INDONESIAN JOURNAL ON GEOSCIENCE
Geological Agency
Ministry of Energy and Mineral Resources

Journal homepage: http://ijog.geologi.esdm.go.id
ISSN 2355-9314, e-ISSN 2355-9306

Comparative Study of Seismic Hazard Analysis Using Classical PSHA and PSHA Method in Java Island, Indonesia

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Manuscript received: January, 23, 2024; revised: June, 6, 2024;
approved: October, 26, 2024; available online: November, 5, 2024

Abstract - In general, seismic hazard analysis is conducted using a probabilistic approach (PSHA), whilst seismic risk analysis is computed using a stochastic approach. To figur out more differences between the two methods, a comparative study of those two approaches needs to be conducted. The study was conducted in Java Island which is the most populated island in Indonesia, and prone to earthquakes, particularly in the southern part due to the subduction of the Australian Plate and many active shallow faults along the island. To find out whether the hazards occurred in the risk analysis were closer to the results of Classical PSHA, it is necessary to examine the comparison of the two methods. The difference between the Event-Based and Classical methods is the use of a synthetic catalog that depends on the input value of SES (Stochastic Event Set). The research began with hazard computation with both methods, where the Event-Based PSHA method was given varying SES values. Determining the SES value in the Event-Based method is an important stage to conduct as a significant input parameter in a risk analysis, particularly the loss analysis. The comparison results conclude that the Event-Based PSHA with SES= 200,000 produced a well-confirmed hazard map compared to the Classical PSHA result with the smallest standard deviation and variation, *i.e.* 0.0172 and 0.0003 respectively.

Keywords: probabilitic approach, Stochastic Event Set, Java Island, Classical PSHA, Event-Based metod

How to cite this article:
Goro, G.L., Irsyam, M., Meilano, I, and Asrurifak, M., 2024. Comparative Study of Seismic Hazard Analysis Using Classical PSHA and PSHA Method in Java Island, Indonesia. *Indonesian Journal on Geoscience*, 11 (3), p.349-363. DOI: 10.17014/ijog.11.3.349-363

Introduction

Various country data compiled by UNDRR (United Nation Office for Disaster Reduction; 2019) states that the highest number of fatalities was the result of geophysical disasters (earthquakes, tsunamis, and volcanoes), although the frequency of the occurrence is low. Meanwhile, Indonesia was in the third highest position after Japan and The United States for the average economic loss due to the earthquake (Marfai *et al.*, 2008; UNDRR, 2019; Yuliastuti *et al.*, 2021).

Previous studies related to Indonesian seismic hazards have been carried out, including studies on the development of Indonesia earthquake hazard map for the period of 2,500 years as the revision of SNI-03-1726-2002 which uses a total probability method with three-dimensional (3D) earthquake sources (Asrurifak *et al*., 2010; Irsyam *et al*., 2013; Muksin *et al*., 2013). The latest study was an earthquake hazard analysis study with a combination of probabilistic and deterministic analysis with the latest earthquake sources and GMPE (Ground Motion Prediction Equation) data in the context of developing a 2017 Indonesia earthquake map. In this research, relevant information from active fault studies used trench excavation and carbon dating methods, earthquake centre relocation, strain analysis (GPS), and base map data including SRTM-30, IFSAR, LiDAr, and other new available data (Marliyani *et al*., 2016; Natawidjaja, 2018; Daryono *et al*., 2019; Irsyam *et al*., 2020).

Java is the 13th largest island in the world and the fifth largest in Indonesia by landmass at about 138,800 km^2 (53,600 sq. mi), and shaped mostly as the consequence of volcanic eruptions from geologic subduction between Sunda Plate and Australian Plate. Moreover, Java is an area disposed to earthquakes. Based on the earthquake catalogue of the Indonesian Agency for Meteorological, Climatological, and Geophysics (BMKG), in the past two decades there have been 316 earthquake events with the magnitudes above 5 Mw, and nineteen events with magnitudes above 6 Mw. Java has 56.7 % of the Indonesian population with the population of over 141 million (Java only) or 145 million (including the inhabitants of the surrounding islands), and is the world most populous island, accordingly Java has high risk of earthquake that needs mitigation studies.

Research related to the source of the earthquake fault in Java has widely been carried out, including the study of three active faults in the West Java region (namely the Cimandiri, Lembang, and Baribis Faults) using the GPS survey method (Abidin *et al*., 2009; Pratama *et al*., 2016; Supendi *et al*., 2018; Daryono *et al.*, 2019). Based on GPS survey results, it was found that the area around the Cimandiri, Lembang, and Baribis Fault zones has a horizontal displacement of around 1 to 2 cm/year or less. The study also studied co-seismic and post-seismic deformations related to the Yogyakarta earthquake of May 2006 and July of the 2006 South Java Earthquake. Another research has been conducted uses campaigns and continues GPS data to make a preliminary estimation of the slip rate of Lembang Fault. The measurements suggest that the Lembang Fault has a shallow creeping and a deeper locking portion. The estimated slip rate is 6 mm/year with fault locking at 3 - 15 km, and shallow creeping at the same rate (Meilano *et al*., 2012; Supendi *et al*., 2018; Nugraha *et al*., 2019).

The earthquake hazard analysis, in general, was used the PSHA (Probability Seismic Hazard Analysis), while the method was used for the risk analysis. On the other hand, for seismic risk analysis, the Event-Based risk analysis method is generally used. In principle, it is a combination of hazard analysis with the Event-Based PSHA method and the vulnerability of the assets which risk will be calculated in the exposure data that will be reviewed. The difference between the Event-Based PSHA method and Classic PSHA is that it uses a kind of synthetic catalogue compilation stage that relies on SES (Stochastic Event Set) input values.

In the OpenQuake engine, the ERF (Earthquake Rupture Forecast) was used by a stochastic event set (SES) calculator to generate n groups of ruptures. Each rupture was used to calculate the ground motion at the location of each asset. In this process, the inter-event variability from the ground motion prediction model is sampled once per rupture, while the intra-event variability is sampled for each location considering the spatial correlation in its residuals (Lazar and Dolšek, 2014). To find out the hazards that occurred in a risk analysis is close to the results of the classical PSHA calculations, it is necessary to examine the comparison of the results of Classical PSHA to Event-Based PSHA methods.

Methods and Materials

The study began by collecting data on earthquake sources which are estimated to influence the occurrence of earthquakes on the island of Java, assuming a maximum distance of 300 km from the site of interest, where the source to site distance of more than 300 km no longer has a destructive impact on building structure. Seismic sources that will be included in the calculation are subduction earthquake sources, shallow faults, and background earthquake sources. Earthquake source data was based on the earthquake catalogue in the preparation of the 2017 earthquake map by the National Earthquake Study Centre (PuSGeN). Sources of subduction earthquakes for Java Island were the Sunda Strait megathrust and the southern part of Java megathrust. While the source of shallow crustal were twenty-five active faults throughout Java (PusGen, 2017; Irsyam *et al*., 2020; Syahbana *et al*., 2020). (Figure 1)

In this study, GMPE (Ground Motion Prediction Equation) Logic Tree was used in accordance with GMPE in the 2017 Indonesian Earthquake Hazard Map computation with updates on several new GMPE following GEM GMPE Logic tree, among others: for active shallow crustal earthquake sources as the fault earthquake and shallow background modelling, used GMPE of Boore Atkinson (2007), Campbell and Bozorgnia (2007, 2008), while for the source of the subduction interface (megathrust) it was combined with the Sinter of Chiou and Young (2007) and the Sinter of Abrahamson *et al*. (2015) (Campbell and Bozorgnia, 2007; Chiou and Youngs, 2008; Boore and Abrahamson *et al*., 2016; Irsyam *et al*. 2017, 2020).

One of the concerns of this study is the calculation of PSHA at the ground surface; therefore the calculation requires the input of site-specific parameters at each site of interest. In this study, considered site-specific parameters include:

1. The typical shear wave velocity at a depth of 30 m from the surface (Vs_{30}) used data from US Geological Survey (Wald and Allen, 2007) which were calculated based on the topography and have been verified with the results of the field measurements in various countries almost all over the world. The data had a grid resolution of 30 arc-seconds (0.00833 degrees).
2. Geological considerations/basin effects determined as parameters of rock depth with a shear wave velocity of 1,000 m/sec ($Z_{1.0}$) and rock depth with a shear wave velocity of 2,500 m/sec ($Z_{2.5}$). Both were using the formula

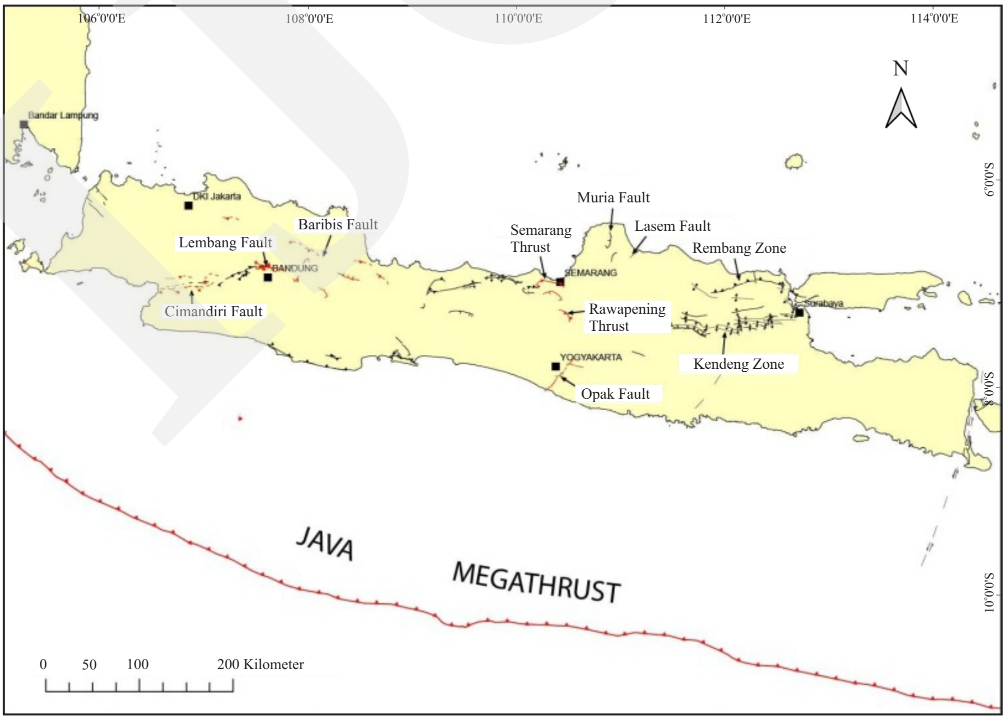

Figure 1. Locality map of active faults in Java and megathrusts considered in hazard calculations (PusGen, 2017).

$$\ln Z_{1.0} = \frac{-7.15}{4} \, x \ln\left(\frac{{Vs_{30}}^{4}+571^{4}}{1360^{4}+571^{4}}\right) \quad \text{...................(1)}$$

$$\ln Z_{2.5} = 7.089 - 1.144 \ln Vs_{30} \quad \text{..................(2)}$$

of Chiou and Young, (2013), for California (Chiou and Youngs, 2008).

Vs_{30} = shear wave velocity at a depth of 30 m from the surface (m/s)

$Z_{1.0}$ = rock depth with a shear wave velocity of 1,000 m/sec (in m)

$Z_{2.5}$ = rock depth with a shear wave velocity of 2,500 m/sec (in km)

This study was conducted hazard calculations with Classical PSHA and Event-Based PSHA, performed using OpenQuake developed by GEM (Global Earthquake Model). Computation was calculating earthquake acceleration on the surface taking into account site specific parameters and GMPE (Ground Motion Prediction Equation). Theoretically, PSHA was assuming that a source model consists of independent sources, independent earthquake ruptures caused by each source following a Poissonian temporal event model (Crowley and Silva, 2013; Dahmoune and Mansour, 2018; GEM, 2020).

The basic concept of PSHA calculation using the two main assumptions are as follows:

1. Seismicity in an area is a collection of independent earthquake sources, where earthquake events at one source are assumed to have no effect on the probability of earthquake events at other sources,
2. Each earthquake source causes independent earthquake ruptures, where it is assumed that the occurrence of an earthquake rupture in a source has no effect on the probability of another potential rupture at the same source.

Two main input components for both Classical and Event-Based PSHA method were

1. Seismic source model (ssm) representing seismic activity in an area. The parameters in the ssm include geometry, earthquake rupture parameters, and magnitude-frequency distribution. It is used to determine the average annual occurrence at a certain magnitude range. Earthquake sources used in the ssm include the following: a source of subduction earthquake, a source of shallow faults, and a source of background earthquakes.
2. The ground motion model or GSIM (Ground Shaking Intensity Model) is a model for calculating ground motion at a certain location based on its specific rupture property. In a simple case, the ground motion model matches the Ground Motion Prediction Equation (GMPE). Whereas, in the case of the more complex PSHA input model, the ground motion model encompasses a set of GMPE where each GMPE is considered for each tectonic region (Crowley and Silva, 2013; GEM, 2020; Herak, 2020; Stewart *et al*., 2015).

Classical PSHA

The workflow of the classical PSHA method shown in Figure 2 used input data: earthquake source systems and ground-motion systems. The Logic Tree Processor (LTP) processes the PSHA input model data which consists of two logic tree structures, consisting of making a seismic source model from a seismic source logic tree and a ground motion model from a ground motion logic tree. The Logic Tree Processor (LTP) uses the Preliminary Seismic Source Model information, and produces the information contained in the Seismic

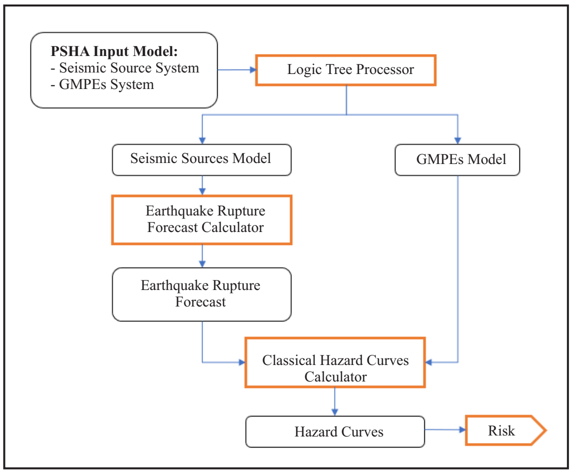

Figure 2. Classical PSHA method workflow using OpenQuake Engine (Monelli *et al*., 2012; GEM, 2020).

Source Logic Tree, namely epistemic uncertainty samples. It creates a Seismic Source Model (*i.e.* a model that describes the geometry and activity levels of each source without epistemic uncertainty). Following the same procedure, LTP performs ground motion modelling where the data structure associated with each tectonic area considers the appropriate GMPE.

PSHA

The working principle of the Event-Based PSHA is to calculate the set of stochastic events and to produce stochastic events by sampling each rupture contained in the ERF (Earthquake Rupture Forecast) based on the probability of its occurrence. Typically, a stochastic event set (SES) contains a large number of seismicity histories, each representing a possible set of events that could be generated by the seismic source considered in the analysis over the time span defined for the hazard calculation (typically fifty years). The calculation of the stochastic event set and the corresponding ground motion field is a very suitable procedure for the calculation of seismic risk involving a number of assets that are closely spaced

Based on the PSHA Classical method workflow and the PSHA Event-Based method (Figure 3), it can be seen that the difference is that in the Event-Based PSHA method there is a stage of entering the stochastic event set (SES) value which is to produce a synthetic earthquake event catalogue in each earthquake source zone within a certain period of time (for example 10,000 years). Then for each event, the estimated distribution of the earthquake was based on the GMPE associated taking the probability density function sample from GMPE. The next step is to calculate the probability of each event and to estimate the hazard taking into account the site-specific amplification.

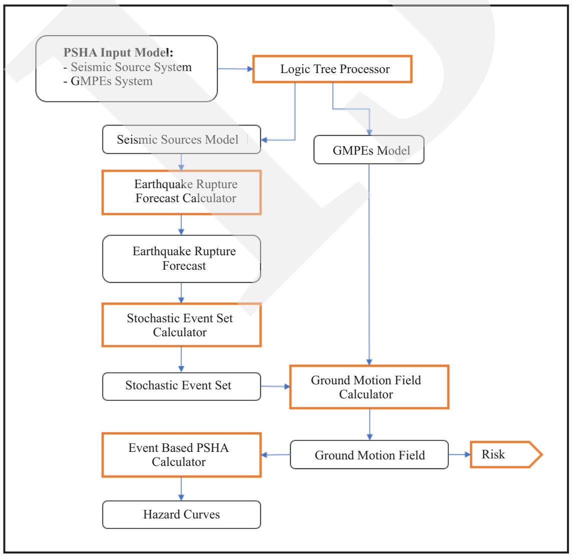

Figure 3. PSHA method workflow using OpenQuake Engine (Monelli *et al.*, 2012; GEM, 2020).

In more detail, the calculation steps using the event-based method are as follows (Schorlemmer *et al.*, 2007; Niño *et al.*, 2014; Silva, 2018):

Sampling the magnitude distribution to obtain individual magnitudes: the magnitude probability density function (pdf) was divided into magnitude range in bins. The magnitude pdf was then made into a uniform pdf with the same fx (x) as the average of the magnitude pdf. The value sample of magnitude (x) on each bin was then randomly generated to get a single magnitude.

From the magnitude, the probability of earthquake occurrence was calculated using the earthquake repetition model, Guttenberg Richter (GR) and/or characteristic (CH) model.

The scaling law was used to calculate the length and the width of the rupture based on the magnitude and the earthquake mechanism.

The next step was randomly determined centroid rupture, which does not extend beyond the periphery of the rupture.

Based on the probability, each event and rupture might be estimated as hazard by considering the site amplification according to the specific site.

Some limitations used in this method include:

- The maximum distance from the earthquake source to the site of interest is 300 km, where it is assumed that a distance above 300 km has no impact on causing to building damage
- To calculate earthquake acceleration in bedrock, the vs30 parameter is used, 800 m/s, which is the hard soil (SB) classification, the Z1.0 and Z.25 values are a function of vs30.

- This research is limited to hazard analysis at probability of exceedance 2 % in fifty years.

Furthermore, comparing the Classical PSHA method and the Event-Based PSHA method was carried out with various stochastic event set (SES) values: 10,000, 50,000, 100,000, and 200,000. The SES of 10,000 to 200,000 was taken from the previous study that stated due to the randomness associated with the calculation of probabilistic losses; it is impractical to obtain the exact solution using an approach for the estimation of the losses. Instead, a sufficiently long SES can be generated in order to achieve statistically valid results. This convergence can be quantitatively evaluated through the estimation of confidence intervals. In this context, a large number of SESs with increasing investigation intervals (from 10,000 to 500,000 years) were generated and employed to derive loss exceedance curve (Silva, 2018).

The outputs of the hazard analysis using the Event-Based method include: gmf (ground motion field) data, hazard map-mean, and hazard curves. The hazard map output data was then plotted with QGIS to produce a hazard map, and then compared to the hazard analysis map results using the Classical PSHA method. The analysis was performed on a peak acceleration spectrum at 0 seconds (Peak Ground Acceleration/ PGA) with the probability of exceedance of 2 % in fifty years.

Result and Analysis

The results of the classical PSHA calculation are the hazard curve and the hazard map-mean. Mapping used the help of QGIS software. The hazard map of the Classical PSHA method is presented in Figure 4. The calculation output using the Event-Based PSHA method includes: Hazard Curve and Hazard Map-mean as well. The hazard maps are presented in Figure 5 to Figure 8 with SES of 10,000, 50,000, 100,000, and 200,000, respectively.

The hazard map from the Classic PSHA in Figure 4 showing the earthquake acceleration at the ground level and at a return period of 2,475 years was in the range of 0.2 to 1.0 g. The lowest earthquake intensity was in the northern part of Central Java. The north coast of Java have moderate intensities in the range of 0.25 to 0.5 g. It is confirmed with a previous study of seismic hazard of cities in Central Java (Purwana *et al.*, 2022; Goro *et al.*, 2023). The seismic intensity around the capital city of Jakarta was 0.5 to 0.6 g for a return period of 2,475 years, which is confirmed to the previous study (Goro *et al.*, 2023). Meanwhile, for the southern part of Java Island, most of them have a high earthquake hazard in the range of 0.5 to 1.0g. The most vulnerable areas are in the southern part of West Java Province, in Sukabumi Regency, and in the southern part of Pandeglang Regency, Banten Province.

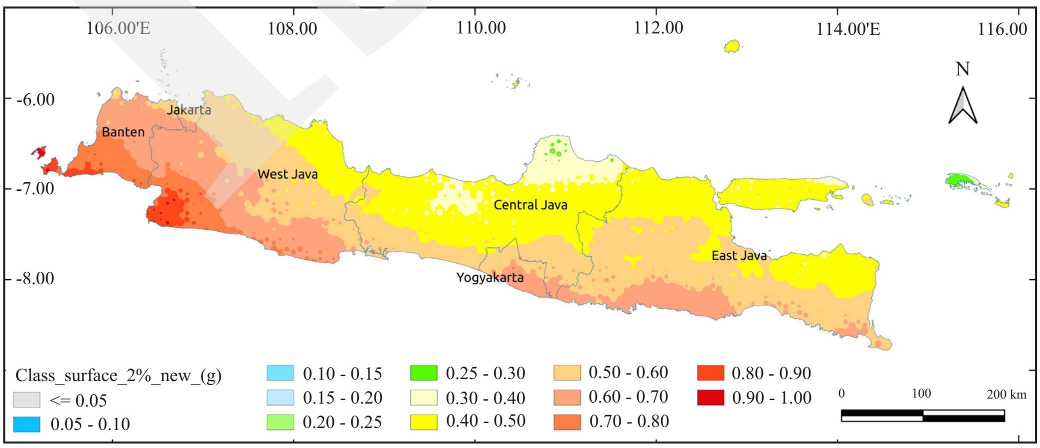

Figure 4. Map showing peak acceleration at the period of 0 second (PGA) on the ground surface, using the Classical PSHA method for probability of exceedance of 2 % in fifty years.

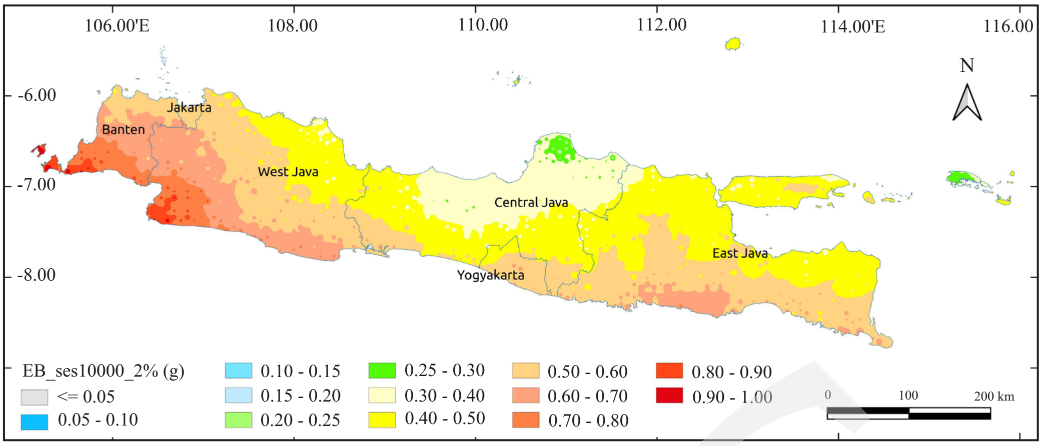

Figure 5. Map showing the peak acceleration at 0 second period (PGA) on the ground surface, using the Event-Based PSHA method with SES= 10,000 for 2% probability of exceedance in fifty years.

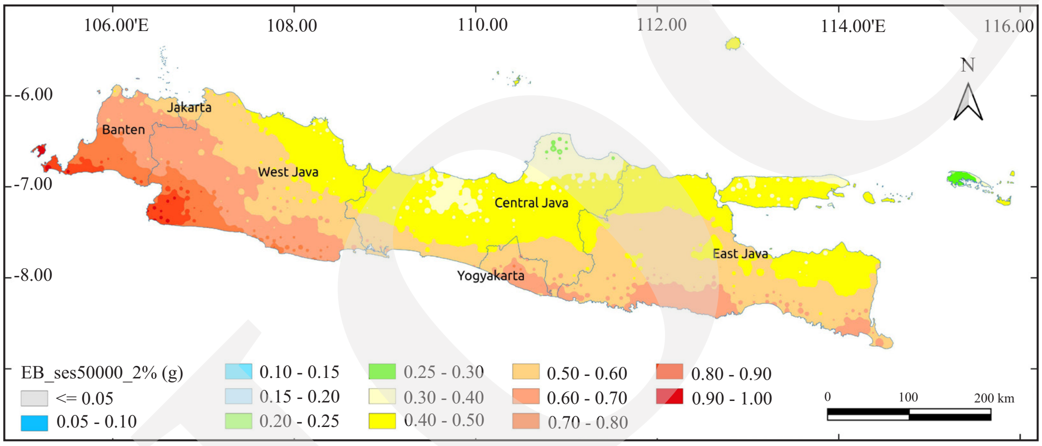

Figure 6. Map showing the peak acceleration at 0 second period (PGA) on the ground surface, using the Event-Based PSHA method with SES= 50,000 for 2% probability of exceedance in fifty years.

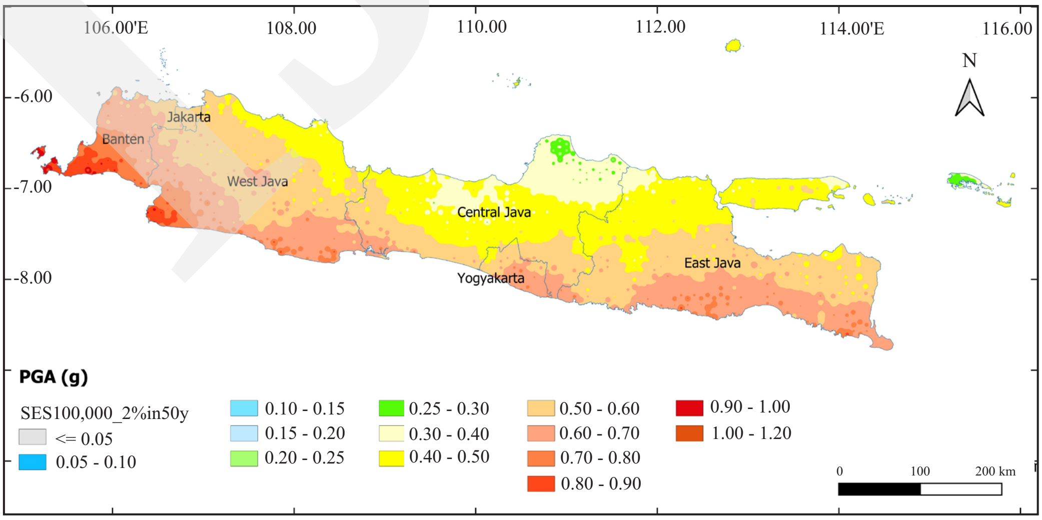

Figure 7. Map showing the peak acceleration at 0 second period (PGA) on the ground surface, using the Event-Based PSHA method with SES= 100,000 for 2% probability of exceedance in fifty years.

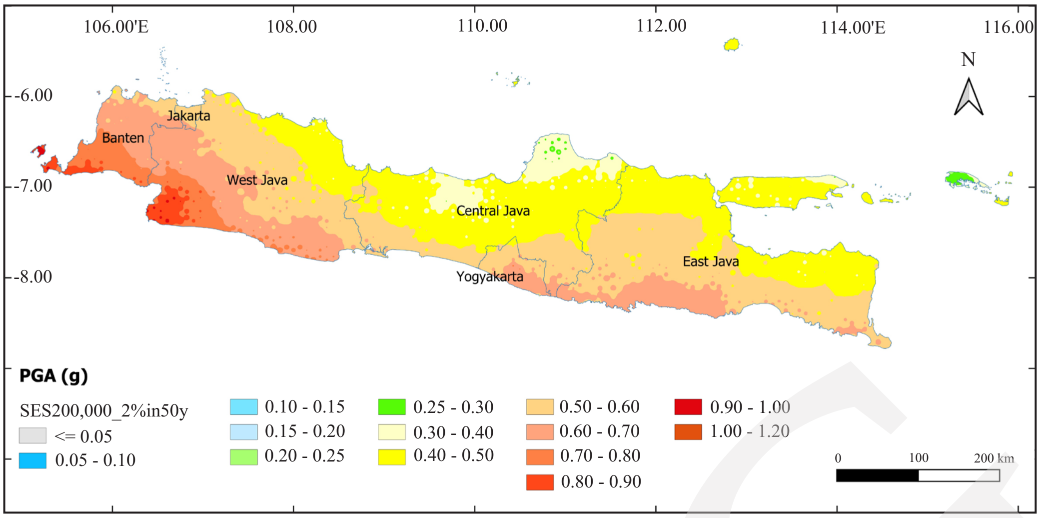

Figure 8. Map showing the peak acceleration at 0 second period (PGA) on the ground surface, using the Event-Based PSHA method with SES= 200,000 for 2% probability of exceedance in fifty years.

Figure 5 showed the results of the calculation of the Event Based PSHA method with a value of SES= 10,000 years, where in general the hazard intensity is smaller than the classical hazard (Figure 4). The area with an earthquake acceleration of 0.3 to 0.4 g is in the Central Java area extending to west and south. The southern region of East Java with an earthquake acceleration of 0.5 - 0.6 g is shifting and shrinking to the south. The results of the Event-Based method with SES= 50,000 (Figure 6) show similarities to the Classical PSHA results, although in the southern coast of East Java was slightly different at areas with an earthquake acceleration range of 0.6 - 0.7 g. The computation of the Event Based method with SES= 100,000 produces a hazard map in Figure 7. When compared to the Classical PSHA results it looks different, particularly at areas with acceleration range of 0.6 - 0.7 g in West Java and Banten which are narrowing towards southwest. Meanwhile at the eastern edge of East Java, the earthquake acceleration increased from a range of 0.4 - 0.5 to 0.5 g - 0.6 g. Figure 8 shows the results of hazard calculations using the Event-Based PSHA method with SES= 200,000. When observed, it was much the same as to the Classical PSHA results compared to the other previous Event-Based PSHA method.

Subsequently, to find out how close the results of the two methods analysis are, the ratio of the peak acceleration of the earthquake which is generated from the two methods is calculated at all sites. The mean value, standard deviation, and variance computed from the ratio of the seismic acceleration are the result of the two different methods in the same site of interest at all sites. The mean value, standard deviation, and variance of these comparisons are presented in Table 1. The average value of the comparison of the results of the two methods is close to 1, which means that the similarity of the results from the two methods is very close. It can also be seen that at a higher SES (SES= 200,000) the average value of the comparison of the results of the two methods is

Table 1. Mean Value, Standard Deviation, and Variance of the Ratio of Acceleration Spectra on the Surface at 0 Seconds (PGA) Between Classical PSHA and PSHA With Varying SES Values, PoEs = 2 % in Fifty Years

SES =	**10,000**	**50,000**	**100,000**	**200,000**
Mean	0.9559	0.9924	1.0062	0.9927
Standard Deviation	0.0458	0.0228	0.0208	0.0172
Variation	0.0021	0.0005	0.0004	0.0003

closer to 1, or it can be concluded that the higher the SES, the results of the analysis using Event-Based PSHA show convergence, based on the results of a previous research (Silva, 2018). Table 1 figured out the standard deviation and variation that were decreasing along with SES value.

The correlation used to examine each pair of measurement variables was to determine whether the two measurement variables tend to move together, that is whether large values of one variable tend to be associated with large values of the other (positive correlation), small- variable value tends to be associated with large values of the others (negative correlation), or whether values of both variables tend to be unrelated, correlation near 0 (zero). Table 2 showed that the increasing SES value on event based PSHA would increase the correlation value of that method in comparison with classical PSHA method.

Hazard curves from several locations were chosen to see how close resemblance of the result

Table 2. Correlation Value of the Ratio of the Acceleration Spectra on the Surface at 0 Second (PGA) between Classical PSHA and PSHA with Varying SES Values, PoEs = 2 % in Fifty Years

Correlations	Classical PSHA
PSHA, SES = 10,000	0.9671
PSHA, SES = 50,000	0.9933
PSHA, SES = 100,000	0.9963
PSHA, SES = 200,000	0.9975

of those two methods. Three following different locations were selected: a location in North Jakarta Municipality (Special Capital District Province), Sukabumi Regency (West Java Province), and Surabaya Municipality (East Java Province). North Jakarta and Surabaya are chosen, because both have urban areas with very dense populations with the earthquake intensity ranged from 0.4 - 0.6 g. While Sukabumi Regency (southern part of West Java Province) is chosen because of a very high earthquake intensity (0.8 - 0.9 g). The hazard curves as the results of classical PSHA and event based PSHA of the three locations are presented in Figures 9 - 11.

The hazard curve comparisons at a location in north Jakarta presented in Figure 9, which indicated that at the peak ground acceleration of 0.05 to 1.0 g all the hazard curves were relatively coincided. But then at accelerations above 1.0 g, the results of the Event-Based analysis with SES= 200,000 more coincides with the curves of the classic PSHA compared to the other three lower SESs. Graph of method results at intensity measure level (iml.) 0.01 - 0.05 g shows a horizontal lines since this calculation is limited to a minimum iml. of 0.05 g.

Figure 10 shows the hazard curve of a location in Sukabumi Regency, with the result of both Classical PSHA and Event-Based PSHA in various SES values. The hazard curves coincide one to

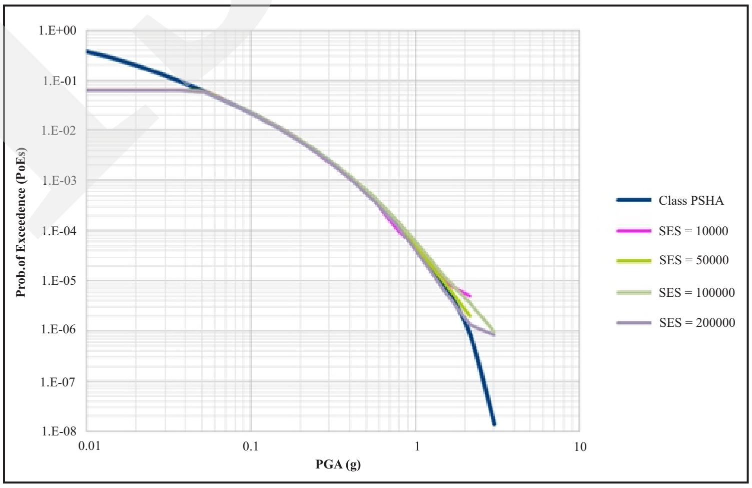

Figure 9. Hazard curve of a location in North Jakarta Municipality (Lon, Lat: 106.90181, -6.16519), Special Capital District of Jakarta Province.

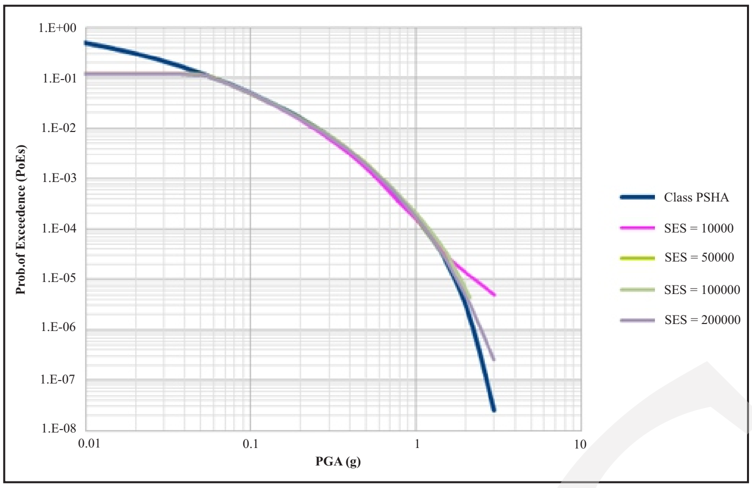

Figure 10. Hazard curve of a location in Sukabumi Regency (Lon, Lat: 106.75426, -6.94333), West Java Province.

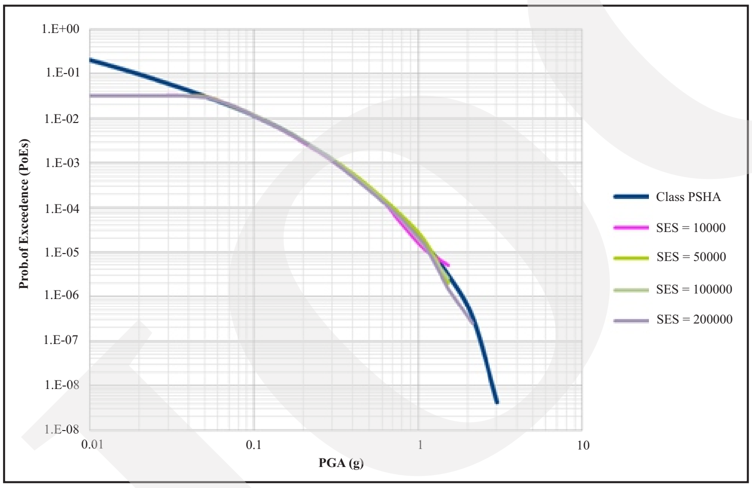

Figure 11. Hazard curve of a location in Surabaya Municipality (Lon, Lat: 112.76414, -7.20402), East Java Province.

another when the ground acceleration is less than 1.5 g. The hazard curve of Event-Based method with SES= 100,000 is nearest to classical curve than others when ground acceleration is more than 1.5 g. Similar to the case of a location in Sukabumi Regency, a site in Surabaya also coincides with all hazard curve at ground acceleration of less than 1.0 g. Whereas at accelerations above 1.0 g, the results of the Event-Based analysis with SES= 100,000 are more concomitant with the curves of the classic PSHA compared to the others.

To examine the proximity of the hazard curve results, the correlation was also calculated as presented in Table 3, which indicates that all correlation value was close to 1. However, the correlation of Event-Based with SES= 100,000 and 200,000 is the closest to 1 than two other lower SESs in three location of interest.

Discussion

The result of Classical PSHA method computation as a hazard map presented in Figure 4, shows that the peak acceleration is lower in the north part of Java and increasing gradually towards the southern part. The highest intensity is in the southern part of West Java Province, which is imposed by Sunda Strait and the south of Java megathrust. The southern part of Java Island experiences a high peak ground acceleration due to the dominance of the subduction seismic sources

Table 3. Hazard Curve Correlation between the Classical PSHA And PSHA Method with Various SES Value, PoEs = 2 % in Fifty Years in Three Different Sites

Event Based PSHA	Classical PSHA Method		
	North Jakarta Municipality	**Sukabumi Regency**	**Surabaya Municipality**
SES = 10,000	0.999984404	0.999946631	0.999950546
SES = 50,000	0.999976809	0.999994070	0.999968806
SES = 100,000	0.99997986	0.999997052	0.999998886
SES = 200,000	0.999998549	0.999991781	0.999969752

of West Java, Central Java, and East Java megathrust. Most of Jakarta, West Java, and Banten Provinces have obtained a high seismic hazard with a PGA about 0.5 - 0.9 g, apart from the influence of subduction in the southern part of West Java and Banten. This is also due to the influence of active faults in West Java, such as Cimandiri, Nyalindung-Cibeber, Raja Mandala, Lembang, and Subang. On the other side, the ground acceleration along the north coast of Java is lower with a range of 0.4 - 0.5 g due to the influence of the earthquake source of shallow faults that stretched from Cirebon in West Java, Semarang in Central Java, and Surabaya in East Java.

The comparison of the hazard map in Figure 4 (Classical PSHA) to five hazard maps of Event Based Analysis (Figures 5 to 8) shows that the hazard map results of the Event-Based PSHA analysis with SES= 200,000 (Figure 8) had the most similarity of the peak ground acceleration (PGA) to the results of the Classical PSHA method in all area. This is possible because the higher the SES input value, the more rupture counts are considered in the calculation, with the consequence that more time required in the calculation. However, it is not definite that a large SES will always give similar hazard results to the Classical PSHA results. For example, the output of Event-Based with SES= 50,000 is closer to Classical PSHA result compared to Event-Based PSHA with SES= 100,000 in Surabaya Municipality.

In order to support the comparison process, it is necessary to compare the results of the two methods, afterward to determine those mean, standard deviation and variation. Statistically, if the standard deviation and variation of a comparison value is small, it can be interpreted that the comparison is close to similarity. The mean, standard deviation, and variation in Table 1 show that Event-Based analysis with SES= 200,000 produced the minimum standard deviation and variation values of 0.0172 and 0.0003, respectively.

Another way to identify the comparability of two variables is by using correlation calculations, where the closer the correlation value to 1, the two variables are getting closer to the similarity. The results of the cross-correlation between the two methods in Table 2 also showed that the nearest value to 1 was achieved in the Event-Based PSHA with SES= 200,000 against the Classical PSHA.

Based on the comparison of the hazard maps, standard deviation values, variation values, and cross-correlation, it can be concluded that the results of the method with SES = 200,000 are well-confirmed to the results of the Classical PSHA method. The use of high SES will produce high number of ruptures that consider in the analysis, although consequently it would be time consuming. This is also supported by a previous research related to the risk analysis with an Event-Based method, wherein the convergence in probabilistic risk analysis has been thoroughly investigated within a probabilistic framework. A single location with the range of exceedance of rates above 10 - 3, SES with at least 200,000 years of events, should be generated to achieve statistically reliable results (Pagani *et al.*, 2014; Silva *et al.,* 2014; Silva, 2018).

Based on the hazard curve comparisons at the three locations, presented in Figures 9, 10, and 11, they indicated that at the peak ground acceleration below 0.05 g, the results of Event-Based PSHA shows much lower, and forms a straight line due to the use of minimum intensity at 0.05 g in the analysis. Subsequently, at the peak ground acceleration of 0.05 to 1.0 g, all the hazard curves coincided. While at accelerations above 1.0 g, the results of the Event-Based analysis with SES= 100,000 and 200,000 are more concomitant with the curves of the Classic PSHA compared to the other two lower SESs. These were also seen in the cross-correlation results where SES= 100,000 and 200,000 have the closest value to 1.

Conclusions

Seismic hazard and risk analysis using the Event-Based approach requires input of high SES (Stochastic Event Set) values to obtain a convergence of results, which is between 10,000 to 500,000 years. The results of the study showed that the Event-Based PSHA method with SES= 200,000 years would provide results that were consistent to the results of the Classical PSHA method.

To determine the most adequate comparison results for Classical PSHA and Event-Based PSHA, two factors need to be considered, including: (1) the minimum value of the standard deviation and the variation of the ratio of intensity measurement of the two methods results (2) the resemblance of the earthquake acceleration value at each location depicted in the hazard map. Meanwhile, the hazard curve is not recommended to be used as a determining factor, because all comparisons are close to one another at PGA about 0.05 to 1.5 g. Thus, the similarity of hazard maps is important in the comparison of these two methods. The comparison of these two methods is to determine the SES value for the later use in risk analysis with the Event-Based approach.

Based on the comparison of hazard maps, standard deviation values, variation values, and cross-correlation, it can be concluded that the results of the Event-Based PSHA method with SES= 200,000 are well-confirmed to the results of the Classical PSHA method. The research results is in accordance with a previous study that a single location and probability of exceedance above 10 - 3, SES with at least 200,000 years of events should be generated to achieve statistically reliable results (Pagani *et al*., 2014; Silva *et al*., 2014; Silva, 2018).

Based on the results of this research, further research can be carried out regarding earthquake risk analysis. To get adequate analysis results, use The Risk Analysis Method, with at least SES= 200,000.

Acknowledgments

The author thanks the Centre for Housing and Settlement Research and Development, Ministry of Public Works and Housing in Bandung, Indonesia, and the National Centre for Earthquake Studies of Indonesia (PuSGeN) for the endorsement to use the server for this research.

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