VIETNAM JOURNAL OF HYDROMETEOROLOGY

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Research Article

Probabilistic seismic hazard assessment for Da Nang city, Vietnam

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Received: 10 November 2022; Accepted: 19 December 2022; Published: 25 December 2022

Abstract: This paper presents the probabilistic seismic hazard assessment (PSHA) results for Da Nang city. A regional earthquake catalog was updated until 2021 and comprehensive seismic source zones within 150 km of Da Nang city were used. The PSHA results for Da Nang city are presented in the form of probabilistic seismic hazard maps, depicting peak horizontal ground acceleration (PGA) 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, as well as the 5–hertz (0.2 s period) and 1–hertz (1.0 s period) spectral accelerations (SA) maps with 5–percent damping on a uniform firm rock site condition, with 2% probability of exceedance in 50 years, corresponding to a 2,475 year return period. The results show that, for the whole territory of Da Nang city, for all four return periods, the predicted PGA values correspond to the intensity of VI to VIII degrees according to the MSK–64 scales. As for the SA maps, for the 2,475–year return period, the predicted SA values at 1.0 s period correspond to the intensity of VI, while the predicted SA values at 0.2 s period correspond to the intensity of VIII to IX according to the MSK–64 scales. These probabilistic seismic hazard maps present short–and long–term forecasts of seismic hazards for Danang city.

Keywords: Probabilistic seismic hazard maps; Peak Ground Acceleration; Spectral acceleration; Seismic source zones; Ground motion prediction equations.

1. Introduction

Da Nang is located on the South-Central Coast of Vietnam, is the commercial and educational center of Central Vietnam, and is one of Vietnam's most important port cities. Da Nang is a class–1 municipality and the fifth–largest city in Vietnam by municipal population. According to the most recent population and housing census results, as of April 1, 2019, the population of Da Nang city reached 1,134,310 people, ranking 39th in the country, accounting for 1.18% of the population nationwide, with the population density reaching 740 people/km² [1]. Da Nang is also the city with the highest urbanization rate in the country: 87.2%. The city has the highest proportion of people living in urban areas in the country. The urban population is usually concentrated in the city center. Along with the fast growth rate and high population density, Da Nang city will have to face a series of challenges and risks from natural hazards. In addition to the types of disasters that cause frequent damage, such as storms, floods and droughts, disasters with a low frequency but destructive nature, such as earthquakes and tsunamis, are also on the list of natural disasters to be avoided in the region [2].

To date, no quantitative seismic hazard assessment studies have been carried out at a detailed level for Da Nang city. The earthquake hazard map established for the whole territory of Vietnam shows that Da Nang city, in particular, and Quang Nam province in general, could be affected by the average earthquakes in the whole country, compared with the highest earthquake hazard area in the Northwest. However, the World experience of earthquake damage has shown that the damage caused by strong earthquakes to the community is not as significant as the damage caused by average earthquakes due to the frequency of occurrence of moderate earthquakes being much higher than that of strong earthquakes. Implementing science and technology tasks to assess and map earthquake hazards and anti–seismic design for big cities in Vietnam, including Da Nang city, is necessary. It should be deployed soon so that the results of seismic hazard assessment can be used effectively in a number of practical fields, such as seismic design for civil works or the development of a public transport network in the city.

This paper presents the results of applying the probabilistic method to evaluate and develop the earthquake hazard maps for Da Nang city, using the earthquake catalog updated to June 2021 and the most comprehensive knowledge on seismically active faults in Da Nang city and surrounding areas.

2. Materials and methodology

This paper uses the classical PSHA methodology proposed by Cornell and Esteva in 1968 [3–4]. 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, $\lambda(M)$ can be estimated through statistical analysis of earthquake catalogs. These rates are the number of earthquakes per unit of 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 earthquake hypocenters. In this case, acceleration exceedance rates due to a single source, say, the i–th source, are computed using the following expression:

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

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 at the site, given that at a distance R_{ij} an earthquake of magnitude M originates. R_{ij} is the distance 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 hazards 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 [5]:

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

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 Da Nang city was carried out through the following steps: (1) Determination of seismic sources in the Da Nang 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. Results

3.1. Seismotectonic characteristics of Da Nang city and its adjacent region

3.1.1. Seismic activity

The study area was enlarged to the entire Central Vietnam territory within 150 km around Da Nang city to incorporate all possible impacts from seismic sources to Da Nang city. Figure 1 shows the seismotectonic map of Da Nang city and surrounding areas, which was established based on up–to–date knowledge of seismically active faults and an earthquake catalog updated until 2021.

The catalog of earthquakes instrumentally observed since 1903, archived at the Institute of Geophysics, contains 13617 earthquakes with magnitudes of 2.5 and above that have been recorded in the study area. Of these, 10 have moment magnitudes exceeding 4.0. Thus, it can be generally assessed that the study area has average seismicity compared to other regions in Vietnam. However, the fact that a 4.7–magnitude earthquake was recorded in Da Nang city in 1947 shows that the possibility of earthquakes causing damage to the urban community of Da Nang city needs to be taken into account.

Based on the known seismic wave attenuation law, the research scope needs to be selected at the minimum distance where the impact of the seismic wave is still valid when traveling from the source to the site. Therefore, depending on the selected seismicity model, the study area is usually selected with a radius of 300 to 500 km around the site to assess earthquake hazards. Thus, in this work, a total of 68 earthquakes were used in the calculation to evaluate the characteristics of the study area's seismicity.

Research results show that earthquakes recently recorded in the Central Vietnam provinces mainly induce seismicity origin, which is generated due to the operation of hydroelectric power plants [5–6]. The earthquake sequences that have been recorded in Bac Tra My district from 2012 to the present, in the A Luoi district from 2014 to the present, and in the Kon Plong district from 2021 to the present are all consequences of the reservoir impoundment processes of the Tranh River 2 (Quang Nam), A Luoi (Thua Thien–Hue) and Thuong Kon Tum (Kon Tum) hydropower plants.

The results of research on stress fields and the tectonic regime of Central Vietnam also show that the study area has undergone various deformation phases, of which the sub–meridian compression phase characterized by the horizontal strike–slip movement is quite common [6]. Figures 2a–2b illustrate the focal mechanisms of two earthquakes recorded at Song Tranh 2 hydropower plant in 2015 obtained by using the moment tensor inversion method. The results show that the right–lateral strike–slip mechanism of the source faults is in the Northwest–southeast direction [7].

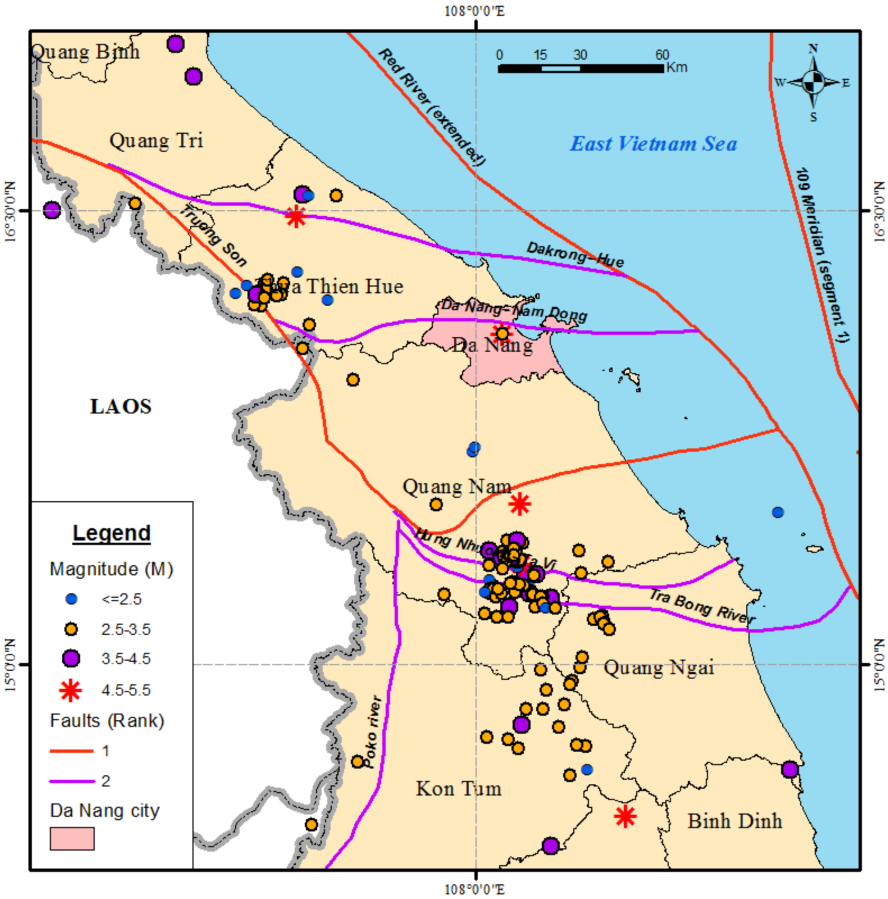

Figure 1. Seismic and tectonic map of Da Nang city and surrounding area.

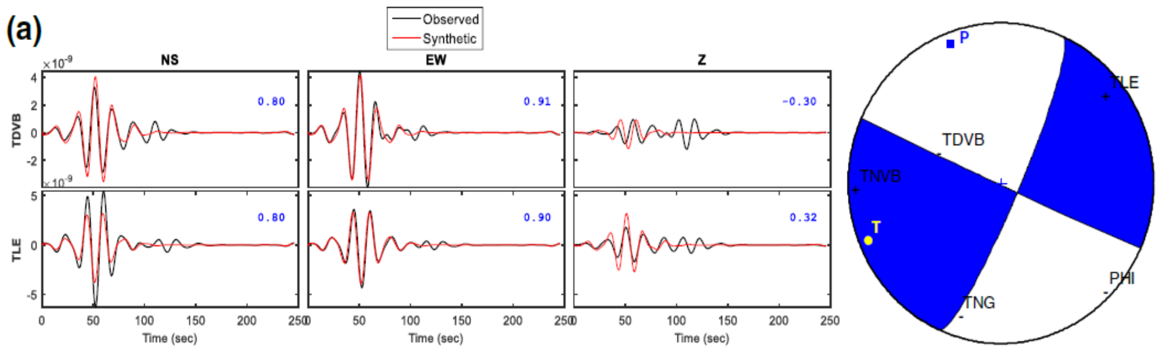

Figure 2a. Moment tensor solution of the April 2, 2015 event in the ST2 region using ISOLA. Waveform match between observed (black) and synthetic (red) seismograms in the frequency range of 0.04–0.1 Hz (left). The first motion polarities of five stations superposed on the mechanism where (+) represent compressions and (−) are the dilatations (right).

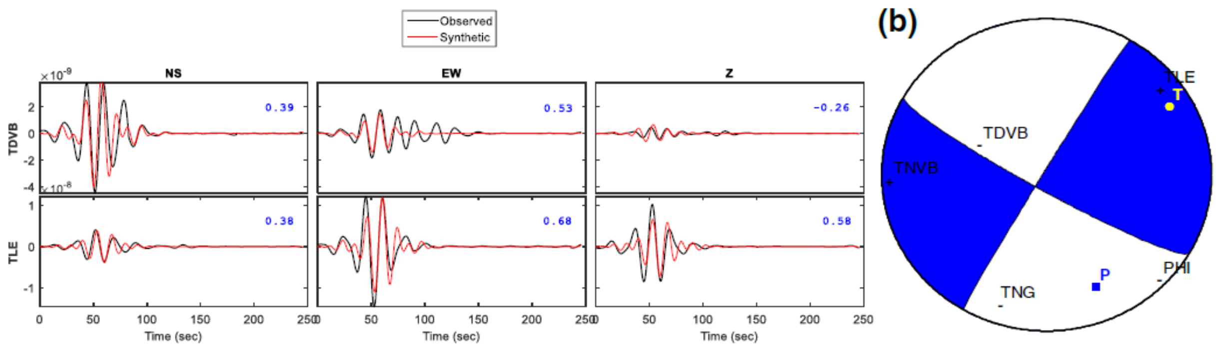

Figure 2b. Same as Figure 2a but for April 26, 2015, in the ST2 region [7].

3.1.2. Seismically active faults

The activity of the capable fault zones in Central and Southern Central Vietnam has been studied [6, 9–12]. Within a radius of 150 km around Da Nang city, 9 fault zones capable of generating earthquakes have been identified, of which 3 are of the 1st rank and 6 of the 2nd rank (Figure 1, Table 1). Below is a detailed description of each such active fault zone to decrease the impact on Da Nang city. It should be noted that the fault classification in this study is based on the seismic activity criterion, so it is different from the fault classification according to geological criterion.

Table 1. The seismically active faults in the study area.

No	Fault name	Rank	Direction	Dip	Mechanism in Pliocene–Quaternary
1	Tam Ky–Phuoc Son	1	Sub–parallel	NNW	Thrust/Right lateral Strikeslip/Normal
2	Red River (extended)	1	NW–SE	NE	Right lateral Strikeslip
3	109^o Meridian (segment 1)	1	NW–SE	E	Normal
4	Da Nang–Nam Dong	2	Sub–parallel	Vertical	Thrust/Right lateral Strikeslip /Normal
5	Dakrong–Hue	2	NNW–SSE	Vertical	Thrust/Right lateral Strike-slip
6	Truong Son	2	NW–SE	SW	Right lateral Strikeslip
7	Tra Bong River	2	NNW–SSE	SSW	Right lateral Strikeslip –Thrust
8	Hung Nhuong–Ta Vi	2	Sub–parallel	Vertical	Thrust/Right lateral Strikeslip
9	Poko river	2	Sub–meridian	W	Normal

3.1.2.1. The 1st rank Tam Ky–Phuoc Son fault

The Tam Ky–Phuoc Son fault was originally a shear zone separating Vietnam–Laos and Kontum's two terrains during the Paleozoic period [13]. The main fault is about 82.9 km long, consisting of three segments with different directions (Figure 1). The results of research on fracture deformation and slip surface by different tectonophysical methods have shown that the fault has a steep slope of 70–75^o to the northeast on the Northwest–southeast segment; the dip angle of 70–80^o to the north on the sub–parallel segment and the dip angle of 80–85^o to the Northwest on the northeast–southwest segment. In the sub–meridian compressive horizontal stress field, the fault displacement in the present time is a right–lateral strike–slip on the Northwest–southeast segment and a left–lateral on the northeast–southwest segment, thrust–left–lateral strike–slip on the northeast–southwest segment and thrust on the sub–parallel segment. The results of measuring radon gas content on 03 survey profiles crossing the northeast–southwest segment of the Tam Ky–Phuoc Son fault show 23 anomalies among 123 survey points. Notably, the anomalies on this fault are mainly concentrated at its intersections with higher–order faults. In addition, some other signs indicate the activity of the Tam Ky–Phuoc Son fault; for example, along the fault, there is a source of hot mineral water appearing in Que Tan and many landslide spots.

In general, the combination of the facts and evidence such as remote sensing, geology, geomorphology, anomalies of radon content in soil gases, hot water, and mineral water exposure, landslide, and seismic hazard allows concluding that the Tam Ky–Phuoc Son fault zone is an active one. Still, the segments' activity level varies from moderate to relatively strong.

3.1.2.2. The 1st rank Extended Red river fault

The extended Red River fault is located on the sea within the study area, with a Northwest–southeast direction. The fault is determined mainly by satellite gravity and magnetic data [9]. The fault geometry reflects the horizontal gravity gradient anomaly zone with average intensity from 0 to 1.5 mGal/km. On the Bouguer gravity anomaly map, the northeast side of the fault is characterized by a relatively positive structure with values ranging from –14 to –22 mGal. In comparison, the southwest side is a relatively negative structure with the values of isolines from –25 to –30 mGal.

The fault is also clearly shown on the aerial magnetic map, with the northeast wing being a positive structure with values from –20 to –40 nT and the southwest side being a negative structure with values from –30 to –50 nT. The fault geometry coincides with the horizontal gradient anomaly zone on the magnetic satellite map with an average intensity of about 0 to 3 nT/km. Also, according to satellite gravity and magnetic data, the fault is inclined to the northeast with an angle of 60–80^o.

Although located in the sea, the 1st rank Extended Red River fault zone is considered capable of shakings affecting Da Nang city from the northeast.

3.1.2.3. The 1st rank 109^o Meridian fault

This fault is detected using various data, including earthquakes, seismic exploration, satellite gravity, volcanic geology, and remote sensing [10, 14]. In the study area, the fault continues the Extended Red River fault on the continental shelf of Central Vietnam in the Northwest–southeast direction.

The fault has a depth of up to 60 km, cutting through the Earth's crust and reaching the lithosphere. This fault zone consists of 3 main and many minor faults running roughly parallel to and close to the 109^{o}E and 110^{o}E meridians. Based on the research results on sedimentation – geodynamics in sedimentary basins along the 109^o Meridian fault zone, it can be confirmed that this fault was strongly active at the beginning of the Cenozoic but weakened until the end of the Late Miocene.

During the Pliocene–Quaternary period, the 109^o Meridian fault has the right–lateral strike–slip mechanism, coupled with subsidence in steps to the east, creating a sedimentary layer of this age to 4000m thick. Then follows a weakened period of this fault. During the Holocene–Present, much evidence shows that it was reactivated again with the bloom of volcanic eruptions in Phu Quy and Hon Tro islands and seismic activity in the Phan Thiet–Vung Tau Sea area.

Up to now, not so many earthquakes have been recorded along the 109^o Meridian fault. However, two earthquake sequences were instrumentally observed along the fault at two different times. The first sequence consists of medium–magnitude earthquakes between August 1963 and January 1965 and clustered along the fault segment bounded by latitudes 10–120. This earthquake series was recorded at the Nha Trang seismic station, but the magnitude is mostly unknown. The second series of earthquakes occurred off the coast of Ba Ria–Vung Tau and Binh Thuan provinces starting in 2005 and lasting until 2017. In this second series of earthquakes, the most notable are two events with Moment magnitudes of 5.2 and 5.3 that occurred on November 8, 2005 [15].

On the continental shelf of Vietnam, N2–Q1 age volcanic eruptions and modern volcanic eruptions are observed along the 109^o and 109^{o}30' meridian. These activities extend from Quang Binh, and Vinh Linh provinces down to Da Nang, Quang Ngai, Ninh Thuan, and Binh Thuan provinces, especially in the Phu Quy, Hon Tro, and the southeastern part of these islands [16]. Even though only a part of the northern segment of the 109^o Meridian fault appears in the study area, the impact of this 1st rank fault needs to be considered in assessing seismic hazards for Da Nang city.

3.1.2.4. The 2nd rank Da Nang–Nam Dong fault

The 2nd rank Danang–Nam Dong fault, also known as Nam Dong–Nam O fault, is the boundary dividing the North Truong Son block into the Nam Dong block in the north and the P'Rao–Thanh My block in the south. The analysis of the fault relationship with the geological formations and its fracture deformation shows that the main fault plane dips almost vertically with a slight inclination to the Northwest and north [5]. The evidence of satellite images, geology–geomorphology, landslides, riverbank erosion along the fault, and earthquake activity has shown that the modern activity of sections of the Nam Dong–Nam O fault zone is mostly moderate, except for the western segment, which shows relatively strong activity. However, this is the most dangerous seismic source affecting Da Nang city, as this fault segment runs through the city.

3.1.2.5. The 2nd rank Dakrong–Hue fault

On the Bouguer gravity anomaly map, the Dakrong–Hue fault is shown as the boundary dividing structural blocks with different anomalies, according to which the gravity field value varies in the range –12 ÷ –24 mGal in the south and –30 ÷ –40 mGal in the north. The gravity anomaly horizontal gradient coincides with the fault with an average value of about 1.0 ÷ 2.0 mGal/km. On the aeromagnetic anomaly map showing the ΔTa component, the Dakrong–Hue fault is clearly the boundary of the blocks with different structures. The northern part is a relatively positive structure, with field values in the range –20 ÷ –30 nT, while this value at the south wing is –30 ÷ –40 nT. The fault zone coincides with the anomalous aeromagnetic horizontal gradient with an average intensity of about 2÷3 nT/km [9].

The Dakrong–Hue fault has a depth of about 15÷20 km, with the mechanism changing from right–lateral strike–slip in the northwest segment, reverse in the middle segment and left–lateral strike–slip in the eastern segment. The analysis of geological maps, geomorphological characteristics, and fracture deformation documents related to the fault shows that the main fault plane is vertically dipped in the segments with the west–Northwest–southeast and inclined to the north at parallel and sub–parallel segments with a plug angle of 70–80^o. The analysis of geological data also shows that during the Pliocene–Quaternary period, the fault had the right–lateral strike–slip mechanism, impacted by the shear stress field with the near–horizontal compression axis in the equatorial direction. The modern activity of the Dakrong–Hue fault is demonstrated by instrumentally–recorded medium–magnitude earthquakes along the fault, hot mineral water sources at Thanh Tan and My An, and soil cracks occurring in Huong Ho, Thien Mu areas, and the inner citadel of Hue.

3.1.2.6. The 2nd rank Truong Son fault

The Truong Son fault acts as the north-eastern boundary of the Indosini block. The fault has the main direction of the Northwest–southeast, starting from Vientiane, where it meets the Dien Bien–Lai Chau fault, to the area of Kham Duc town in Phuoc Son district, then ends when it encounters the Po Co River and the Tam Ky–Phuoc Son faults. The fault is clearly shown on topographic maps, satellite images and aero–photos. The study of geomorphologic data has shown that the Truong Son fault has a steep slope of 70–80^o to the northeast. In the modern tectonic stress field, the kinematic mechanism of the Truong Son fault zone is the right–lateral strike–slip for the Northwest–southeast segment and the normal–right–lateral strike–slip for the sub–a meridian segment in the sub–meridian compression stress field.

The modern activity of the fault is shown through the phenomenon of cracking – landslide, which is quite common and often occurs in the weathered crust, on steep slopes, in the territory of Huong Phong, Hong Thuong and Hong Van communes (A Luoi district, Thua Thien–Hue province) and Huc Nghi and Ta Long communes along Ho Chi Minh Road in Dak Rong district, Quang Tri province. In addition, the modern activity of the fault zone might cause the cracks in basaltic eruption rocks of the Late Miocene – Pleistocene age, and the emergence of hot mineral water in Lang Eo and Lang Ruo areas (Dak Rong commune, Dak Rong district, Quang Tri province) as well as earthquakes in A Luoi, Thua Thien Hue province.

3.1.2.7. The 2nd rank Tra Bong River fault

The Tra Bong River fault appears at the northern edge of the Kon Tum block, with a convex arc to the south, and the dominant direction is sub–latitude. The fault is clearly shown in satellite images. The results of the analysis of fracture data show that the fault has a slope of about 70–90^o to the south on the sub–latitude segment, 80–90^o to the south–southwest on the Northwest–southeast segment, inclined 85–90^o to the southeast on the northeast–southwest segment and has a vertical dip angle on the northeast–southwest segment. The results of the telluric magnetic survey on the Nam Tra My–Bac Tra My profile show that the Tra Bong River fault has a depth of more than 30 km in an almost vertical direction. On the Tra Bong–Nui Thanh profile, the Tra Bong River fault also has an almost vertical dip angle to a depth of more than 30 km. In the tectonic stress field from the Pliocene up to now, the Tra Bong River fault has the following mechanism: right–lateral strike–slip in the Northwest–southeast segment, reverse and strike–slip in the sub–parallel and Northwest–southeast segments, left–lateral and reverse in the northeast–southwest and northeast–southwest segments. The modern activity of the fault is best shown through the series of medium and small–magnitude earthquakes recorded along the fault (Figure 1). This also promotes the Tra Bong River fault up to the 2nd rank in terms of seismic activity.

3.1.2.8. The 2nd rank Hung Nhuong–Ta Vi fault

The Hung Nhuong–Ta Vi fault has a total length of 131.3 km, playing the role of the boundary between the Tra My–Tra Bong block (the northern edge of the Kontum block) in the north and the Ngoc Linh block (the center of the Kontum outcrop) in the south. This fault is very clearly shown on the Landsat 5–TM satellite image as a line that coincides with the boundary between regions with different structures, or as a zone with a relatively high density of linear textures, especially in the Northwest–southeast segment. In the field, the fault is clearly shown by the valleys stretching along the Northwest–southeast and sub–parallel segments, separating the mountain ranges that stretch in the same direction but differ in elevation and slope steepness.

The results of research on rupture characteristics along the fault through the tectonophysical method have shown that the fault is inclined 75–90^o to the northeast on the sub–parallel segment and dipping vertically on the Northwest–southeast segment. The results of magnetotelluric measurements on the Nam Tra My–Bac Tra My and Tra Bong–Nui Thanh profiles show that the Hung Nhuong–Ta Vi fault has a nearly vertical dip angle, cutting through the Earth's crust to a depth of 20 to more than 30 km. Along the Hung Nhuong–Ta Vi fault, some hot and mineral water sources are also sources (Phuoc Cong, Ban Co, Phuoc Tho, Nghia Ky). Along the fault, there are 33 earthquakes instrumentally recorded on the segment from Tra Leng to Tra Ka, of which the largest event is the M = 3.6 earthquake on March 2, 2012 in the Tra Giac commune area. The evidence and data of geology, topography, remote sensing, hot water, mineral water, earthquakes, and fractures allow assessing that the Hung Nhuong–Ta Vi is an active fault and can be classified into a group of 2nd rank faults.

3.1.2.9. The 2nd rank Po Co River fault

The Po Co River fault extends 119.7 km in the sub–meridian direction in the study area. Starting from the area of Kham Duc town, the Po Co River fault runs south along the Dak Se stream valley, through Lo So pass, then along the Po Co River valley, through Dak Glei town, Plei Can town (Ngoc Hoi district, Kon Tum province), then runs south along Sa Thay stream for about 60 km more. The Po Co River Fault has many high–rank faults in the same direction, with a length extending up to several tens of kilometres developing along the flanks. A series of parallel lineaments on the satellite images and topographic maps show the Po Co River fault.

In the neo–tectonic framework, the fault acts as the boundary between the Kon Tum block in the east and the Sekong block in the west. The fault zone appeared in the early Paleozoic, closely related to the pre–Cambrian crust–breaking process in the west of the Kon Tum outcrop, creating a large spreading zone to reveal the oceanic crust. Therefore, along the fault zone, many formations belong to the early Paleozoic phyolite complex. Magmatic activity along the fault zone developed through many stages until Quaternary, leaving intrusive bodies of different compositions, ages, and sizes.

The results of analysis by the tectonophysical method along the Po Co River fault show that the main fault plane dips to the west with an angle of 60–70^o, and the displacement mechanism is dominantly normal in the Pliocene–Quaternary period, causing a drop of steps from the wings to the centre with a vertical amplitude of about 800–1300 m, and the estimated speed of 0.16–0.26 mm/year [6].

3.2. Seismic source model

One of the important inputs for earthquake hazard calculations is the seismic source model of the study area. In this study, an aerial source model is used, assuming 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 [17].

The seismic sources of Da Nang city and its vicinity were determined based on known seismicity and seismotectonic characteristics. 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 epicentre distribution, a set of faults in cases

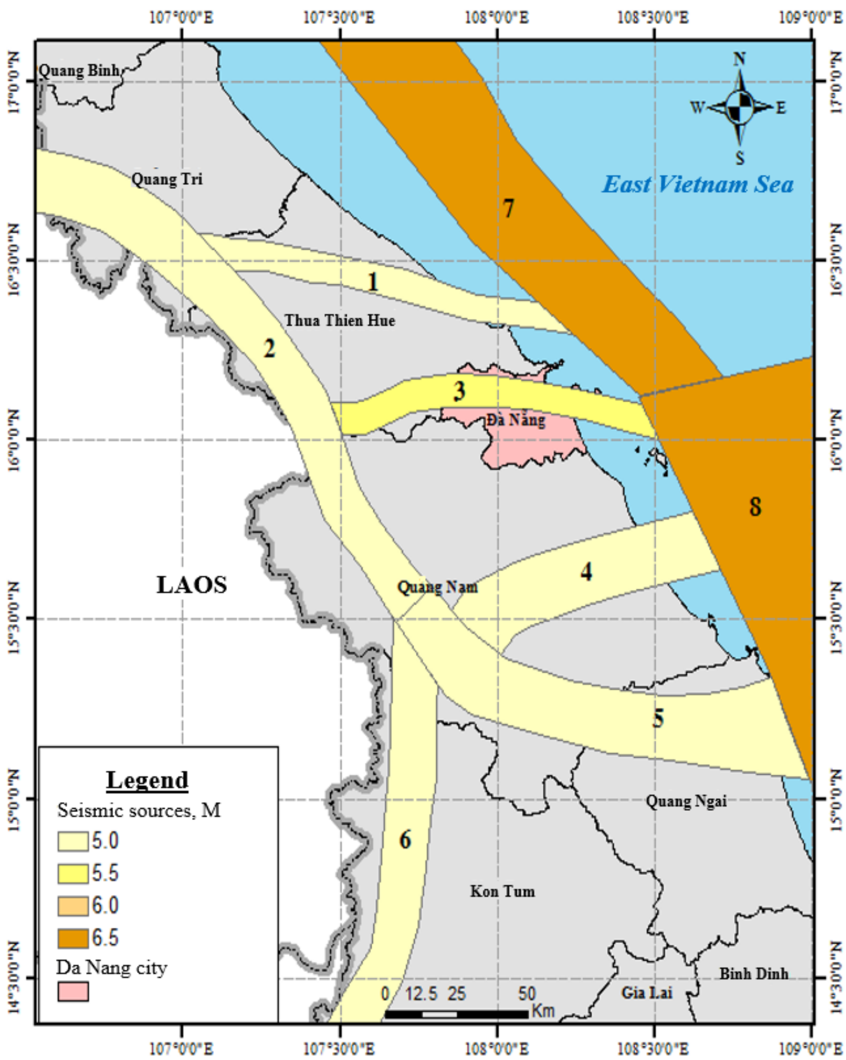

Figure 3. Map of the earthquake source zones in Da Nang city and its vicinity. The numbers on the map coincide with the ordinal numbers of the source zones given in Table 2.

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 epicentres.

An important basis for reference and identification of areal sources in the study area is the seismotectonic model of the territory of Vietnam and the East Vietnam Sea region, built on the basis of inheriting the previous research results as well as updating new earthquake and tectonic data [18–21]. Earthquake data, including historical earthquakes, earthquakes collected from field investigations, and instrumentally recorded earthquakes, were collected in the study area within a radius of 150 km from the Da Nang city center and used with the active faults data to delineate seismic source zones. A total of 8 source zones considered to have seismic impacts on Da Nang city are identified using this approach, including (Figure 3): 1) Dakrong–Hue; 2) Truong Son; 3) Danang; 4) Tam Ky–Phuoc Son; 5) Hung Nhuong–Ta Vi; 6) Po Co River; 7) Red River–Chay River; 8) The 109^o Meridian (Segment 1).

3.3. Earthquake catalog

The earthquake catalog of the study area was established, covering the observation period from 1903 to 2021, based on the earthquake database of archived at the Earthquake Information and Tsunami Warning Center, Institute of Geophysics, Vietnam Academy of Science and Technology. The catalog contains 136 earthquakes of magnitude 2.5 or greater, including historical, field investigation and instrumental earthquakes, collected from the National seismic network of Vietnam and international seismic centers such as ISC, USGS, NEIS, and BEJ. All earthquakes recorded in the area within φ = 17.5–23.5^o N; λ = 102.0–108.5^o E.

Data treatment plays an important role in a seismic hazard assessment procedure, particularly in the case of probabilistic application. One of the basic requirements of the earthquake data to be used is that they have to be statistically independent. For this reason, statistical procedures were applied to remove all foreshocks and aftershocks from the catalog. Then, the catalog was grouped by the seismic source zones into sub–catalogs prior to the hazard computation.

The principle of aftershocks removal is well–known and can be expressed simply as follows. Let t be the origin time of earthquake occurrence, h is a focal depth, M is the magnitude, i and j be the order numbers of these earthquakes in a catalog, and j > i. The second event can be considered as the aftershock of the first one if the following conditions are satisfied: the epicentral distance between the two events is less than a given value $R(M_i)$, $h_j - h_i \leq H(M)$; and $M_j \leq M_i$, where T(M), R(M) and H(M) are empirical functions [7, 22]. The algorithm of foreshock removal is similar.

Foreshocks and aftershocks were removed from each source zone's earthquake sub–catalog. The earthquake sub–catalogs used for the calculation contain main shocks only to ensure the reliability of the calculation results. In addition, only earthquakes of magnitude 4.0 and above are used for the calculations to ensure the completeness of the earthquake catalog.

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

To calculate and map the seismic hazard of the study region, the following seismic hazard parameters, characterizing the level of seismicity, were estimated for each seismic source zone:

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

Detail description of the seismicity parameters estimation methods for a seismic source can be found in previously published documents [7, 10, 19–21, 23]. In this study, the Maximum likelihood method proposed by Aki and Utsu is applied to estimate the parameters a and b for each seismic source zone [24–25]. The parameter estimation algorithms always consider the error of determining the earthquake magnitude M [26–27]. The lower bound of the magnitude value M_0 = 4.0 is selected for all source zones to conform to the unified scaling law of earthquakes throughout the territory of Vietnam [7].

In practice, applying statistical methods to estimate the seismicity parameters for a seismic source zone is often difficult in case the zone contains too few earthquakes. In many cases, the only solution suggested by seismologists is to apply the rule of "seismotectonic similarity" [28]. In this study, the Poko River fault is similar to the Truong Son fault since it was previously named Poko–Kham Duc and is connected to the Truong Son fault from the Laos territory [28]. Since 2015, within the framework of a national research project, Vu Van Chinh has renamed this fault the Poko River [6]. The results of the estimation of earthquake parameters for source zones in Da Nang city and surrounding areas are listed in Table 2.

Table 2. Seismic hazard parameters were estimated for the seismic source zones of Da Nang city and the surrounding area.

N_0	Seismic source zone	λ_0	M_0	M_{maxML}	$M_{max.obs}$	B_{ML}	H (km)
1	Dakrong–Hue	0.02	4.0	5.3	4.8	1.0	10
2	Truong Son	0.02	4.0	5.0	4.0	0.84	12
3	Danang	0.02	4.0	5.3	4.8	1.0	12
4	Tam Ky–Phuoc Son	0.02	4.0	5.2	4.7	1.0	10
5	Hung Nhuong–Ta Vi	0.02	4.0	5.0	4.7	1.0	12
6	Po Co river	0.02	4.0	5.0	2.6	1.0	10
7	Red river–Chay river	0.36	4.0	6.3	4.9	0.89	17
8	The 109^{o} Meridian (segment 1)	0.02	4.0	6.6	4.8	0.86	12

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

3.5. Ground motion prediction models

Although more than half a century has passed since the first seismic hazard map of Vietnam was published, until now, no ground motion prediction equation (GMPE) has been developed for the territory of Vietnam. It is simply because of the lack of strong ground motion data recorded strong earthquakes in Vietnam's territory. Although the seismic hazard map of Vietnam has been updated to the 5th generation, with different GMPEs have been applied to the Vietnamese territory so far, the choice of the most suitable GMPE out of hundreds of the published ones, built for different regions around the world, could not avoid the uncertainty.

Since 2019, a new approach to selecting GMPE for Vietnam has been used based on the results of testing the theoretical GMPEs worldwide with earthquake data recorded throughout the territory of Vietnam. In the testing process, the broadband seismic data of 39 earthquakes with magnitudes in the range of 3.5 M 4.5 observed at 55 seismic stations throughout Vietnam in the period 2010–2017 are used to test the suitability with 28 published GMPEs of the world. Note that 39 selected earthquakes are distributed in all 4 seismic tectonic zones in the territory of Vietnam [6]. The testing process includes the following steps [29]:

(1) Processing of earthquake data: observational data, including 665 seismograms of 39 earthquakes, were converted into accelerograms;

(2) Calculation of acceleration values for each GMPE: using the parameters such as earthquake magnitude, hypocentral distance, coordinates of the epicenter, V_{S30} value at stations, the values of peak ground acceleration (PGA) at stations corresponding to each earthquake were calculated corresponding to the 28 selected theoretical GMPEs;

(3) Comparison of the calculated and the observed PGA values at the stations: To evaluate the fit for each GMPE, the mean deviation value X_k^j for each GMPE was calculated (j = 1÷4 is the seismotectonic province index; k = 1÷28 is the index corresponding to the ordinal number of the GMPE to be evaluated).

(4) Selection of the GMPE that is most suitable for the study area: The selected GMPEs are those with the lowest deviation value.

It should be noted that the approach as mentioned above is also applied in building the sixth-generation probabilistic seismic hazard maps for the territory of Vietnam, which have been put into application in the new "National Regulation on data of natural conditions for use in construction" QCVN 02:2020/BXD issued by the Ministry of Construction of Vietnam [23, 30].

According to the test result, the model of [31] proved to be the most suitable for the tectonic seismic zone 3 – Central Vietnam [23]. This is the basis for applying the model of [31] in calculating earthquake hazards for Da Nang city [31]. The ground motion attenuation model of [31] can be written as:

$$\ln(Y) = \ln[Y_{REF}(M_w, R, SoF)] + \ln[S(V_{s30}, PGA_{REF})] + \varepsilon\sigma \quad (5)$$

where

$$\ln(Y_{REF}) = \begin{cases} a_1 + a_2(M_w - c_1) + a_3(8.5 - M_w)^2 + [a_4 + a_5(M_w - c_1)]\ln(\sqrt{R^2 + a_6^2}) + a_8F_N + a_9F_R + S \\ \quad for\ M_w \le c_1 \\ a_1 + a_7(M_w - c_1) + a_3(8.5 - M_w)^2 + [a_4 + a_5(M_w - c_1)]\ln(\sqrt{R^2 + a_6^2}) + a_8F_R + a_9F_R + S \\ \quad for\ M_w > c_1 \end{cases} \quad (6)$$

and

$$\ln(S) = \begin{cases} b_1 \ln\left(\frac{V_{S30}}{V_{REF}}\right) + b_2 ln\left[\frac{PGA_{REF}+c(\frac{V_{S30}}{V_{REF}})^n}{(PGA_{REF}+c)(\frac{V_{S30}}{V_{REF}})^n}\right] & for\ V_{S30} \le V_{REF} \\ b_1 ln\left[\frac{\min(V_{S30}, V_{CON})}{V_{REF}}\right] & for\ V_{S30} > V_{REF} \end{cases} \quad (7)$$

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); Mw 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 c1 in the reference ground–motion model is the hinging magnitude and it is taken as Mw 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 estimator's parameters of the nonlinear site function; c and n are the period–independent coefficients of the reference ground–motion model. The reference V_{S30} (V_{REF}) 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. The R_{jb} model calculates the distance from the source to a location in this study. The values of parameters a_1, a_2, a_3, a_4, a_6, a_9, b_1, b_2, ϕ, σ, τ are given in the paper [31].

3.6. Probabilistic seismic hazard maps of Da Nang city

The seismic hazard assessment results for Da Nang city are presented in terms of probabilistic seismic hazard maps. CRISIS2015 program was used to compute hazards [32]. The seismic source model used for computation is shown in Table 1. The lower magnitude threshold for all seismic source zones was chosen to be $M_0 = 4.0$. The Median values of peak ground acceleration (PGA) and spectral acceleration (SA) computed at each point of a 0.01° × 0.01° grid covering the study area were used to compile seismic hazard maps.

Figures 4a–4d illustrate the probabilistic seismic hazard maps of Da Nang city, representing the spatial distribution of the median values of horizontal PGA (in the unit of % g) with 10%, 5%, 2% and 0,5% probabilities of exceedance in 50 years and V_{S30} site condition of 750 meters per second, corresponding to return times of 475, 975, 2,475 and 9,975 years, respectively. Figures 5a–5b illustrate SA maps of Da Nang city at 0.2 s and 1.0 s periods; both correspond to the return period of 2,475 years.

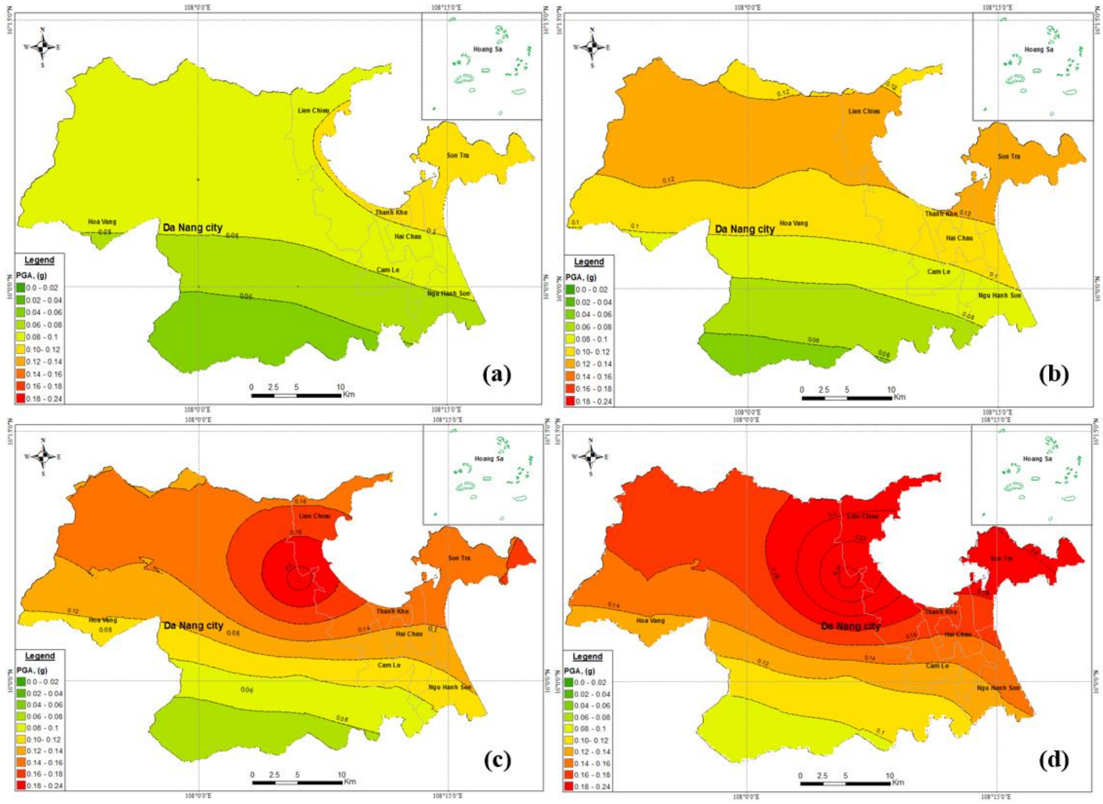

Figure 4. Maps showing peak ground acceleration (PGA) in Da Nang city: (a-d) 10%, 5%, 2%, 0.5%, respectively probability of exceedance in 50 years and V_{S30} site condition of 750 meters per second.

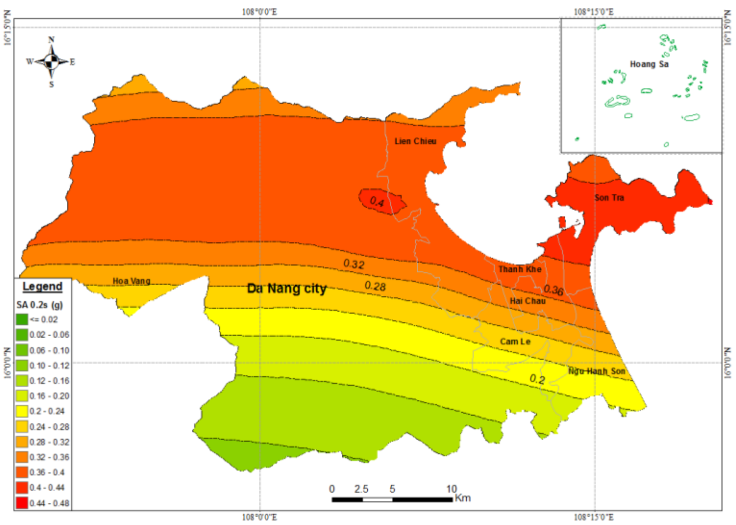

Figure 5a. Map showing 5–hertz (0.2 s period) spectral acceleration in Da Nang city for 2% probability of exceedance in 50 years (2,475–year return period) and V_{S30} site condition of 750 meters per second.

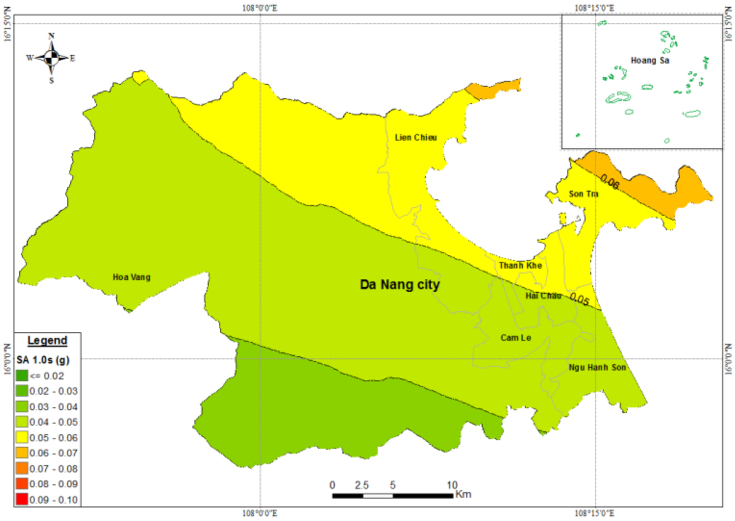

Figure 5b. Map showing 1–hertz (1.0 s period) spectral acceleration in Da Nang city for 2% probability of exceedance in 50 years (2,475–year return period) and V_{S30} site condition of 750 meters per second.

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

(1) The spatial distribution of PGA values reflects the resonance of seismic shakings from two 1st rank seismic sources in the sea area and the Da Nang source zone running through the city.

(2) The highest ground motion values are observed in the north and northeast of Da Nang city, in the Son Tra and Lien Chieu districts, and the Thanh Khe district. This is the urban area of Da Nang city, where many residential neighborhoods and socio–economic activities are concentrated. The intensity of shakings gradually decreases towards the south of the city.

(3) For the entire Da Nang city, PGA values are in the range of 0.04–0.1 g, 0.05–0.12 g, 0.06–0.2 g, and 0.08–0.24g corresponding to a return period of 475, 975, 2.475, 2,475 and 9,975 years, respectively. Thus, the maximum ground motion in Da Nang city for all four return periods does not exceed the VIII intensity level according to the MSK–64 scales.

(4) For the entire Da Nang city, the 0.2 s SA values for the 2.475–year return period are in the range of 0.1–0.4 g, equivalent to the intensity from VIII to IX, according to the MSK–64 scale. Meanwhile, the 1.0 s SA values for the same 2.475–year return period are in the range of 0.03–0.06 g, which are equivalent to an intensity VI according to the MSK–64 scales.

4. Discussion

During the last decade, coupled with updating input data, Vietnam's earthquake hazard assessment techniques have continuously upgraded. Previously, several studies related to the seismic assessment of the Da Nang area [19–21]. Although aiming at different goals, these works use the same methodology that is widely applied today [3–4]. In addition, using the same seismotectonic model for the territory of Vietnam and the East Vietnam Sea region provided consistency in the seismic source zones used [18].

On the other hand, updating input data and improving computational techniques also lead to differences in the input data used in the above works. The main differences are discussed below.

1) Different attenuation equations reflect advanced techniques for calculating seismic hazards over time. In the works published before 2016, the GMPEs were selected based on the assumption that the study area has a stable tectonic regime. Since 2016, the logic tree technique has been applied in hazard calculation, allowing us to consider both the

assumptions about the study area's stable and active tectonic regime. Therefore, the selected GMPEs represent both regimes of tectonic activity.

2) The use of different M_{max} values for the 109° Meridian source zone. According to seismic data, the 109° Meridian source zone consists of two segments with different seismic activity. Usually, the value $M_{max} = 6.1$ is assigned to the segment north of the Tuy Hoa shear (segment 1), while the value $M_{max} = 6.6$ is assigned to the southern one (segment 2). Depending on which part of the fault is nearest to the site to be assessed, the M_{max} values will be assigned accordingly. In case the study area covers the entire fault, the source region is assigned the maximum value of $M_{max} = 6.6$. In this work, seismic effects on Da Nang city are assumed to be caused by the entire 109° Meridian source zone.

To investigate the variation of ground shaking values obtained from different studies, the spatial query was carried out at the same place, namely the People's Committee of An Hai Tay Ward, Son Tra District, Da Nang city on the maps published in the studies mentioned above. Except for the maps published in 2013 and 2014 in which Da Nang city is out of the mapping scope, couples of the PGA and I (MSK–64) values with the same return period calculated from the works published in 2015, 2016 and this study are compared in Table 3.

The difference between the corresponding peak ground acceleration (PGA) values is not significant, while there is a consistency between the seismic intensity values I (MSK64 scale) (Table 3). The 2016 map shows higher intensity values than the two other maps due to the favor of the GMPE representing a seismically stable region to those representing a seismically active region. Overall, the variation of ground motion parameters does not change the general picture of the seismic hazard in the Da Nang area.

Table 3. Results of the spatial query at the People's Committee of An Hai Tay Ward, Son Tra District, Da Nang city, from different studies.

Long	Lat	The PGA/I–MSK64 values										Version
		475 years		975 years		2475 years		4975 years		9975 years		
108,232	16,064	0.08	VII	0.10	VII	0.12	VIII	–	–	0.13	VIII	2015
		0.11	VII	0.16	VIII	–	–	0.28	IX	0.33	IX	2016
		0.10	VII	0.12	VIII	0.14	VIII	0.16	VIII	0.17	VIII	2022

5. Conclusion

In this study, the probabilistic approach is applied to assess the earthquake hazard for Da Nang city, using an updated earthquake catalog up to 2021 and a model of seismic source zones in Central Vietnam and adjacent sea areas. The earthquake catalog is processed to ensure completeness and statistical independence of the events. The maximum likelihood method is applied to estimate the Gutenberg–Richter earthquake recurrence law parameters for each seismic source zone. The ground motion prediction model of [31] was selected for the seismic hazard calculation.

The results are presented in the form of probabilistic seismic hazard maps, depicting peak horizontal ground acceleration (PGA) 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, as well as the 5–hertz (0.2 s period) and 1–hertz (1.0 s period) spectral accelerations (SA), maps with 5–percent damping on a uniform firm rock site condition, with 2% probability of exceedance in 50 years, corresponding to a 2,475 year return period. The results show that, for the whole territory of Da Nang city, for all four return periods, the maximum predicted PGA values are not exceeding the intensity of VIII according to the MSK–64 scales. As for the SA maps, for the 2,475–year return period, the predicted SA values at 1.0 s period correspond to the intensity of VI, while the predicted SA values at 0.2 s period are not exceeding the intensity of IX according to the MSK–64 scales.

These are the first detailed probabilistic seismic hazard maps established for Da Nang city, which have many advantages. In addition to using the last–update input data, the advantages in methodology and technique are also applied in the analysis process. The first novelty to be mentioned in this study is the application of a new ground motion prediction model, which has proven to be the most suitable for Vietnamese conditions. It is worth mentioning that this is the first-time spectral acceleration (SA) maps have been compiled for Da Nang city. The probabilistic seismic hazard maps provide short–, medium– and long–term quantitative forecasting information on earthquake hazards. They can be used as a reference in antiseismic design and many earthquake engineering applications for Da Nang city.

Author contribution statement: Conceived and designed the study; Selection of research methods: N.H.P., V.T.H.Q., P.T.T.; Analyzed and interpreted the data; analysis tools and mapping: N.H.P., V.T.H.Q., P.T.T., D.V.L., V.T.T., N.T.H. wrote the manuscript: N.H.P., V.T.H.Q., P.T.T.

Acknowledgment: This research is funded by the People's Committee of Da Nang city.

Competing interest statement: The authors declare no conflict of interest.

References

1. Completed results of the 2019 Vietnam population and housing census. Statistical publishing house, 2020.
2. Prime Minister of Vietnam. The Decision No. 18/2021/QD–TTg Regulation on forecasting, warning, communication of natural disasters and disaster risk levels, April 22, 2021.
3. Cornell, C.A. Engineering seismic risk analysis. *Bull. Seismol. Soc. Am.* **1968**, *58(5),* 1583–1606.
4. Esteva, L. Bases para la formulación de decisiones de diseño sísmico. Instituto de Ingeniería, Universidad Nacional Autónoma de México, 1968.
5. Cornell, C.A.; Vanmarcke, E.H. The Major Influences on Seismic Risk. Proceeding of the 4th World Conference on Earthquake Engineering, Santiago, Chile, 1969.
6. Minh, L.H. Study of the seismotectonic impact to the stability of the Tranh River hydropower plant No. 2, Bac Tra My region, Quang Nam province. Final report of the National scientific research project, Institute of Geophysics, Hanoi, 2016. (in Vietnamese)
7. Nguyen, H.P.; Pham, T.T.; Nguyen, T.N. Investigation of long–term and short–term seismicity in Vietnam. *J. Seismol.* **2019**, *23*, 951–966.
8. Tuan, T.A.; Purnachandra Rao, N.; Gahalaut, K.; Trong, C.D.; Dung, L.V.; Chien, C.; Mallika, K. Evidence that earthquakes have been triggered by reservoir in the Song Tranh 2 region, Vietnam. *J. Seismol*. **2017**, *21*, 1131–1143.
9. Duong, N.A. Assessment of seismic hazard for development planning, ensuring the safety of hydropower and irrigation works and cultural relics of Thua Thien–Hue province. Final report of the ĐTL.CN.51/16 independent project, 2020. (in Vietnamese)
10. Phuong, N.H. Assessment of earthquake and tsunami hazards in the Ninh Thuan province for site approval of the NPPs. Final report of the National level project, Institute of Geophysics, Institute of Science and Technology (in Vietnamese), 2013.
11. Phuong, N.H.; Truyen, P.T. Analysis of earthquake data to assess the stability of the present tectonic regime", thematic report within the KC09.38/16–20 project "Study of the tectonic characteristics and the impact of the human activities capable of changing the tectonic stress field related to the seismic hazard in the sea area from Tuy Hoa to Vung Tau", 2020. (in Vietnamese)

12. Linh, D.V. Study of the tectonic characteristics and the impact of the human activities capable of changing the tectonic stress field related to the seismic hazard in the sea area from Tuy Hoa to Vung Tau, Final report of the KC.09.38/16–20 National level project, 2020. (in Vietnamese)
13. Tri, V.T.; Michel, F.; Vuong, V.N.; Hoang, H.B.; Michael, B.W.F.; Tuan, Q.N.; Claude, L.; Tonny, B.; Thomsen, K.T.; Punya, C. Neoproterozoic to Early Triassic tectono–stratigraphic evolution of Indochina and adjacent areas: A review with new data. *J. Asian. Earth. Sci.* **2020**, *191*, 104231.
14. Linh, D.V. History of the Cenozoic tectonic evolution of the Southern Central Vietnam and relationship with earthquakes. Ph.D. thesis in Geology, the Ho Chi Minh city Institute of Technology, 2009. (in Vietnamese)
15. Phuong, N.H.; Truyen, P.T. Analysis of earthquake data to assess the stability of the present tectonic regime", thematic report within the KC09.38/16–20 project "Study of the tectonic characteristics and the impact of the human activities capable of changing the tectonic stress field related to the seismic hazard in the sea area from Tuy Hoa to Vung Tau" (in Vietnamese), 2020.
16. Vu, P.N.; Vu, P.N.H.; Binh, N.X. Young Volcanic Eruption (Pliocene-Quaternary) Activities on the Southern continental Shelf of Vietnam (According to Geophysical Data). *VN J. Earth Sci*. **2008**, *30*, 289–301.
17. Budnitz, R.J.; Apostolakis, G.; Boore, D.M.; Cluff, L.S.; Coppersmith, K.J.; Cornell, C.A.; Morris, P.A. Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on uncertainty and use of experts. NUREG/CR-6372 UCRL-ID-122160, 1997, 1, pp. 280.
18. Nguyen, H.P.; Pham, T.T. Development of a fault–source model for earthquake hazard assessment in Vietnam. *VN J. Earth Sci*. **2007**, *29*, 228–238.
19. Probabilistic seismic hazard assessment for the South Central Vietnam Central Vietnam. *VN J. Earth Sci*. **2014**, *36*, 451–461.
20. Phuong, N.H.; Truyen, P.T. Probabilistic seismic hazard maps of Vietnam and the East Vietnam Sea. *VN J. Mar. Sci. Technol.* **2015**, *15(1)*, 77–90. Doi:10.15625/1859-097/15/1/6083.
21. Phuong, N.H.; Truyen, P.T.; Nam, N.T. Probabilistic seismic hazard assessment for the Tranh river hydropower plant No2 site, Quang Nam province. *VN J. Earth Sci*. **2016**, *38(2)*, 188–201.
22. Keilis–Borok, V.I.; Knopoff, L.; Rotwain, I.M. Burst of aftershocks, long–term precursors of strong earthquakes. *Nature* **1980**, *283*, 259–263.
23. Phuong, N.H. Earthquake Hazards in the territory of Vietnam and adjacent seas. Natural science and technology Publishing house, **2021**, pp. 314. (in Vietnamese)
24. Aki, K. Maximum likelihood estimate of b in the formula log N = a–bM and its confidence limits. *Bull. Earthq. Res. Inst*. **1965**, *43*, 237–239.
25. Utsu, T. A Method for Determining the Value of b in a Formula log n = a – bM showing the Magnitude–Frequency Relation for Earthquakes. *Geophys. Bull. Hokkaido Univ*. **1965**, *13*, 99–103.
26. Amorese, D. Applying a Change–Point Detection Method on Frequency–Magnitude Distributions. *Bull Seismol. Soc. Am.* **2007**, *97*, 1742–1749.
27. Amorese, D.; Rydelek, P.A.; Grasso, J.R. Package "GRTo" – Tools for the Analysis of Gutenberg–Richter Distributions of Earthquake Magnitudes. **2015**. https://cran.r–project.org/package=GRTo.
28. Xuyen, N.D. Study on earthquake prediction and ground motion in Vietnam. Final report of the National level project, Institute of Geophysics, Institute of Science and Technology (in Vietnamese), 2004.

29. Khoi, L.Q. Verification of the Ground Motion Prediction Models using broadband seismic data collected in Vietnam. Final report of a research project on basical level. Institute of Geophysics, 2018. (in Vietnamese)
30. Minh, N.D. National Regulation on data of natural conditions used in construction (Draft). Appendix 4 – The earthquake data for QCVN 02:2020/BXD, Institute of Construction Science and Technology, Ministry of Construction, 2020.
31. Akkar, S.; Sand, I.M.A.; Bommer, J.J. Empirical ground–motion models for point– and extended–source crustal earthquake scenarios in Europe and the Middle East. *Bull. Earthq. Eng.* **2014**, *12*, 359–387.
32. Ordaz, M.; Martinelli, F.; Aguilar, A.; Arboleda, J.; Meletti, C.; Amico, D.; Crisis, V. Program for computing seismic hazard. 2015. Online available: http://www.r-crisis.com/download/binaries/.