earthquake with magnitude M in the catalog, the subsequent shocks are identifed as aftershocks if they occur within a specified time interval T(M), and within a distance interval L(M). Foreshocks are treated in the same way as aftershocks, i.e., if the largest earthquake occurs later in the sequence, the foreshock is treated as an aftershock. Consequently, the time-space windows are reset according to the magnitude of the largest shock in a sequence. Usually, these algorithms do not distinguish between direct and indirect aftershocks, i.e., 1st-generation aftershocks and aftershocks of aftershocks. An approximation of the windows sizes according to (Gardner and Knopoff 1974) is shown in equation 5.

$$d = 10^{0.1238*M+0.0983}\ (\text{km});\quad t = \left\{\begin{matrix} 10^{0.032*M+2.7389}\ if\ M \geq 6.5 \\ 10^{0.5409*M-0.547}\ else \end{matrix}\quad (days)\right\} \qquad (5)$$

6. Estimation of seismic hazard parameters for the seismic source zones

In order to calculate the seismic hazard of Hanoi region, the following earthquake hazard parameters, characterizing level of seismicity, were estimated for each seismic source zone:

- Constants a, b in the Gutenberg-Richter magnitude-frequency relation and their deductive values λ, β;
- Expected maximum magnitude M_{max};
- Mean return period T(M) of the strong earthquakes with magnitude M.

The maximum likelihood method proposed by Aki and Utsu (Utsu, 1965; Aki, 1965) was applied to estimate the a and b parameters of the Gutenberg-Richter equation for the territory of Vietnam and its seismotectonic provinces. With the magnitude M assumed a continuous random variable, the probability density function (pdf) of M can be expressed by:

$$f(M) = bln(10)\frac{10^{-bM}}{10^{-bM_{min}}-10^{-bM_{max}}} \qquad (6)$$

where M_{min} and M_{max}, respectively, are the minimum and the maximum magnitude considered. If $M_{max} >> M_{min}$, equation (6) becomes:

$$f(M) = bln(10)10^{-b(M-M_{min})} \qquad (7)$$

The maximum likelihood estimation of equation (7) is the b-value which maximizes the likelihood function (Fisher 1950), that is:

$$b^{\wedge} = \frac{1}{\ln(10)(\mu^{\wedge}-M_c)} \qquad (8)$$

where $\mu^{\wedge}$ is the sampling average of the magnitudes, and M_c is the threshold magnitude which usually corresponds to the minimum magnitude for the completeness of the seismic catalog. The uncertainty is estimated by (Aki 1965):

$$\sigma^{\wedge}_{b^{\wedge}} = \frac{b^{\wedge}}{\sqrt{N}} \qquad (9)$$

where N is the number of earthquakes.

Assuming the Poisson occurence of earthquakes with the activity rate λ and the doubly truncated Gutenberg-Richter distribution F(x) of earthquake magnitude x, the maximum magnitude value can be estimated for each source zone using the doubly truncated exponential distribution (Nguyen, H.P. et al., 2012):

$$F(x) = P(X \le x) = \frac{A_1 - A(x)}{A_1 - A_2}; M_{\min} \le x \le M_{\max} \qquad (10)$$

where

$A_1 = \exp(-\beta M_{\min}), A_2 = \exp(-\beta M_{\max}), A_x = \exp(-\beta x);$

M_{max} is the maximum regional magnitude value, M_{min} is the threshold magnitude and β is a parameter. The probability that *X,* the largest magnitude within a period of t years will be less than some specified magnitude *x* is given by:

$$G(x|t) = P(X \le x) = \exp\{-v_0 t\left[\frac{A_2 - A(x)}{A_2 - A_{10}}\right]\} \qquad (11)$$

where G is the distribution function, $v_0 = \lambda[1 - F(M_0)], A_{10} = \exp(-\beta M_0)$ and M_0 is the threshold magnitude. Finally, The sought parameters $\hat{\beta}$ and $\hat{\lambda}$ can be obtained by solving the system of equations:

$$\begin{cases} \frac{\delta \ln L(\theta|X)}{\delta\lambda} = 0 \\ \frac{\delta \ln L(\theta|X)}{\delta\beta} = 0 \end{cases} \qquad (12)$$

Although the statistical procedure was preferable to be used for estimating of the seismic hazard parameters for each source zone, in such cases when the number of earthquakes within a source zone is not enough for a statistical analysis, a rule called "faults with similar activity" was applied. The rule can be stated as follows: given two source zones with similar tectonic condition, if for some reasons the seismic hazard parameters can only be estimated for one of them, the similar parameters can be asigned to the other one (Nguyen Dinh Xuyen et al., 2004; Nguyen Dinh Xuyen and Le Tu Son, 2009; Bui Cong Que et al., 2010).

Table 1 lists the seismic hazard parameter estimated for the seismic source zones of Hanoi region. The explanation for parameters listed in this table are given as follows : λ_0-annual exceedance rate corresponding to M_0; N-number of earthquakes within each source zone; $M_{max.obs.}$-observed maximum magnitude; M_{maxML}-maximum earthquake value estimated by the maximum likelihood method; M_0-lower threshold of magnitude value used; B_{ML}-the b value (in the Gutenberg-Richter relationship) derived from the maximum likelihood results; H-thickness of the active layer of each source zone.

7. Ground motion prediction models

The establishment of an attenuation equation to be applied to a study region is important and usually considered as a separate stage in PSHA procedure. In Vietnam, due to the lack of strong ground motion data, for a long time no local attenuation equations have been developed. Although since 2011, two attenuation equations have been published by Vietnamese scientists, none of them are used, until now, as the reliability of these equations has been in the process of verification (Nguyen, L. M. et al., 2012; T. V. Hung and Kiyomiya, 2012). For domestic hazard calculation, the suitable ground motion prediction models have to be selected from a set of ground motion prediction equations (GMPEs) developed for different regions in the World.

However, the selection of GMPEs suitable for application in Vietnam is not a simple work. Up to now, there are so many GMPEs published for different regions of the world. Meanwhile, the most welknown GMPEs, which are being used worldwide, are also being updated by their authors (BrianS-J. Chiou and Robert R. Youngs, 2008). On the other hand, investigations show large variation of the hazard calculation results when applying different GMPEs to the same study area. Having a prolonged territory, which stretches 15 degrees from north to south, Vietnam is characterized by a differetiated seismicity. So, the application of a single GMPE for the whole territory of Vietnam is not an optimal idea. Results of a recent research on seismicity have shown that it is more appropriate to divide the territory of Vietnam into four seismotectonic provinces with different level of seismic activity, which are Northeastern, Northwestern, Central and Southern Vietnam (Nguyen Dinh Xuyen et al., 2004; Nguyen H.P. et al., 2019). The selection of suitable GMPEs for Vietnam therefore can be carried out on the basis of seismotectonic regionalization.

To select suitable GMPEs for Vietnam, a test has been carried out to compare the calculation results of 25 published GMPEs with seismograms of 39 earthquakes recorded in the territory of Vietnam and to find the GMPEs, best fit to Vietnamese data (Le Q.K. et al., 2018). As Hanoi city is located on the boundary of Northeastern and Northwestern seismotectonic provinces, an attemt has been made to select the GMPEs for these two provinces. In results of the best fit test, two GMPEs that can be applied to Hanoi region, which are the Campbell & Bozorgnia (2008) and Akkar et al., (2014). These GMPEs then were used for seismic hazard assessment of Hanoi city.

According to Campbell & Bozorgnia (2008), the median estimate of ground motion can be calculated from the general equation

$$ln\hat{Y} = f_{mag} + f_{dis} + f_{flt} + f_{hng} + f_{site} + f_{sed} \quad (13)$$

where $\hat{Y}$ is the median estimate of the geometric mean horizontal component ground motion in terms of PGA (g), PGV(cm/s), PGD (cm) or PSA (g); M is the moment magnitude; f_{mag} is the magnitude term, f_{dis} is the distance term, f_{flt} is the fault mechanism term, f_{hng} is the hanging-wall term, f_{site} is the shallow site response term, f_{sed} is the basin response term.

The magnitude term is given by the expressions:

$$f_{mag} = c_0 + c_1 \qquad M \leq 5.5;$$
$$f_{mag} = c_0 + c_1 M + c_2(M - 5.5) \qquad 5.5 \leq M \leq 6,5;$$
$$f_{mag} = c_0 + c_1 M + c_2(M - 5.5) + c_3(M - 6.5) \qquad M > 6.5$$

The distance term is given by the expression:

$$f_{dis} = (c_4 + c_5 M)\ln(\sqrt{R_{RUP}^2 + c_6^2}),$$

The style-of-faulting (fault mechanism) term is given by the expressions

$$f_{flt} = c_7 F_{RV} f_{flt,Z} + c_8 F_{NM},$$

$$f_{flt,Z} = z_{TOR};\ Z_{TOR} \geq 1;\ f_{flt,Z} = 1;\ Z_{TOR} \geq 1$$

The hanging-wall term is given by the expressions

$$f_{hng} = c_9 f_{hng,R} f_{hng,M} f_{hng,Z} f_{hng,\delta}$$

The shallow site response term is given by the expression:

$$f_{site} = c_{10}\ln\left(\frac{V_{S30}}{k_1}\right) + k_2\{\ln\left[A_{1100} + c\left(\frac{V_{S30}}{k_1}\right)^n\right] - ln[A_{1100} + c]\};\ V_{S30} < k_1;$$
$$f_{site} = (c_{10} + k_2 n)\ln\left(\frac{V_{S30}}{k_1}\right);\quad k_1 \leq V_{S30} < 1100;$$
$$f_{site} = (c_{10} + k_2 n)\ln(\frac{1100}{k_1})\ ;\ V_{S30} \geq 1100$$

The basin response term is given by the expression

$$f_{sed} = c_{11}(Z_{2.5} - 1)\ ; \qquad Z_{2.5} < 1;$$
$$f_{sed} = 0\ ; \qquad 1 \leq Z_{2.5} \leq 3;$$
$$f_{sed} = c_{12} k_3 e^{-0.75}[1 - e^{-0.25(Z_{2.5}-3)}]\ ;\ Z_{2.5} > 3$$

where R_{RUP} is the closest distance to the coseismic rupture plane (km); R_{JB} is the closest distance to the surface projection of the coseismic rupture plane (km); F_{RV} is an indicator variable representing reverse and reverse-oblique faulting; F_{NM} is an indicator variable representing normal and normal-oblique faulting; Z_{TOR} is the depth to the top of the coseismic rupture plane (km); δ is the dip of the rupture plane (°); V_{S30} is the time-averaged shear-wave velocity in the top 30 m of the site profile (m/s); A_{1100} is the median estimate of PGA on a reference rock outcrop; $Z_{2.5}$ is the depth to the 2.5 km/s shear-wave velocity horizon, typically referred to as basin or sediment depth (km); c_i are empirical coefficients, and c, n and k_i are theoretical coefficients.

The final functional form of ground-motion predictive model proposed by Akkar et al., (2014) is given in Eqs. (14)–(16):

$$\ln(Y) = \ln\,[Y_{REF}(M_w,\ R,\ SoF)] + \ln\,[S(V_{s30},\ PGA_{REF})] + \varepsilon\sigma \tag{14}$$

where

$$\ln(Y_{REF}) = \begin{cases} a_1 + a_2(M_w - c_1) + a_3(8.5 - M_w)^2 + [a_4 + a_5(M_w - c_1)]\ln(\sqrt{R^2 + a_6^2}) + a_8 F_N + a_9 F_R + S \\ \qquad for\ M_w \leq c_1 \\ a_1 + a_7(M_w - c_1) + a_3(8.5 - M_w)^2 + [a_4 + a_5(M_w - c_1)]\ln(\sqrt{R^2 + a_6^2}) + a_8 F_R + a_9 F_R + S \\ \qquad for\ M_w > c_1 \end{cases} \tag{15}$$

and

$$\ln(S) = \begin{cases} b_1\ln\left(\frac{V_{S30}}{V_{REF}}\right) + b_2 ln\left[\frac{PGA_{REF} + c(\frac{V_{S30}}{V_{REF}})^n}{(PGA_{REF} + c)(\frac{V_{S30}}{V_{REF}})^n}\right] & for\ V_{S30} \leq V_{REF} \\ b_1 ln\left[\frac{\min(V_{S30}.V_{CON}}{V_{REF}}\right] & for\ V_{S30} > V_{REF} \end{cases} \tag{16}$$

where ln(Y) is the median spectral acceleration; ln(Y_{REF}) is the reference ground-motion model through the nonlinear site amplification function ln(S); M_w is moment magnitude; R is the source-to-site distance measure, (km), for which R_{JB},R_{epi},R_{hyp} are used for different models; F_N and F_R are the style-of-faulting dummy variables, that are unity for normal and reverse faults, respectively, and zero otherwise. The parameter c_1 in the reference ground-motion model is the hinging magnitude and it is taken as M_w 6.75; σ is the total aleatory variability of the model, which is composed of within-event (φ) and between-event (τ) standard deviations (SDs); b_1 and b_2 are the period-dependent estimators parameters of the nonlinear site function; c and n are the period-independent coefficients of the reference ground-motion model. The reference V_{S30} (VREF) is 750 m/s in the nonlinear site model and V_{CON} = 1,000 m/s that stands for the limiting V_{S30} after which the site amplification is constant. PGA_{REF} is the reference rock site PGA calculated from the reference ground-motion model.

8. Probabilistic seismic hazard maps of Hanoi city

Results of seismic hazard assessment for Hanoi city are presented in terms of probabilistic seismic hazard maps. Program CRISIS2015 was used to compute hazard (Ordaz et al., 2015). The seismic source model used for computation is shown in Table 1. For all seismic source zones, the lower threshold of magnitude was chosen to be M_0=4.0. The Median peak ground acceleration (PGA) and spectral acceleration (SA) values computed at each point of a 0.01° × 0. 01° grid covering all over the study area were used to compile seismic hazard maps.

Figs. 3-5 illustrate the probabilistic seismic hazard maps of Hanoi city, representing spatial distribution of the median values of horizontal PGA and 0.2 sec and 1.0 sec SA (in unit of % g) with 10%, 5%, 2% and 0,5% probabilities of exceedance in 50 years and V_{S30} site condition of 760 meters per second, corresponding to return times of 475, 975, 2,475 and 9,975 years, respectively.

Analyzing the hazard maps of Hanoi city, the following can be concluded:

(1) Spatial distribution of seismic shakings in Hanoi city has a prolonged shape in NW-SE direction, where the highest hazard concides with location of three active faults named Red River, Chay River and Lo River crossing the Hanoi city. For all four return periods, in the PGA and 0.2 sec. SA maps, the maximum shakings are observed in a narrow zone located in the central part of the city, bounded from the north by such distics as Dan Phuong, Hoai Duc, Ha Dong, Thanh Tri, Thuong Tin and from the south by such districts as Ba Vi, Son Tay, Thach That, Quoc Oai, Chuong My and Ung Hoa (see Figs 3 and 4). Distribution of shaking in the 1.0 sec. SA maps has different shape, with decreasing values in the direction from northeast to the south of the city (see Fig. 5).

(2) For the whole territory of Hanoi city, the PGA values are in the range of 0.08-0.13 g, 0.10-0.19 g, 0.15-0.29 g and 0.23-0.41g, corresponding to a return period of 475, 975, 2,475 and 9,975 years, respectively. In the downtown area, the highest shaking values are predicted in such districts as Ha Dong, Thanh Xuan, Cau Giay, Ba Dinh, Dong Da and part of the Tay Ho, Hoan Kiem, Hai Ba Trung and Hoang Mai districts. For all four return periods, the shakings in these districts can reach to the VIII and IX intensity levels according to the MSK-64 scale.

(3) For the whole territory of Hanoi city, the 1.0 sec. SA values are in the range of 0.03-0.05 g, 0.04-0.06 g, 0.05-0.08 g and 0.07-0.12 g, corresponding to a return period of 475, 975, 2,475 and 9,975 years, respectively. Thus, maximum shaking

intensity in within the city can only reach to the VI and VII levels according to the MSK-64 scale. In the downtown area, the highest shaking values are predicted in such districts as Tay Ho, Hoan Kiem, Ba Dinh, Cau Giay, Dong Da, Hai Ba Trung, Thanh Xuan and Ha Dong. Maximum shaking in these districts can reach to the VI level according to the MSK-64 scale at the return periods of 475 and 975 years, and to the VII level according to the MSK-64 scale at the return periods of 2,475 and 9,975 years.

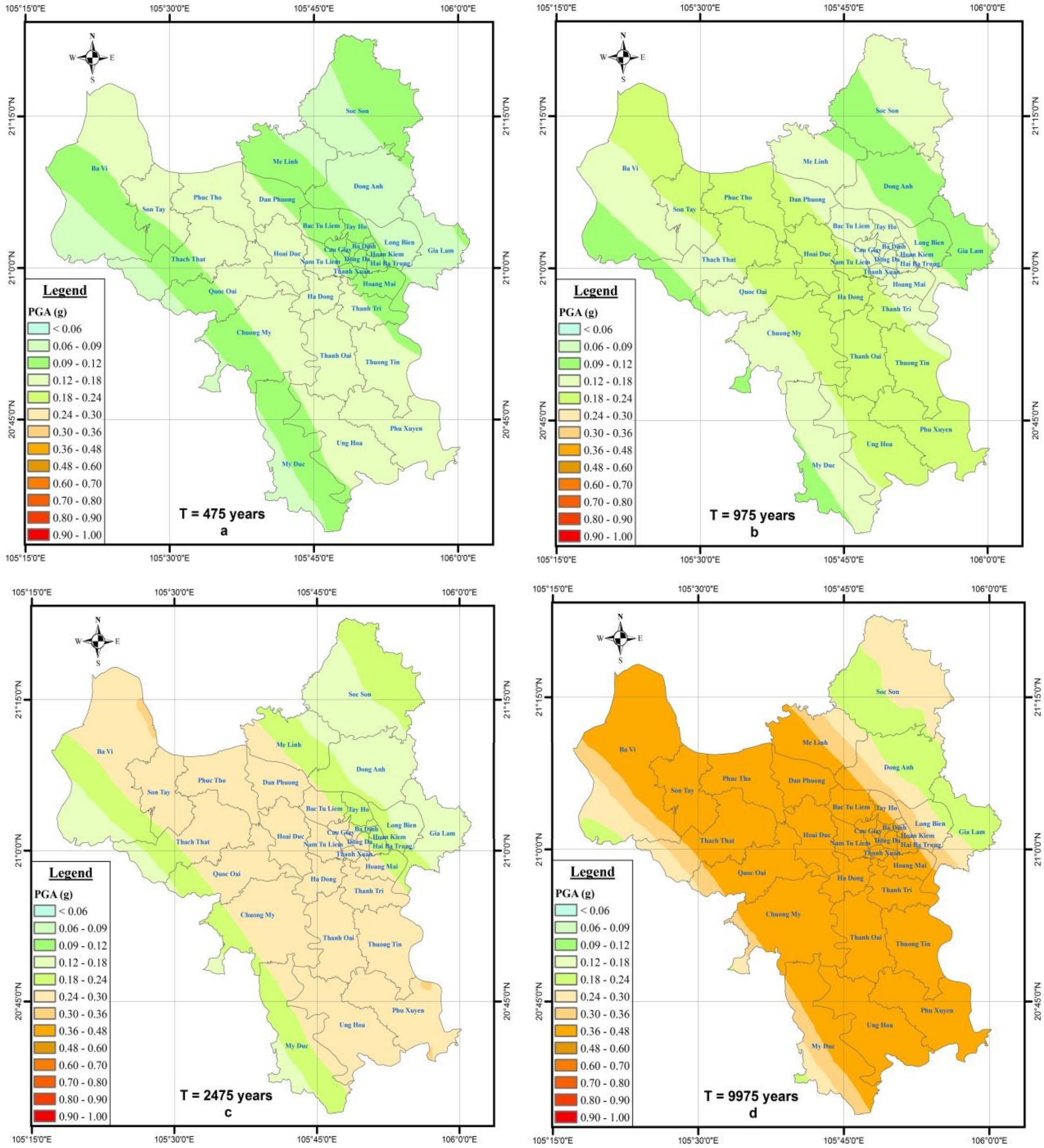

Figure 3. Maps showing peak ground acceleration in Hanoi city for 10%, 5%, 2% and 0.5% probabilities of exceedance in 50 years and VS30 site condition of 760 meters per second

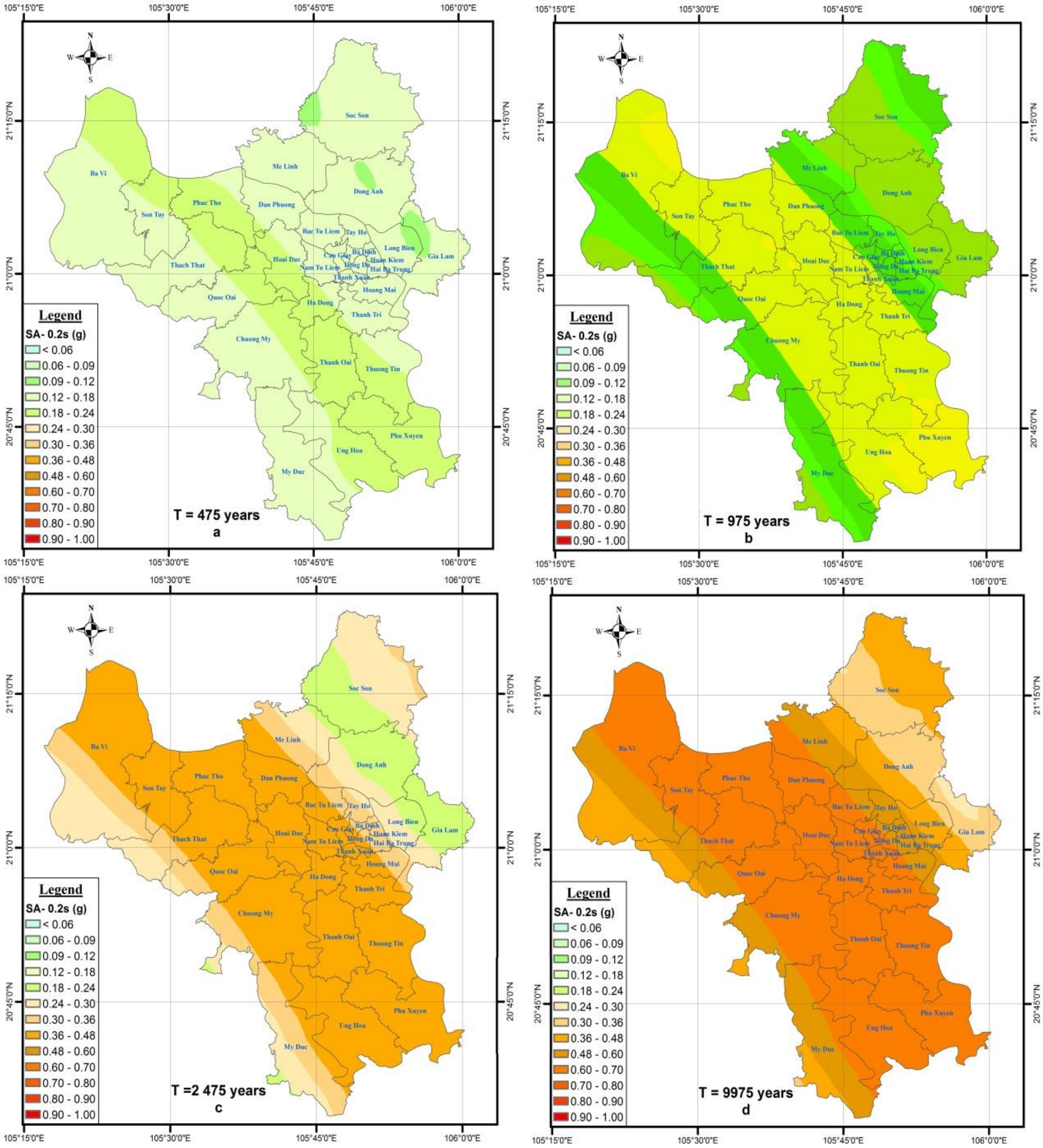

Figure 4. Maps showing 5-hertz (0.2-second) spectral acceleration in Hanoi for 10%, 5%, 2% and 0.5% probabilities of exceedance in 50 years and VS30 site condition of 760 meters per second

(4) For the whole territory of Hanoi city, the 0.2 sec. SA values are in the range of 0.13-0.19 g, 0.17-0.28 g, 0.22-0.44 g and 0.28-0.64 g, corresponding to a return period of 475, 975, 2,475 and 9,975 years, respectively. The maximum shaking intensity of VIII level according to the MSK-64 scale are predicted for all downtown districts at the return periods of 475 and 975 years. For return periods of 2,475 and 9,975 years, the maximum shaking of X intensity level according to the MSK-64 scale are predicted for such downtown districts as Cau Giay, Thanh Xuan and Ha Dong and a part of the Ba Dinh, Dong Da and Hoang Mai.

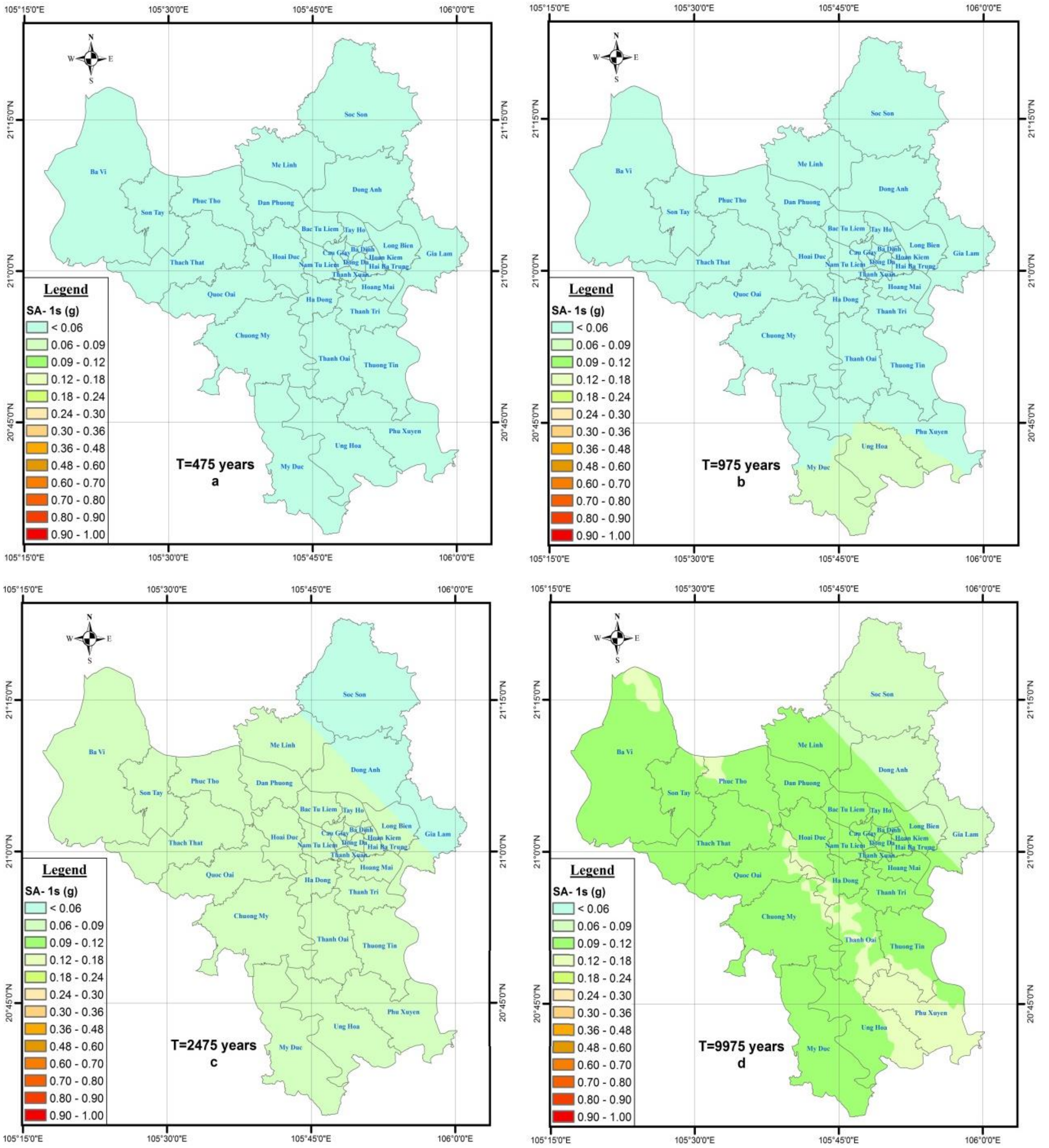

Figure 5. Maps showing 1-hertz (1.0-second) spectral acceleration (SA) in Hanoi for 10%, 5%, 2% and 0.5% probabilities of exceedance in 50 years and VS30 site condition of 760 meters per second

9. Discussions

In this study, the last updated version of the probabilistic seismic hazard maps of Hanoi city are presented. These new seismic hazard maps have advantages over those, published previously. Some advantages of the newly obtained results are discussed in detail below.

(1) On the extents of study area, before 2012, all the probabilistic seismic hazard maps were compiled for the Old Hanoi area. Only since 2012, the new Hanoi area is chosen for seismic hazard mapping (Nguyen

Hong Phuong, 2016; Nguyen Anh Duong et al., 2017). In this study, all PSH maps are compiled for the the extended Hanoi city area.

(2) On the input data, this stuy uses an earthquake catalog updated until 2018 and most complete knowledge on the seismically active fault systems in the territory of Vietnam and adjacent sea areas for calculation and mapping seismic hazard of Hanoi city. This obviously can be noticed as a considerable advatage of this study over other previously published ones.

(3) In this study, some advanced techniques and widely accepted seismology-based principles in modern methodology were also implemented in compiling the new hazard maps. One of the significant changes in implementation of seismic hazard analysis is that the input models were improved by using new and most suitable for Hanoi region GMPEs (Le Q. K. et al., 2018).

(4) On the parameters used for hazard mapping, this study is also exceeding the others. Previously, Nguyen Hong Phuong (2016) published the PGA maps corresponding to four time periods of 100, 200, 500 and 1000 years, respectively and the SA maps for 2500 year period and for 0.3s and 1.0 s periods, respectively. But as discussed above, these maps are compiled for the old Hanoi area only. Meanwhile, in a study by Nguyen Anh Duong et al. (2017), a PGA map published for extended Hanoi city, but only for 500 year span, and no SA maps compiled in this study. Thus, the new PSH maps presented in this study are the most comprehensive, if we take into account the fact that they are compiled for the extended Hanoi city area, with four periods of time used for calculation of both PGA and SA.

Comparison of the PGA and SA calculation results is somehow difficult due to the uncompatibility of the choice of time periods. However, some coincidence can be noticed, as, for example between the results of this study and other previously published ones. As for example, in the study by Nguyen Anh Duong et al. (2017), the maximum PGA value of Hanoi for 500 year period is PGA=0.13 g, while for this study, for the same time period we obtained PGA=0.136. The PGA and SA results obtained previously by Nguyen Hong Phuong (2016) are also comparable with results presented in this study.

It worth emphasising that in every country, updating the values of ground motion parameters in seismic hazard maps play important role in revision of national seismic-design regulations for buildings, bridges, highways, railroads, and other structures. In Vietnam, up to now these seismic design regulations are still based on the PGA map published in 2004 by Institute of Geophysics, VAST, and this fact needs to be considered in the near future.

10. Conclusions

In this study, the methodology of probabilistic seismic hazard assessment proposed by Cornell and Esteva in 1968 was applied for Hanoi city, using an earthquake catalog updated untill 2018 and a comprehensive seismotectonic model of the territory of Vietnam and adjacent sea areas.

Statistical methods were applied for declustering the earthquake catalog, then the maximum likelihood method was used to estimate the parameters of the Gutenberg–Richter Law and the maximum magnitude for each seismic source zone. As a result of a GMPE test, two attenuation models, which are most suitable for Hanoi region were selected for use in hazard analysis.

Results of PSHA for Hanoi city are presented in the form of probabilistic seismic hazard maps, depicting peak horizontal ground acceleration (PGA) as well as 5-hertz and 1-hertz spectral accelerations (SA) with 5-percent damping on a uniform firm rock site condition, with 10%, 5%, 2% and 0,5%

probability of exceedance in 50 years, corresponding to return times of 475; 975; 2,475 and 9,975 years, respectively. The results of PSHA show that, for the whole territory of Hanoi city, for all four return periods, the predicted PGA values correspond to the intensity of VII to IX degrees according to the MSK-64 scale. As for the SA maps, for all four return periods, the predicted SA values at 1.0 s period correspond to the intensity of VI to VII, while the predicted SA values at 0.2 s period correspond to the intensity of VIII to X according to the MSK-64 scale.

The probabilistic seismic hazard maps of Hanoi city display earthquake ground motions for various probability levels and can be applied in seismic provisions of building codes, insurance rate structures, risk assessments, and other public policy.

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