Journal of the Civil Engineering Forum, May 2023, 9(2):117-126
DOI 10.22146/jcef.5469
Available Online at https://journal.ugm.ac.id/v3/JCEF/issue/archive

The Study of Seismic Hazard in Near-Fault Areas Using Probabilistic and Deterministic Approach

Grisella Aglia, Martin Wijaya*, Paulus P. Rahardjo
Department of Civil Engineering, Universitas Katolik Parahyangan, Bandung, INDONESIA
Jalan Ciumbuleuit no. 94 Bandung
*Corresponding author: mwijaya@UNPAR.ac.id

SUBMITTED 31 August 2022 **REVISED** 1 December 2022 **ACCEPTED** 30 January 2023

ABSTRACT Earthquake is one of the most common natural disasters in Indonesia and usually destroys both high and low-rise buildings as well as triggers liquefaction and Tsunami. This means it is important to provide a robust building design with the ability to resist earthquake load and other induced phenomena. One of the methods commonly used to determine the relevant response spectrum of the bedrock is seismic hazard analysis which can be either Probabilistic Seismic Hazard Analysis (PSHA) or Deterministic Seismic Hazard Analysis (DSHA). The application of PSHA allows the representation of the response spectrum of an earthquake using the return period, thereby providing the engineers with the flexibility of selecting the appropriate natural period. In PSHA, all sources are considered when determining the response spectrum and all uncertainties has been considered through probability approach. On the other hand, DSHA is based on geological observations and empirical data that can be easily understood. Earthquake source must be identifiable and uncertainties are considered by either taking median value or median plus one standard deviation value. This research discussed the greater influence of seismic hazard analysis on the bedrock response spectrum of near-fault areas including Bandung situated at a distance of 12.9 km from Lembang Fault, Palu at 3 km from Palu Fault, and Yogyakarta at 8.5 km from Opak Fault. Moreover, EZFRISK Program was used to generate a response spectrum at bedrock and the results showed that PSHA is consistently more conservative than DSHA. It was also noted that there are significant differences at shorter periods for Palu site but these differences were observed at the natural period between 1s and 2s for Bandung and Yogyakarta sites.

KEYWORDS Earthquake, Near-fault Areas, Seismic Hazard Analysis, PSHA, DSHA

1 INTRODUCTION

Earthquake is a common natural disaster in Indonesia. For example, Yogyakarta experienced an earthquake induced by Opak Fault in 2006 and this caused severe damage to the densely populated area with 5716 reported to be dead, 37927 injured, and between 0.5 to 1 million homeless (Consultative Group on Indonesia, 2006). Dozens of earthquake occurrences have also been linked to Opak Fault in the last 200 years such as the big one that occurred in 1867 reaching VIII MMI (Adelayanti, 2020). Another example is Sulawesi earthquake and tsunami which was triggered by Palu-Koro Fault (VII-VIII MMI) in September 2018 and caused liquefaction and landslide in Palu (Cilia et al., 2021). It affected 2.4 million people including 2000 reported to be dead, more than 4600 injured, and over 210000 displaced from their houses. Recent findings also showed the existence of the Lembang Fault located approximately 10 km north of Bandung City (beneath Lembang City) and active with small earthquake activity (Rasmid, 2014). Daryono et al. (2019) reported that the fault has caused at least three earthquakes and its vertical displacement was 40 cm in 2300 - 600 BCE with the magnitude estimated to be 6.5 Mw and likely to be reactivated to cause damage in near-fault areas.

Engineering design requires considering seismic hazard specifically when the site project is prone to earthquake (Vaziri et al., 2022). The incorporation of earthquake effect on structure commonly requires a response spectrum at the surface. This can be achieved using the following steps:

1. Determining the response spectrum of the bedrock at the site which is referred to as the

target response spectrum
2. Selecting the seed motion based on the appropriate earthquake
3. Creating synthetic ground motion
4. Propagating ground motion from bedrock to the surface (with or without structural model)

The response spectrum of the bedrock at the site can be determined through seismic hazard analysis which is commonly separated into deterministic seismic hazard analysis (DSHA) and probabilistic seismic hazard analysis (PSHA) as previously indicated (Cornell, 1972; Baker, 2008; SNI 1726, 2019). The two methods (Kramer, 1996) require the identification of earthquake sources including the distance and magnitude. The attenuation equation can also be used to determine the effect of distance including the geometric spreading and damping between the project site and earthquake sources as well as the reconstruction of the bedrock response spectrum. The difference between PSHA and DSHA is the consideration of uncertainties in the analysis. The following uncertainties are usually considered in PSHA (Kramer, 1996):

1. Probability of distributing potential rupture locations
2. Recurrence relationship
3. Uncertainties inherent in the predictive relationship
4. Uncertainties in earthquake location, size, and ground motion parameter prediction

In PSHA, the target response spectrum depends on the desired return period and is normally referred to as the uniform hazard spectrum. The overall model for PSHA is presented in Figure 1. Meanwhile, the target spectrum in DSHA is known as the deterministic spectrum.

DSHA is based on geological knowledge or field evidence and observation to select a reasonable maximum potential for earthquake based on individual sources. The overall model for this method is presented in Figure 2.

PSHA and DSHA have been compared in Table

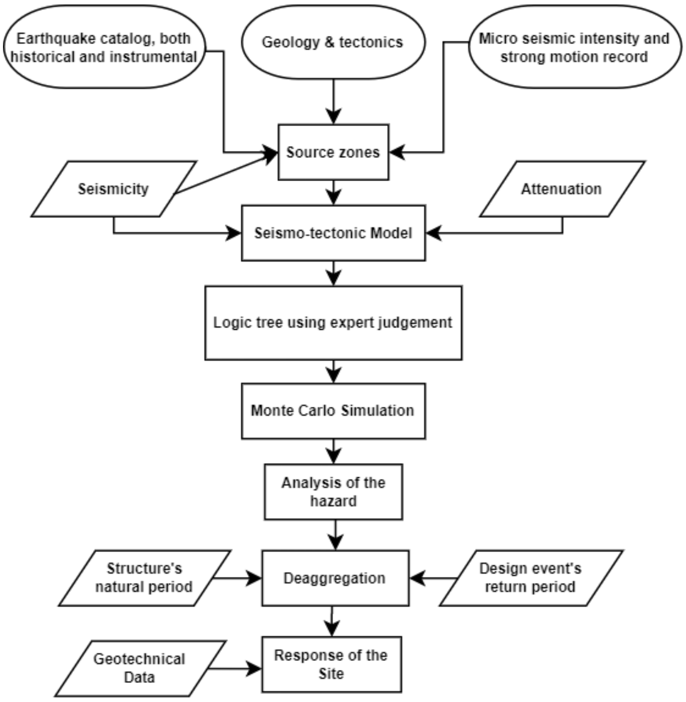


Figure 1 Overall model for PSHA modified from Vaziri et al. (2022)

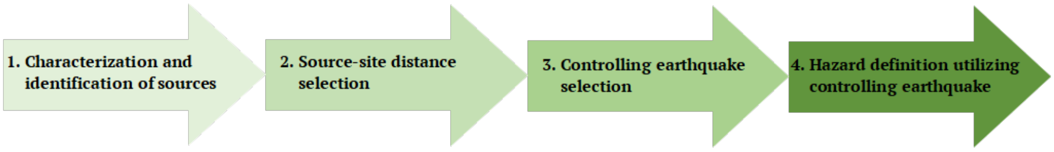


Figure 2 Overall model for dSHA (Vaziri et al., 2022)

Table 1. Advantages and disadvantages of PSHA and DSHA (Vaziri et al., 2022; Krinitzsky, 2003; Wang, 2011; Baker, 2008)

Seismic Hazard Analysis	PSHA	DSHA
Advantages	Based on (Vaziri et al., 2022) (a) Widely used and known all around the world (b) Provides a forecast for seismicity and ground movement using seismogenic origin models (c) Considers all possible earthquake events	(a) Provides reliable evaluation of seismic hazard from geology regardless of time. (b) Maximum credible earthquake (MCE) is commonly taken at median plus one standard deviation (84 percentile). However, it is possible to select a higher percentile for more conservative values or less for lower conservative values, indicating flexibility in meeting the project requirement. (c) Identifies individuals' faults with their estimated MCE and provides earthquake potential from each fault on hotspots and zones within the source area.
Disadvantages	(a) It is not based on valid physics because earthquake does not have regular occurrence through space and time (b) The probabilistic values for the operating basis earthquake (OBE) are produced by tinkering with the exceedance and this normally leads to arbitrary results with no basis in either science or engineering. The probability calculation also contains uncertainty. (c) Seismic probabilistic uses the mean value of ground motions obtained from the projection through time. The number can be added with 50% to be considered equivalent to 84 percentiles but the values do not represent the motion from the accelerograph. (d) PSHA assumes the possibility of combining earthquakes to project earthquake occurrences through time but this can make the individual earthquake sources lose their identities. (e) De-aggregation focuses on smearing earthquake in a region together into an amalgam in order to provide a value that represents no individual earthquake or a specific place in the region. This nonrepresentative value is normally projected through thousands of years into the future based on unverifiable calculation because there are no data for projection and later mathematically "deaggregated" into fragments to fill a grid with dubious interpretations. (f) It is difficult to understand and use.	(a) It cannot be used on unidentifiable earthquake sources. (b) Error in determining earthquake sources. (c) Error in assigning earthquake potentials of fault. (d) There is no information on the recurrence of the controlling earthquake due to its neglect of time and frequency dimensions. (e) Difficult to determine the worst-case event because different earthquake sources can be the worst case at different period. (f) It is not a true worst-case event determinant because larger earthquake or ground motion can always occur in the future and the use of the 84th percentile (mean plus one standard deviation) does not necessarily produce this scenario due to the absence of a theoretical upper bound on the amplitude of the ground motion.

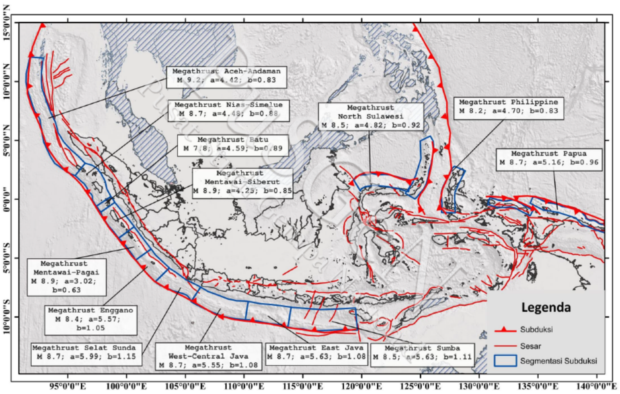
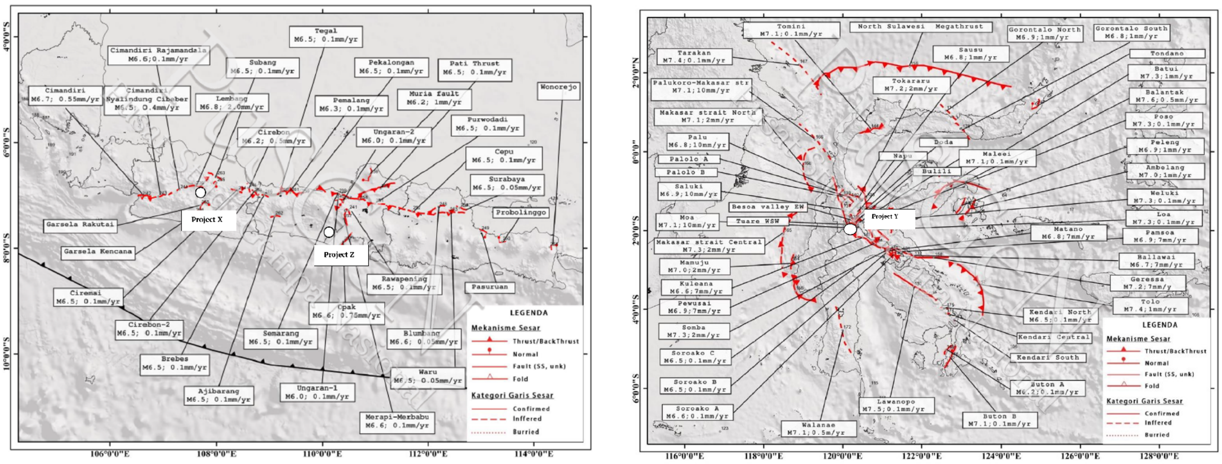


Figure 3 Megathrust earthquake sources (PUSGEN, 2018)



(a) (b)

Figure 4 Fault earthquake sources (a) Java and (b) Sulawesi (PUSGEN, 2018)

1 based on their advantages and disadvantages. Pailoplee et al. (2009) constructed a seismic hazard map based on PSHA and DSHA in Thailand. The results showed that DSHA map provided extremely high seismic hazard levels in some areas in Thailand and surrounding countries.

Meanwhile, PSHA map had the same trend but with a lower seismic hazard level. Eftekhari et al. (2021) also studied the effect of near-fault areas on PSHA in Iran and found large variations in the spectral accelerations among different locations at short oscillator periods and the absence of any significant difference at longer periods. However, the results obtained using PSHA and DSHA methods can complement each other in seismic hazard analysis (Moratto et al., 2007) and this is the reason they can be considered when constructing a target response spectrum (SNI 1726, 2019). This study, therefore, compares the target response spectrum produced for the three sites of Yogyakarta, Palu, and Bandung using PSHA and DSHA in order to determine the method with a more critical target spectrum.

2 METHODS

2.1 Project Location

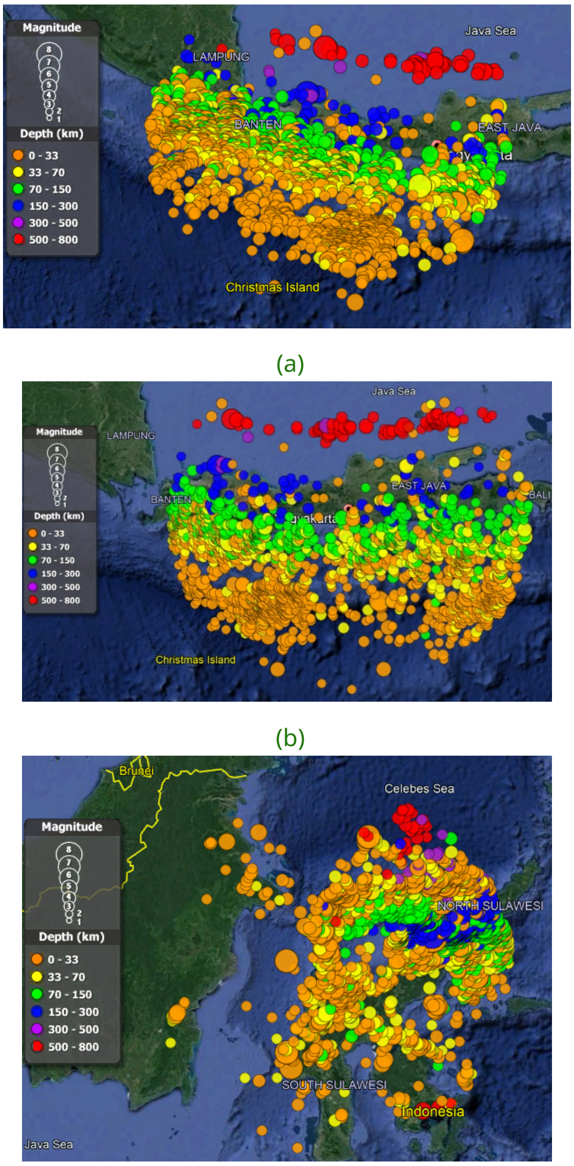
The faults reviewed in this study were located at a distance of 0 – 15 km from the site. For example, Project X is located approximately 12.86 km from Lembang Fault, Project Y is 3.05 km from Palu Fault, and Project Z is 8.48 km away from Opak Fault. The information from the 2017 Indonesian Earthquake Map showed that Lembang Fault has a maximum magnitude of 6.8 Mw with a slip rate of 2 mm/year, Opak Fault has 6.8 Mw with 0.75 mm/year, and Palu Fault has 6.8 Mw with

10 mm/year, respectively. This was the reason the three project locations are classified as near-fault areas (ASCE, 2017; SNI 1726, 2019).

2.2 Earthquake Data Collection

Earthquake catalog provided by Indonesian National Seismic Map (PUSGEN, 2018) was used to obtain Megathrust and Fault Earthquake Sources as indicated in Figures 3 and 4.

Earthquake catalog provided by the U.S. National Earthquake Information Service (USGS, 2022) was also used to obtain the background earthquake including shallow crustal and Benioff with a focus on those within a 500 km radius from the site. It is important to note that this study is only interested in the mainshock in relation to the background earthquake but the database can also contain foreshocks and aftershocks. This means there is a need to separate foreshock, mainshock, and aftershock earthquake. Gardner and Knopoff method (Gardner and Knopoff, 1974; Knopoff and Gardner, 1972) was adopted to filter out foreshock and aftershock based on the assumption that they are all related to each other and exhibit non-Poissonian-distribution. It is also important to note that the determination of non-Poissonian and Poissonian-

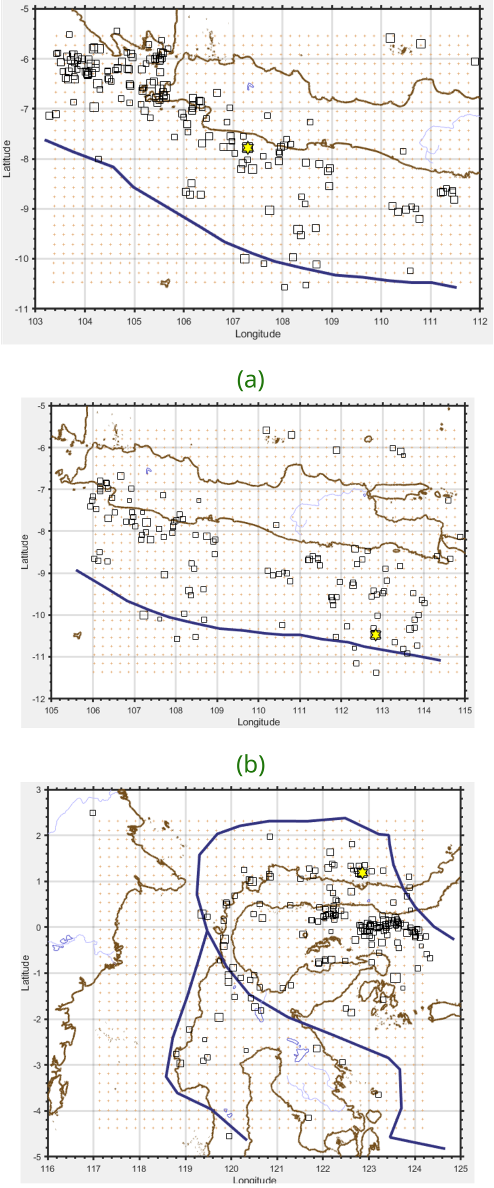


(a)

(b)

(c)

Figure 5 Background earthquake sources in three locations (a) Bandung, (b) Yogyakarta, and (c) Palu (USGS, 2022)



(a)

(b)

(c)

Figure 6 Mainshock (a) Bandung, (b) Palu, and (c) Yogyakarta (Gardner and Knopoff, 1974)

Table 2. Advantages and Disadvantages of PSHA and DSHA (Vaziri et al., 2022 ; Wang, 2011; Krinitzsky, 2003 ; Baker, 2008)

Earthquake Sources	Attenuation Equation
Shallow Crustal	Boore-Atkinson NGA Equation (Boore et al., 2014) The Campbell-Bozorgnia NGA Equation (Campbell and Bozorgnia, 2014) The Chiou-Youngs NGA Equation (Chiou and Youngs, 2014)
Megathrust	BCHYDRO Equation (Abrahamson et al., 2016) Atkinson-Boore equation BC rock and global source subduction (Atkinson and Boore, 2003) Zhao et al. equation with vs30 variable (Zhao et al., 2006)
Intraslab (Benioff)	Equation AB intraslab seismicity Cascadia region BC-rock condition (Atkinson and Boore, 2003), Cascadia. Geomatrix equation for slab seismicity rock, 1008 srl. July 25 2006. (Youngs et al., 1997) Equation AB 2003 intraslab seismicity worldwide data region BC-rock condition (Atkinson and Boore, 2003), worldwide.

distributed shocks can be used to identify the mainshock. Therefore, the status of the background earthquake before the filtering process is presented in Figure 5 but only the mainshock is indicated in Figure 6 using Gardner and Knopoff method.

2.3 Attenuation Equation

The attenuation equation is normally used to estimate the level of ground shake caused by an earthquake with a certain magnitude, the distance between the source and a site, as well as the condition of the source. This means it represents the function related to the source information and wave propagation path of earthquake as well as the local condition of the site. The function was developed based on statistical regression analysis of the actual recording of ground motion or accelerograph on site (PUSGEN, 2018). The attenuation equation selected based on PUSGEN (2018) is presented in the following Table 2.

2.4 Seismic Hazard Analysis

Seismic Hazard Analysis using PSHA and DSHA methods was conducted through the EZ-FRISK program (Fugro, 2021). Earthquake sources used for PSHA were described in Section 3.1, including Megathrust, Benioff, and Shallow Crustal. Meanwhile, those used for DSHA included determined earthquakes such as Lembang, Opak, and Palu Faults. It is pertinent to note that the Uniform Hazard Spectra (UHS).

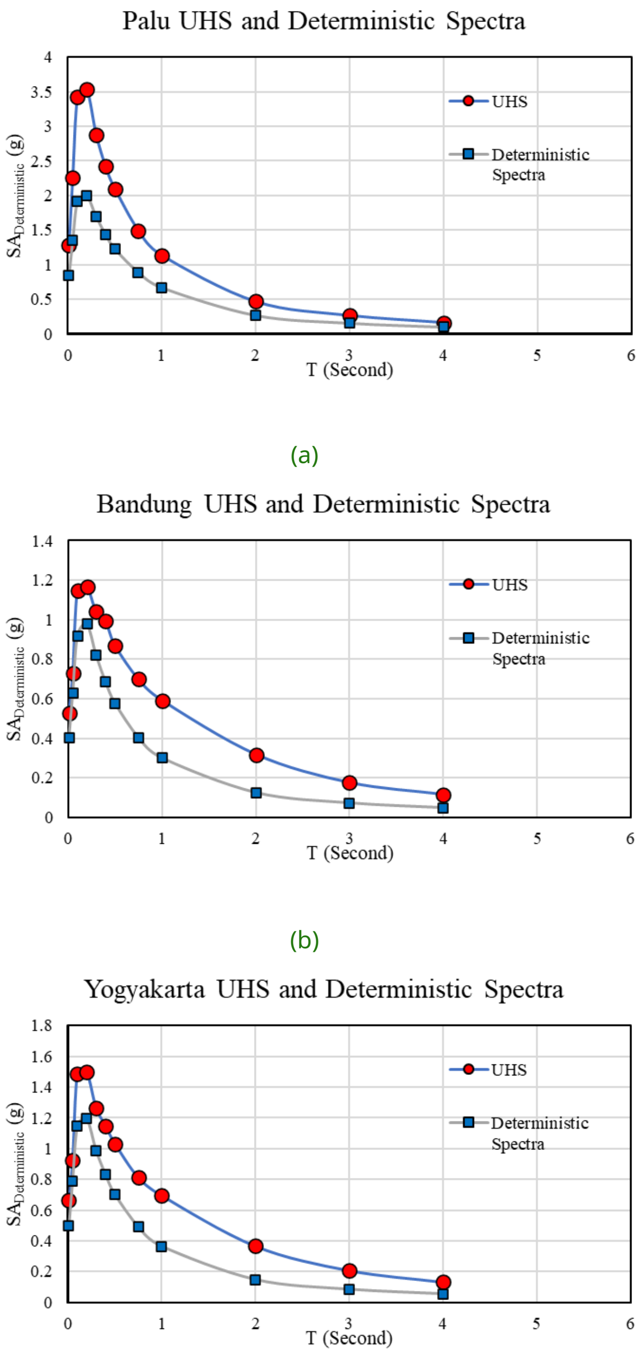
3 RESULTS

UHS and Deterministic Spectra in Figure 7 showed that the DHSA values in the three locations are consistently lower than PSHA values. Moreover, UHS is significantly higher than Deterministic Spectra and converges at the higher natural period at Palu. It was also discovered that UHS for both Bandung and Yogyakarta sites are higher than Deterministic Spectra. Meanwhile, the difference is not significant at the lower natural period but quite significant at the natural period between 1 and 2 seconds.

4 DISCUSSION

4.1 Palu

The results showed that the application of PSHA at Palu site is much more conservative than DSHA, specifically for low-rise buildings with a low natural period as indicated in Figure 7a. Meanwhile, there was no significant difference in UHS and Deterministic Spectra for high-rise buildings with a natural period of more than 2 seconds.



(a)

(b)

(c)

Figure 7 UHS (Uniform Hazard Spectra) and Deterministic Spectra for Three Locations (a) Bandung, (b) Palu, and (c) Yogyakarta

4.2 Bandung

Figure 7b shows that PSHA was more conservative than DSHA at Bandung site. This was indicated by the placement of UHS above Deterministic Spectra and this means Lembang Fault has the potential to provide more impact on the low-rise buildings. It was also noted that PSHA is significantly more conservative on a longer period, specifically between 1 and 2 seconds.

Sari and Fakhrurrozi (2020) applied PSHA in Bandung Basin and PGA presented in Figure 8 showed that the sampling locations were far from Lembang Fault. However, it is interesting to note that PGA obtained from the spatial interpolation near Lembang Fault was estimated at 0.5 g and this is similar to the value obtained in this research. This means it is possible to adopt the PGA map from Sari and Fakhrurrozi (2020) to determine PGA located near the fault.

4.3 Yogyakarta

Figure 7c shows that PSHA was also more conservative than DSHA at Yogyakarta site, but the difference is not significant at the lower period. Putra et al. (2018) also applied DSHA to construct a seismic hazard map. Their results showed PGA surface map around Opak Fault ranged from 1.1 to 1.2 while the amplification factors vary widely from 0.5 to 0.4. This indicated a large variation of bedrock PGA. The surface PGA and amplification factor obtained from the study area by Putra et al. (2018), respectively. This means the bedrock PGA is approximately 0.5 g which is very close to the value obtained using DSHA. According to Putra et al. (2018), the entire area near Opak Fault is at high risk of seismicity.

5 CONCLUSION

This study compared PSHA and DSHA on the occurrence of earthquake near-fault areas. There is a consistent trend of UHS from PSHA being more conservative than Deterministic Spectrum (DSHA) for all the sites studied. This is associated with the greater impact of all surrounding faults compared to the closest specific fault from the respective sites.There was a significant difference between UHS and Deterministic Spectra at a short period in Palu but recorded at natural periods between 1 and 2 seconds for Bandung and Yogyakarta.

DISCLAIMER

The authors declare no conflict of interest.

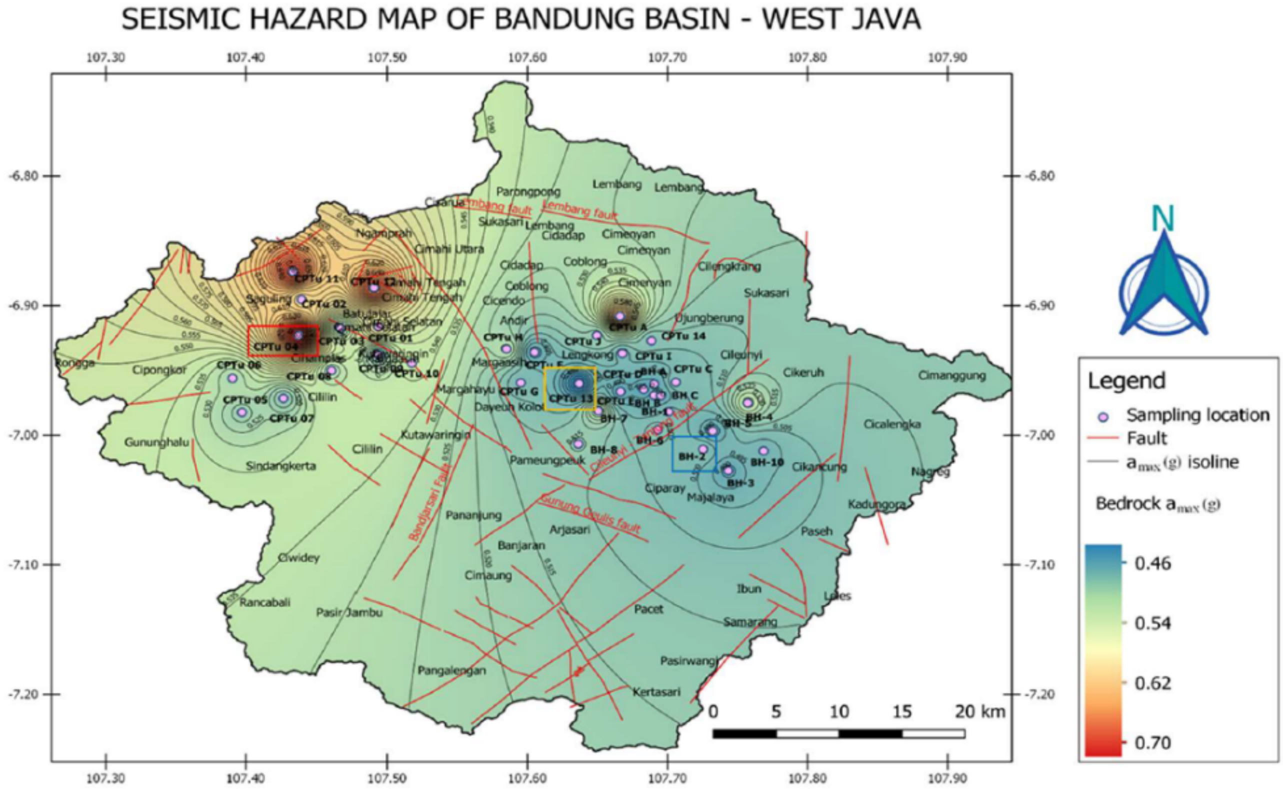


Figure 8 Seismic hazard map of Bandung Basin (Sari and Fakhrurrozi, 2020)

REFERENCES

Abrahamson, N., Gregor, N. and Addo, K. (2016), ‘BC Hydro Ground Motion Prediction Equations for Subduction Earthquakes’, *Earthquake Spectra* **32**(1), 23–44.

Adelayanti, N. (2020), Reflections and Lessons from the 2006 Jogja Earthquake, PhD thesis, Universitas Gadjah Mada.

ASCE (2017), Minimum Design Loads and Associated Criteria for Buildings and Other Structures, American Society of Civil Engineers.

Atkinson, G. M. and Boore, D. M. (2003), ‘Empirical Ground-motion Relations for Subduction-zone Earthquakes and Their Application to Cascadia and Other Regions’, *Bulletin of the Seismological Society of America* **93**(4), 1703–1729.

Baker, J. W. (2008), ‘An Introduction to Probabilistic Seismic Hazard Analysis (PSHA)’, *White paper, version* **1**, 72.

Boore, D. M., Stewart, J. P., Seyhan, E. and Atkinson, G. M. (2014), ‘NGA-West2 Equations for Predicting PGA, PGV, and 5% Damped PSA for Shallow Crustal Earthquakes’, *Earthquake Spectra* **30**(3), 1057–1085.

Chiou, B. S.-J. and Youngs, R. R. (2014), ‘Update of The Chiou and Youngs NGA Model for The Average Horizontal Component of Peak Ground Motion and Response Spectra’, *Earthquake Spectra* **30**(3), 1117–1153.

Cilia, M. G., Mooney, W. D. and Nugroho, C. (2021), ‘Field Insights and Analysis of The 2018 Mw 7.5 Palu, Indonesia Earthquake, Tsunami and Landslides’, *Pure and Applied Geophysics* **178**(12), 4891–4920.

Consultative Group on Indonesia (2006), *Preliminary Damage and Loss Assessment: Yogyakarta and Central Java Natural Disaster*, Consultative Group on Indonesia.

Cornell, C. A. (1972), ‘Engineering Seismic Risk Analysis’, *Bulletin of the seismological society of America* **58**(3), 311–313.

Daryono, M. R., Natawidjaja, D. H., Sapiie, B. and Cummins, P. (2019), ‘Earthquake Geology of The Lembang Fault, West Java, Indonesia’, *Tectonophysics* **751**, 180–191.

Eftekhari, S. N., Sayyadpour, H. and Kowsari, M. (2021), 'A near-fault Probabilistic Seismic Hazard Assessment for Yasouj, Located in The Kazerun Fault System, Southwest Iran', *Natural Hazards* **105**, 1945–1961.

Fugro (2021), *Ez-Frisk User's Manual*, Fugro Consultants Inc. Houston, TX.

Gardner, J. and Knopoff, L. (1974), 'Is the Sequence of Earthquakes in Southern California, with Aftershocks Removed, Poissonian?', *Bulletin of the seismological society of America* **64**(5), 1363–1367.

Knopoff, L. and Gardner, J. (1972), 'Higher Seismic Activity During Local Night on The Raw Worldwide Earthquake Catalogue', *Geophysical Journal International* **28**(3), 311–313.

Kramer, S. L. (1996), *Geotechnical Earthquake Engineering*, Pearson Education India.

Krinitzsky, E. L. (2003), 'How to Combine Deterministic and Probabilistic Methods for Assessing Earthquake Hazards', *Engineering Geology* **70**(1-2), 157–163.

Moratto, L., Orlecka-Sikora, B., Costa, G., Suhadolc, P., Papaioannou, C. and Papazachos, C. (2007), 'A Deterministic Seismic Hazard Analysis for Shallow Earthquakes in Greece', *Tectonophysics* **442**(1-4), 66–82.

Pailoplee, S., Sugiyama, Y. and Charusiri, P. (2009), 'Deterministic and Probabilistic Seismic Hazard Analyses in Thailand and Adjacent Areas Using Active Fault Data', *Earth, planets and space* **61**, 1313–1325.

PUSGEN (2018), 'Kajian Gempa Palu Provinsi Sulawesi Tengah 28 September 2018 (M7. 4)', *Pusat Studi Gempa Nasional, Balitnamg PUPR* .

Putra, M. F. N. et al. (2018), 'Analisis Site Effect Berdasarkan Data Mikrotremor Dan Nilai Peak Ground Acceleration Pada Sesar Opak, Kabupaten Bantul Daerah Istimewa Yogyakarta'.

Rasmid, R. (2014), 'Aktivitas Sesar Lembang Di Utara Cekungan Bandung', *Jurnal Meteorologi Dan Geofisika* **15**(2).

Sari, A. M. and Fakhrurrozi, A. (2020), 'Seismic Hazard Microzonation Based on Probability Seismic Hazard Analysis in Bandung Basin', *RISET Geologi dan Pertambangan* **30**(2), 215–228.

SNI 1726 (2019), 'Tata Cara Perencanaan Ketahanan Gempa untuk Struktur Bangunan Gedung dan Nongedung'.

USGS (2022), 'Earthquake Lists, Maps, and Statistics'. Last accessed April 2022.
URL: *https://earthquake.usgs.gov/earthquakes/search/*

Vaziri, J., Soleymani, A., Hasani, H., Mosavi Nezhad, S. M. and Momivand, K. (2022), A Comprehensive Review on Deterministic Seismic Hazard Analysis (DSHA) and Probabilistic Seismic Hazard Analysis (PSHA) Methods, PhD thesis.

Wang, Z. (2011), 'Seismic Hazard Assessment: Issues and Alternatives', *Pure and Applied Geophysics* **168**, 11–25.

Youngs, R., Chiou, S.-J., Silva, W. and Humphrey, J. (1997), 'Strong Ground Motion Attenuation Relationships for Subduction Zone Earthquakes', *Seismological research letters* **68**(1), 58–73.

Zhao, J. X., Zhang, J., Asano, A., Ohno, Y., Oouchi, T., Takahashi, T., Ogawa, H., Irikura, K., Thio, H. K., Somerville, P. G. et al. (2006), 'Attenuation Relations of Strong Ground Motion in Japan Using Site Classification Based on Predominant Period', *Bulletin of the Seismological Society of America* **96**(3), 898–913.

[This page is intentionally left blank]