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A new approach to structural seismic responses in Mataram City: Based on the Probabilistic Seismic Hazard Analysis (PSHA) results obtained after Lombok earthquakes 2018

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Abstract. In the last few years, several major earthquakes in Indonesia have provided enough reasons for updating the existing building seismic resistance code. SNI 1726-2019 is the latest Indonesia seismic code. However, the variation of Probabilistic Seismic Hazard Analysis (PSHA) results due to the 2018 Lombok Earthquake has been disregarded in this code because it adopts the 2017 seismic maps from National Center for Earthquakes Studies. This study investigated spectral acceleration parameters according to previous seismic codes (SNI 1976-2012) and current seismic codes (SNI 1976-2019) as well as the PSHA results obtained after the Lombok earthquakes in 2018. Spectral accelerations were applied to a building structure located in Mataram City to analyze the seismic building responses. The results indicate that seismic parameters of PSHA result associated with Lombok earthquakes yield structures of higher seismic demand than SNI 1726-2012 or SNI 1726-2019 codes, especially for structures located in medium soil type. The current code needs to be improved immediately to promote resilience and resistance against earthquakes in this area.

1. Introduction

A series of Lombok earthquake events in 2018 were triggered by upward fault activities in the north of Lombok. The activities generated six earthquakes that had a magnitude greater than 5.5. Furthermore, apart from earthquakes of relatively smaller magnitudes, the National Agency for Meteorology, Climatology, and Geophysics recorded that aftershocks with a lower magnitude were more than 2000 events. The first earthquake began with a magnitude of 6.4 on July 29, 2018. Then, on August 5, 2018, an earthquake with a magnitude of 6.9 at a hypocenter depth of 34 km again hit the northern part of Lombok. Four days later, on August 9, 2018, an earthquake with a magnitude of 5.9 occurred, with the center taken to the west. Ten days later, on August 19, 2018, two large earthquakes with a magnitude of 6.3 occurred in the afternoon at a hypocenter depth of 7.9 km and a magnitude of 7.0 (later updated to a magnitude of 6.9) occurred at night at a hypocenter depth of 25 km with a position to the east. The sixth earthquake with a magnitude of 5.5 occurred on August 25, 2018, centered on the east of Lombok. Figure 1 shows the topography and tectonic areas of Indonesia where the island of Lombok is indicated by a red circle [1]. Then, the occurrence of six major earthquakes is explained in Figure 2 as

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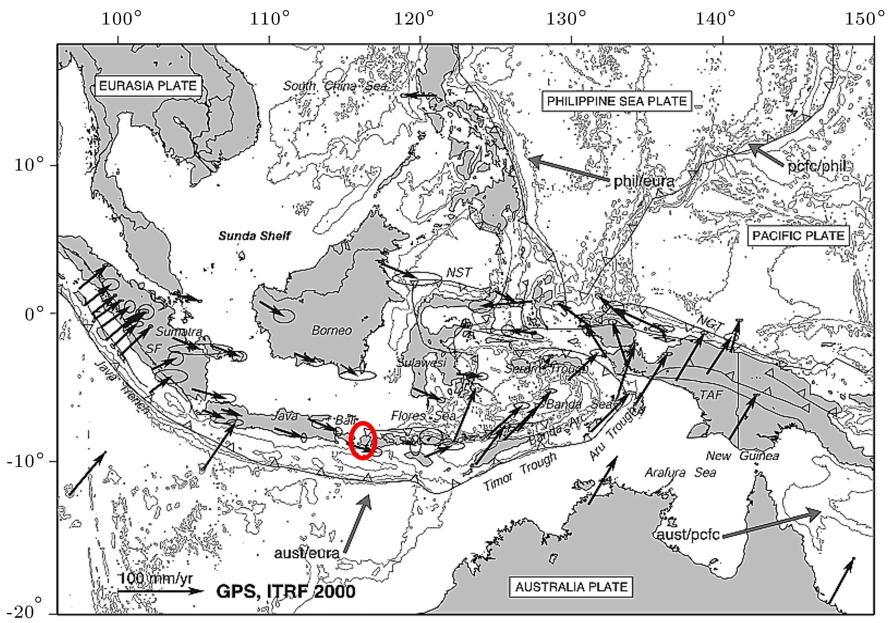


Figure 1. Topography and tectonics of the Indonesia region with the Island of Lombok in a red circle [1].

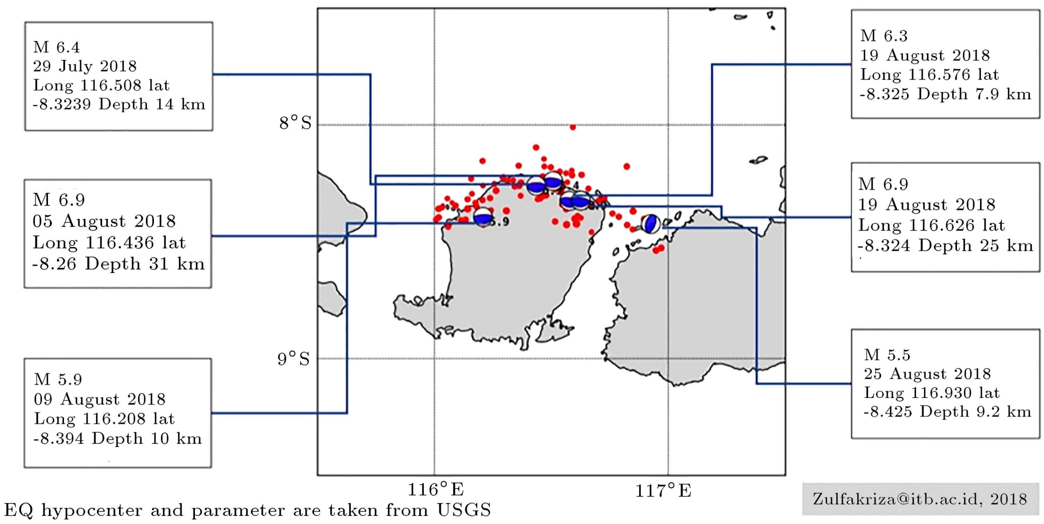


Figure 2. Distribution of Lombok earthquake occurrence [2].

a black circle and blue inside; meanwhile, the red circle provides the distribution of aftershocks that occurred from July 29 September 10, 2018. The USGS catalog presents the focal mechanism of earthquake and hypocenter data [2]. According to the national disaster management agency, this series of earthquakes damaged buildings including 71962 damaged houses, 671 damaged educational facilities, 52 health facilities, and 128 prayer facilities. They even collapsed in some areas including Mataram City [2–6].

The significant scope of damage to building structures caused by strong earthquakes has inevitably urged the government to renew the existing building seismic-resistant design code. Changes in the code carried out by the government worldwide are intended to accommodate the latest earthquake events [7–17]. This includes evaluation of seismic performances in existing structures after such large earthquakes stroke the countries [18–22]. In Indonesia, one of the government's seismic codes was SNI 1726-2002 [23] and then, it was updated to SNI 1726-2012 [24]. The latest version was published in 2019 [25].

In the case of SNI 1726-2002, the seismic hazard map was divided into six earthquake zones, each of which was classified based on the peak acceleration of the bedrock and had the same response design spectrum. However, based on the latest geological studies of the earth's plate, which influenced the earthquake region, the code was improved into SNI 1726-2012. According to this code, each region or location has a different response design spectrum because it was already determined based on the ground motion parameters, S_S and S_1. Peak Ground Acceleration (PGA) of SNI 1726-2002 is based on a 10% probability that it will be exceeded in 50 years. The return period was 500 years. After several great earthquakes, there was a change in the Indonesian seismic hazard map; therefore, this code was replaced by SNI 1976-2012. The replacement of the seismic code has a peak ground motion with a 2% probability of being exceeded in 50 years or with a return period of 2475 years for spectral acceleration. The seismic hazard map is updated and the latest seismic code, SNI 1976-2019, is produced. The seismic spectral acceleration is based on the 2017 seismic hazard map National Earthquake Center [26,27].

The National Center for Earthquake Studies updated the National Earthquake Map in 2017. A series of research results, studies, and publications related to Indonesia's latest earthquake source parameters, including geology in some areas and earthquake relocation data, have significantly contributed to updating the source maps and the cases of hazards. Therefore, SNI 1726-2012 was renewed to SNI 1726-2019 and it has become the current seismic code in Indonesia. In this code, some major earthquake-prone areas exhibit increased spectral acceleration [27,28]. However, changes in spectral acceleration are not significantly detected for the area like Mataram City that has not been affected much through seismic occurrence. In fact, strong earthquakes in 2018 stroke Lombok area. The increase in the spectral acceleration is not so sharply seen in Lombok because SNI 1976-2019 accommodated the 2017 earthquake map.

According to the referenced research [29], theoretically, spectral acceleration is the uncertainty associated with the building collapse caused by earthquakes. The structures exhibit resistance without collapsing, depending on the spectral acceleration produced according to ground motion characteristics. In the case of the Lombok earthquake in 2018, many damaged structures were found even in Mataram City, a major city in Lombok Island, which was located around 47 km away from the largest epicenter of the earthquake series. Probabilistic Seismic Hazard Analysis (PSHA) results obtained based on the Lombok earthquakes strongly influenced the spectral acceleration, as determined in [30,31].

Considering the 2018 Lombok earthquakes, an analysis was conducted based on PSHA using a detailed tectonic background and appropriate ground motion equations. The analysis managed to determine the seismic parameters that are more suitable for the ground motion due to a strong earthquake, and the result was compared with the model outcome published by the National Center for Earthquake Studies in 2017. The sources used in the National Center for Earthquake Studies include subduction, back-arc, and strike-slip faults for Lombok and surroundings. Meanwhile, in 2018, the case of Lombok earthquake used only subduction and back-arc, given their dominance. The earthquake data records used in the Lombok earthquake model remained valid up to 2018, while the data used in National Center for Earthquake Studies model were valid up to 2016. Thus, a and b values were updated to a greater degree in the recent Lombok earthquake 2018 model. However, the ground motion equations of the National Center for Earthquake Studies and the Lombok earthquake 2018 are nearly identical. Furthermore, it was found that Lombok and its surrounding islands exhibited a significant seismic hazard compared to the model presented by the National Earthquake Study Center in 2017, because the model was estimated before the 2018 earthquake. Therefore, updating the seismic hazard map for Lombok and surrounding islands was proposed by considering the impacts of strong earthquakes [30].

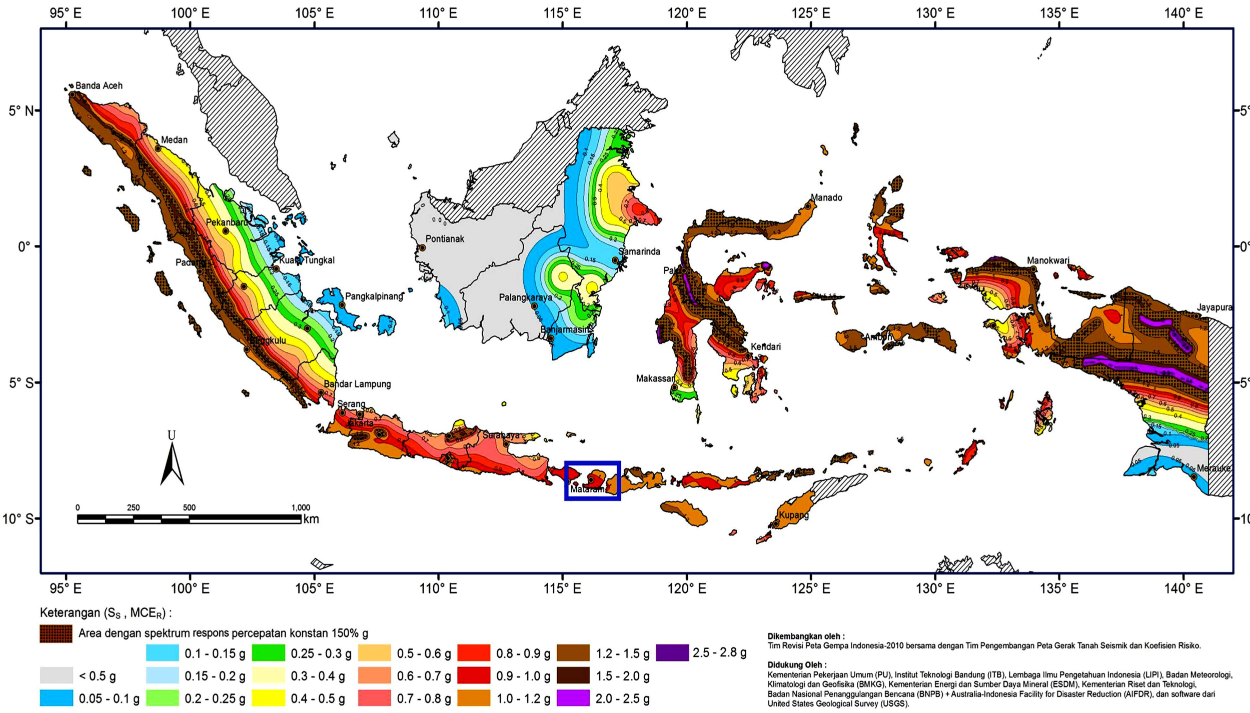
Furthermore, the effect of the 2018 Lombok earthquake PSHA results on the seismic coefficient C_S of buildings was reported in [31]. It was described that due to the impact of the large earthquake, C_S increased in Mataram City by 10.8% for medium soil compared to the C_S calculated using the applicable SNI at that time, namely SNI 1976-2012. Increase in C_S was found to be much greater for soft soil, which was 13.2%. It is recommended that the seismic code be updated by considering the ground motion due to the Lombok earthquake.

In this paper, the seismic design parameters of the spectral acceleration due to the Lombok 2018 earthquake are compared with the latest code, namely SNI 1976-2019. The change in spectral acceleration must definitely affect the building seismic demand parameters. A comprehensive overview of the performance of the structures due to the change of spectral acceleration is done in terms of lateral force and building displacement of a four-story building located in Mataram City. The approaches established based on previous national seismic codes, SNI 1976-2012, are included.

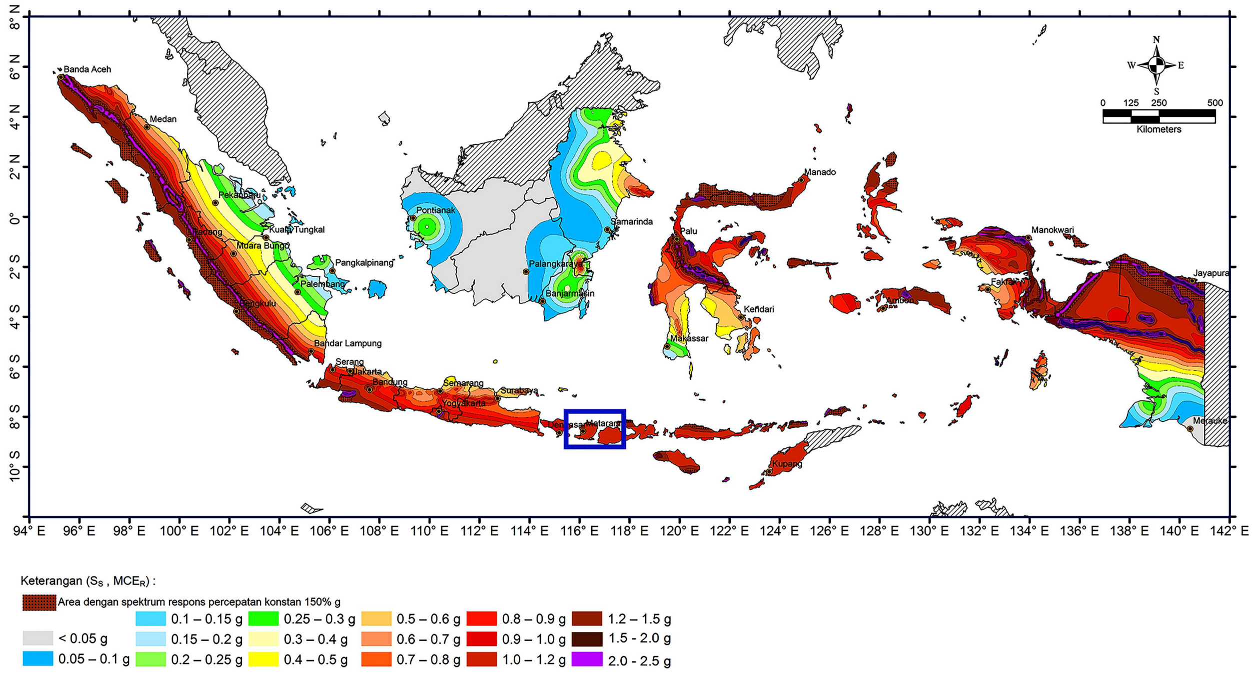
2. Materials and methods

2.1. Seismic acceleration map

The seismic design maximum acceleration maps of the bedrock for a short time period ($T = 0.2$ s (S_S)) and a long time period ($T = 1$ s (S_1)) with a 2% probability of being exceeded in 50 years are provided by SNI 1726-2012 and SNI 1726-2019 codes, as presented in Figures 3 and 4, respectively. Figure 3 shows the spectral acceleration maps in bedrocks for a short period, $T = 0.2$ s, from SNI 1976-2012 and SNI 1976-



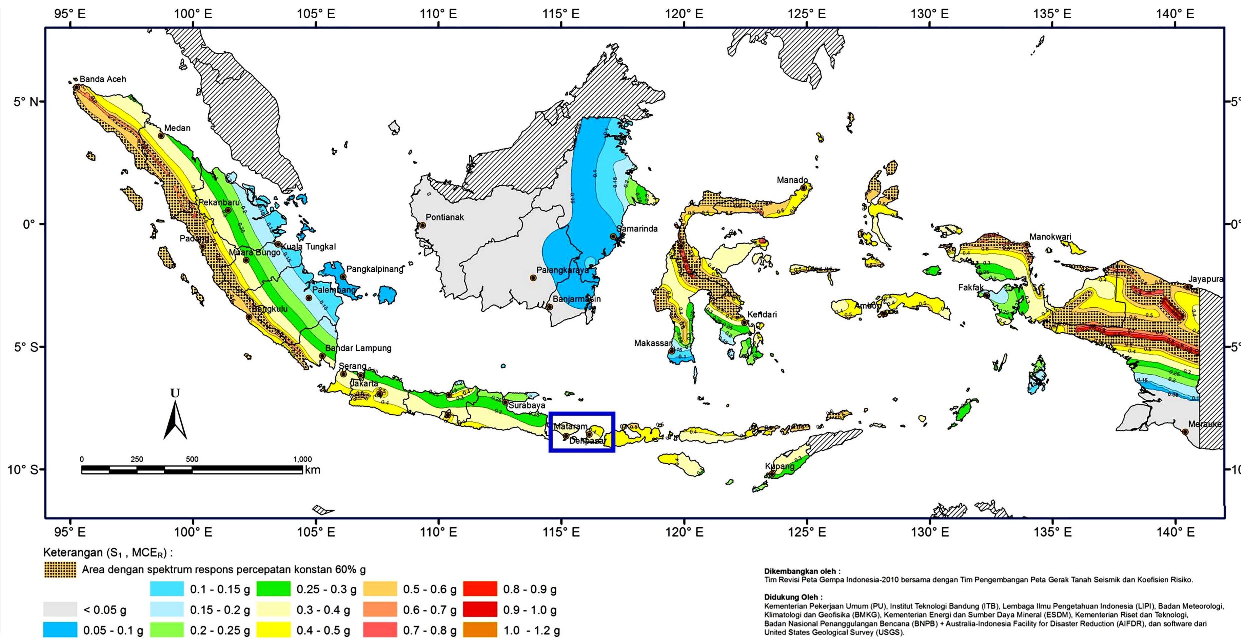
(a) SNI 1976-2012



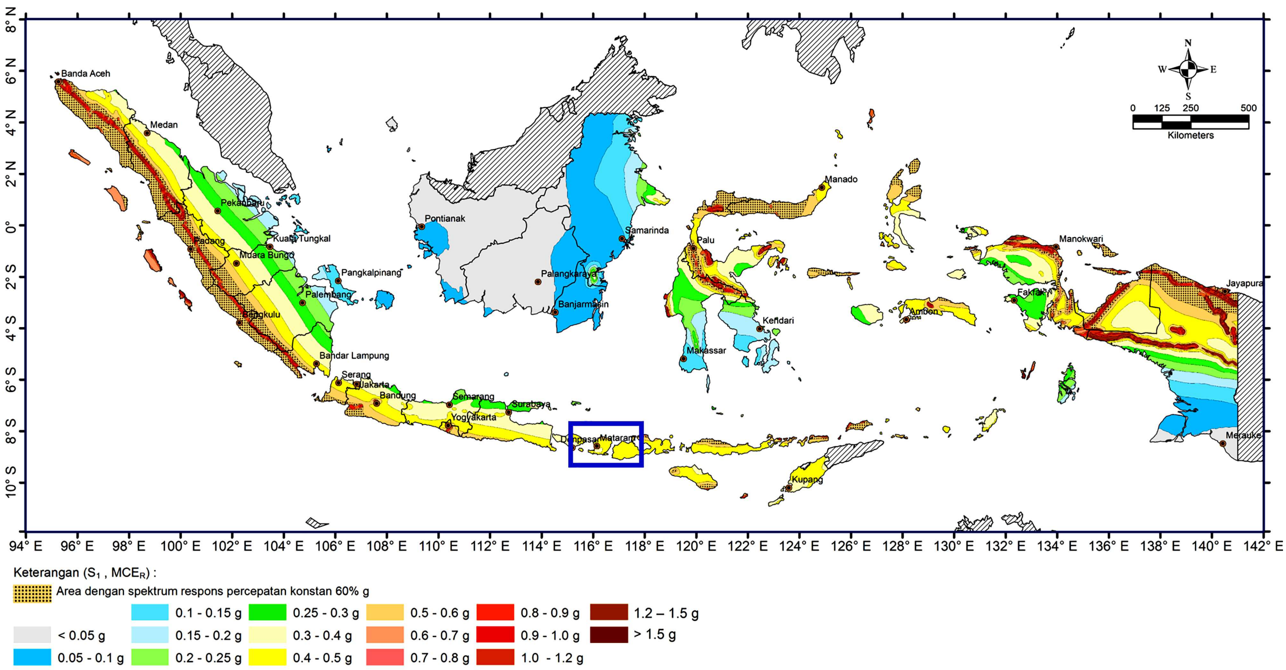
(b) SNI 1976-2019

Figure 3. Spectral acceleration maps in bedrocks for the short period, $T = 0.2$ s, from SNI 1976–2012 [24] and SNI 1976–2019 [25].

2019. Meanwhile, Figure 4 shows spectral acceleration maps in bedrocks for a long period, $T = 1$ s, from SNI 1976-2012 and SNI 1976-2019. In Figures 3 and 4, the locations of Lombok and its surroundings are marked by a blue box shape. The seismic acceleration map in bedrock based on the PSHA results obtained after the Lombok earthquake is given in Figure 5 which consists of maps for short and long periods. The epicenter location of a series of earthquakes was in Lombok in 2018 and is marked by a blue circle on the map. The earthquake data set was collected from United States Geological Survey (USGS), International Seismological



(a)



(b)

Figure 4. Spectral acceleration maps in bedrocks for the long period: $T = 1$ s, from (a) SNI 1976–2012 [24] and (b) SNI 1976–2019 [25].

Centre (ISC), and in Indonesian: Badan Meteorologi, Klimatologi, dan Geofisika (BMKG) for a period of 1922 to 2018. The earthquake with a magnitude M_w of 4.5 was considered for the spectral acceleration calculation because this magnitude is a standard for earthquakes related to seismic disaster risk.

Based on the spectral acceleration maps in bedrocks using the three approaches described earlier and the soil amplification factor of the building site location, the maximum spectral acceleration was calculated for short (S_{MS}) and long (S_{M1}) periods. Once the S_{MS} and S_{M1} were obtained, the design spectral accelerations, S_{DS} and S_{D1}, were calculated for the short and long periods, respectively. Furthermore, the response spectrum curve was generated according to S_{DS} and S_{D1}. The designed response spectrum was then applied to evaluate the seismic responses of the intended buildings.

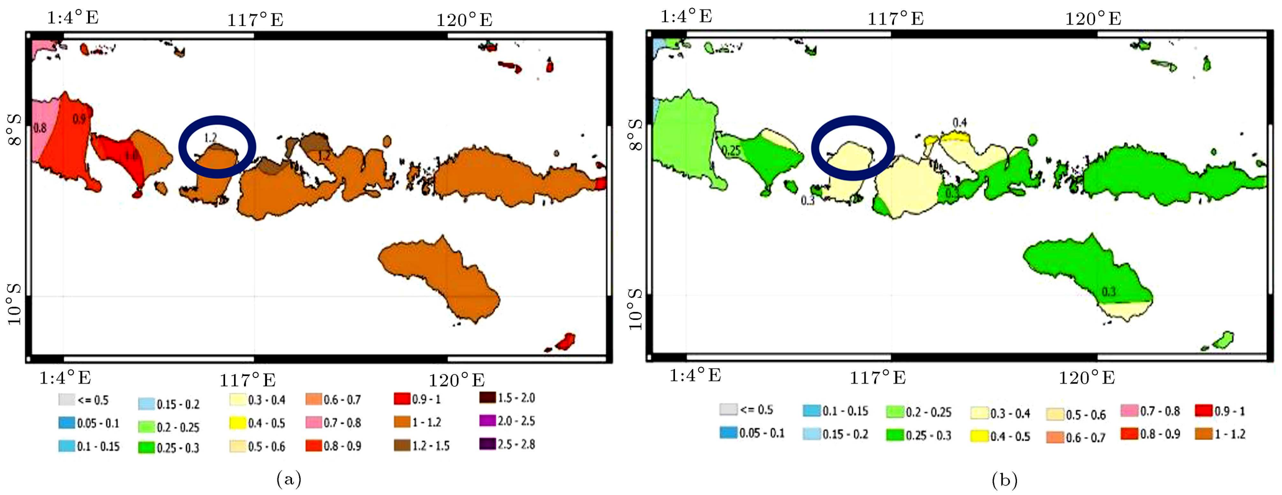


Figure 5. Lombok earthquake spectral acceleration maps in bedrocks for Mataram and surroundings: (a) for short period, $T = 0.2$ s and (b) for long period, $T = 1$ s [30,31].

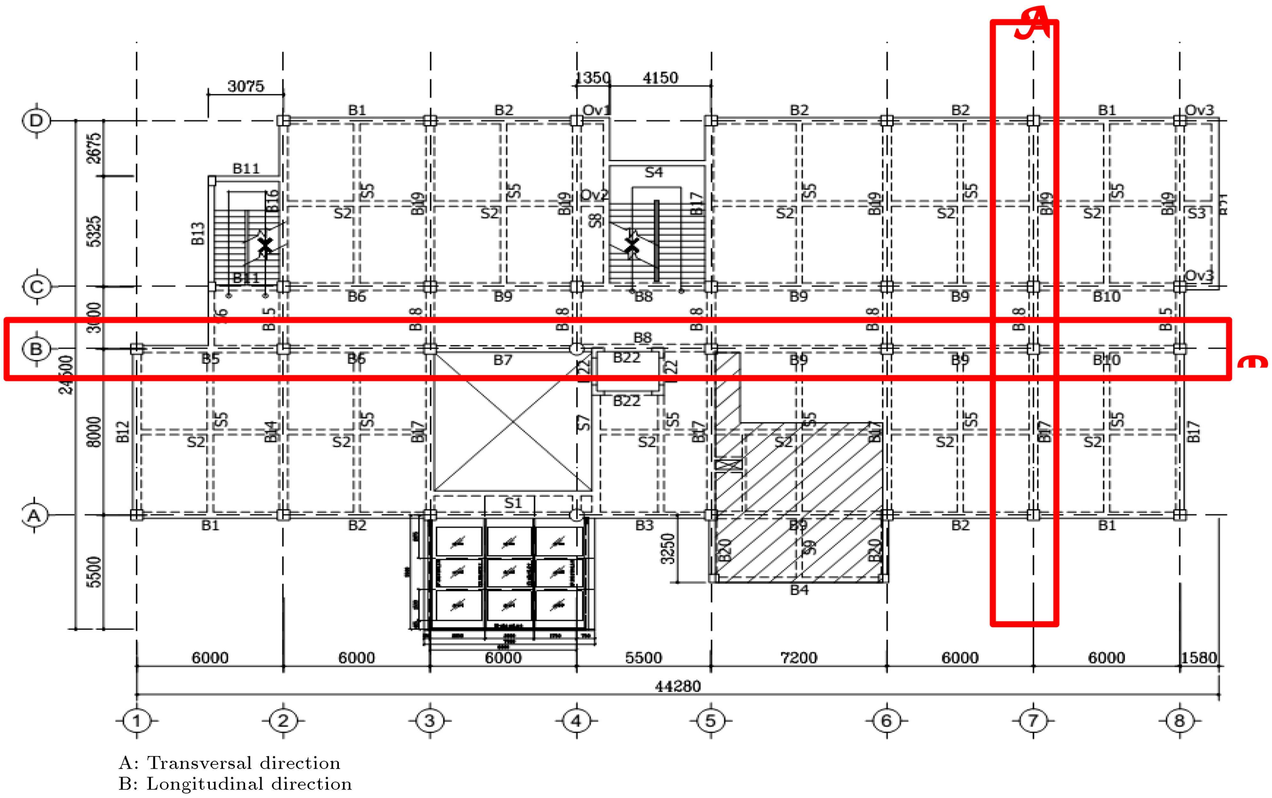


Figure 6. Plan of building in each story and the overview frame.

2.2. *Building configuration*

The designed response spectrum was produced using three earthquake acceleration maps: SNI 1726-2012, SNI 1726-2019, and PSHA results obtained after Lombok earthquakes mentioned earlier. The differences in the design spectral acceleration were considered and applied as the parameter for analyzing the seismic response coefficient and structural responses.

Seismic coefficient and structural responses were observed at Mataram State Islamic University, which is located in Mataram City at coordinates of latitude: −8.610232 and longitude: 116.100845. This educational building represents a four-story reinforced concrete structure. The height of each story is 3.9 m. The longitudinal direction consists of 8 spans with a total length of 44.28 m. Meanwhile, four spans are in the transversal direction, with the total span length of 24.5 m. The overview frame in longitudinal and transversal directions used for seismic structural analysis is shown in Figure 6.

3. Results and discussion

3.1. Spectral acceleration parameter

According to the referenced study [32], the shear wave velocity in the surface sediment layer in Mataram City ranged between 135 m/s and 201 m/s. Therefore, based on the shear wave propagation velocity, Mataram City is included in the SD site class (medium soil) and SE site class (soft soil). The spectral accelerations of this area calculated based on SNI 1726-2012, SNI 1726-2019, and Lombok earthquake 2018 PSHA results are presented in Figure 7(a) for medium soil and SD and Figure 7(b) for soft soil, SE.

From the seismic acceleration map of SNI 1726-2012, it is found that spectral acceleration value of the bedrock acceleration parameters for $T = 0.2$ s (S_S) is 0.966 g and for $T = 1$ s (S_1) is 0.386 g. Meanwhile, based on SNI 1726-2019, S_S and S_1 values increase to 1.1 g and 0.45 g, respectively. The above increase rates are about 14% and 17% for S_S and S_1, respectively. The acceleration value in the case of SNI 1726-2019 is more significant than that in the case of SNI 1726-2012 because some major earthquakes occurred in some areas in Indonesia between 2012 and 2017. As described earlier, the 2017 seismic acceleration maps from the National Center of Earthquake Studies were incorporated into SNI 1726-2019. However, when the effect of the 2018 Lombok earthquake was considered, the S_S value changed to 1.143 g. This value increased by 18% against the S_S value in the case of SNI 1726-2012 and increased by 4% compared to S_S value from SNI 1726-2019. Meanwhile, the S_1 value changed to 0.309 g, which decreased compared to the S_1 value on both seismic codes.

Furthermore, the values for short-period maximum acceleration (S_{MS}) and short-period design acceleration (S_{DS}) in the case of the Lombok earthquake 2018 PSHA results were found to be higher than those calculated based on SNI 1976-2019. However, at $T =$ 1 s, S_{M1} and S_{D1} are more generous in the case of SNI 1726-2019. This finding holds in the case of both medium and soft soils.

The 2018 Lombok earthquake PSHA result has a more significant impact on short-period spectral acceleration, while both seismic codes have a more significant effect on the long-period spectral acceleration. This is because acceleration in the long period is more influenced by far-field earthquakes, while acceleration in the short period due to the PSHA results obtained from the 2018 Lombok earthquakes is highly affected by near-field earthquakes. The near-field earthquakes tend to occur in shorter periods with higher acceleration. Meanwhile, the far-field earthquakes occur in a more extended period [33,34]. The difference in the value of spectral acceleration for the short period, S_{DS}, and for the long period, S_{D1}, can affect the seismic design category of the building [35,36]. However, S_{DS} value was greater than 0.5 g in the case of either codes or the Lombok earthquake 2018 and the S_{D1} was more significant than 0.2 g. Thus, there is no change in the seismic design category of the three approaches, namely remaining in the D-seismic design category. A building in this category needs a more detailed design in reinforcement due to possible severe ground shaking [35].

3.2. Response design spectrum curve

In principle, the typical shape of the response design spectrum between both codes and the 2018 Lombok earthquake PSHA results is substantially similar, as shown in Figure 8. Figure 8(a) describes medium soil, while Figure 8(b) describes soft soil. SNI 1726-2019 considered the existence of a more extended period on the spectral response curve. In both medium and soft soils, PSHA results obtained based on Lombok earthquakes had a greater spectral acceleration in short periods. For medium soils, the highest acceleration of the SNI 1726-2019 response design spectrum curve

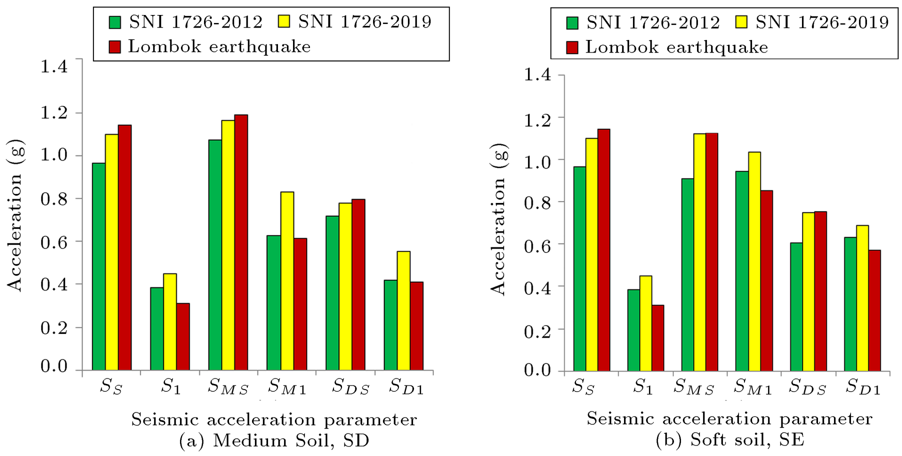


Figure 7. Spectral acceleration parameters.

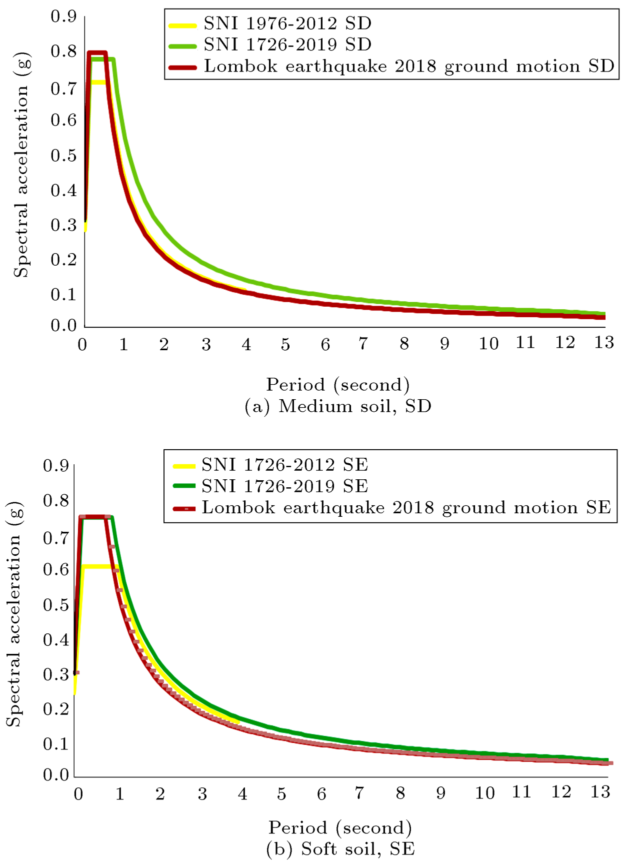


Figure 8. Response spectrum curve.

was 0.777 g, observed in the range of 0.143 s to 0.714 s. Higher acceleration was found in the Lombok earthquake's response design spectrum, i.e., 0.795 g, over a more extended period, from 0.103 s to 0.516 s. The outdated code, SNI 1726-2012, gives the lowest acceleration on the curve peak.

Considering the spectral acceleration of the soft soil, it is observed that the acceleration peaks of the curve are lower than those that occurred in medium soil among the three response design spectrum curves. The value of spectral acceleration in soft soil is generally significantly higher than that in medium soil. This finding holds in the case of Mataram City for the long-term period only. However, in the short period, the spectral acceleration value in soft soil is observed to be lower. This anomaly occurs because the short-period amplification factor in medium soils is lower than that in soft soils. The anomaly in which case the SNI-1726-2019 spectral acceleration design of soft soil is lower than that of medium soil was observed in 17 regions. It was found that even the spectral acceleration of the site class of hard soil (SC) was higher in earthquake-prone areas [28].

3.3. Seismic response coefficient, C_S

Seismic response coefficient (C_S) is used to calculate the building's base shear in static equivalent analysis. This coefficient is a function of several building parameters, consisting of spectral acceleration design, building fundamental period of vibration, building importance factor related to the building occupancy category, and building response modification factor which is determined based on the building type of seismic force-resisting system [24,25,36,37].

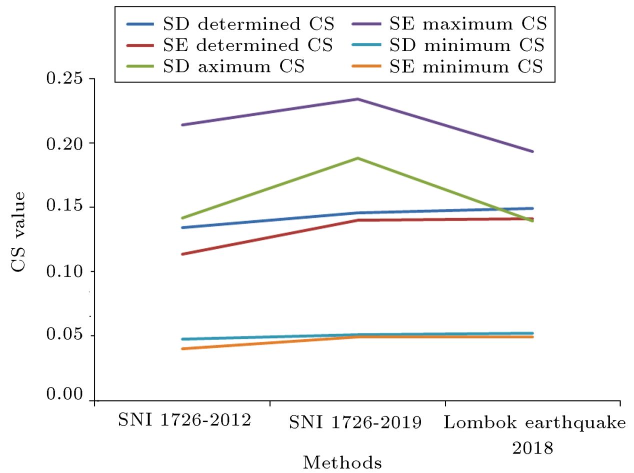


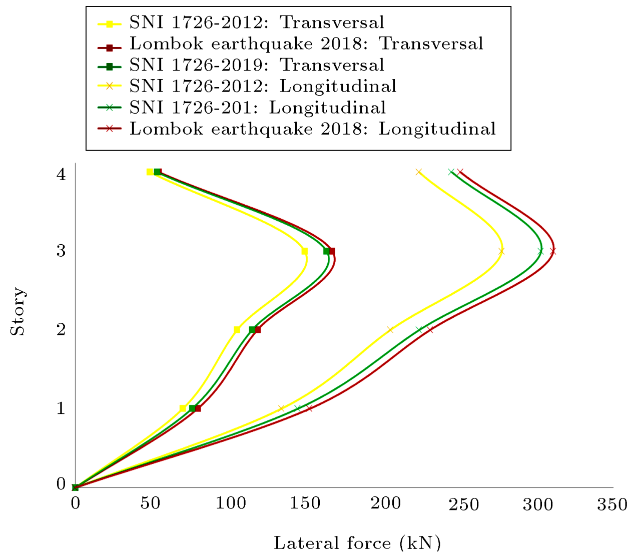
Figure 9. C_S value determined by the three approaches.

In this study, C_S value is determined under several conditions: risk category for educational facilities = 4; importance factor = 1.5; and response modification factor = 8. According to Figure 9, the determined C_S and minimum C_S values are lower than the maximum C_S values for medium soils. Meanwhile, in soft soil, the maximum C_S is greater than the determined C_S and minimum C_S. S_{DS} affects the determined C_S and maximum C_S, while S_{D1} affects the maximum C_S. The S_{DS} in medium soil is higher than that in soft soil such that it generates a higher determined C_S and minimum C_S. Likewise, S_{D1} is found to be greater in soft soil; thus, the maximum C_S is found to be greater in soft soil. This trend occurs in both codes due to the 2018 Lombok earthquake.

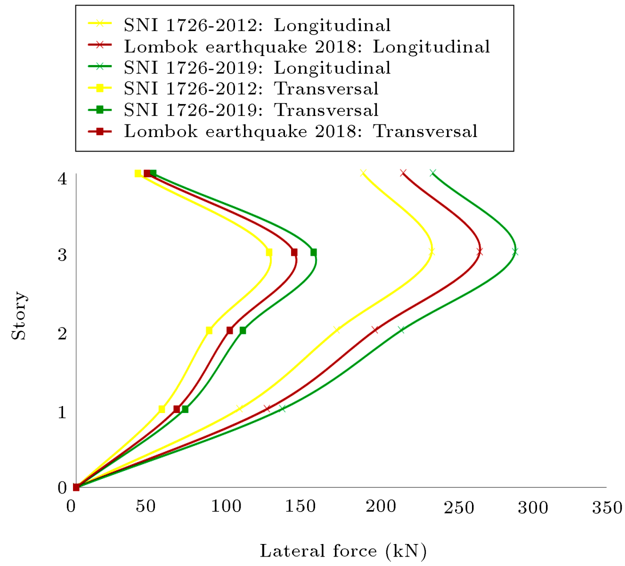
Due to the effect of S_{DS} in the 2018 Lombok earthquake, which is the greatest among the three methods, this method has the highest value on the determined C_S and minimum C_S. However, the highest S_{D1} is found based on SNI 1726-2019 such that the greatest value of maximum C_S has been achieved using this method. In principle, the determined C_S cannot be greater than the maximum C_S and it cannot be lower than the minimum C_S. The determined C_S due to the 2018 Lombok earthquake is slightly greater than the determined C_S in the case of SNI 1726-2019 for both medium and soft soils.

3.4. Building seismic responses

The lateral forces, shown in Figure 10, are measured in the overviewed frame section of longitudinal and transverse directions of the building. In medium soils,

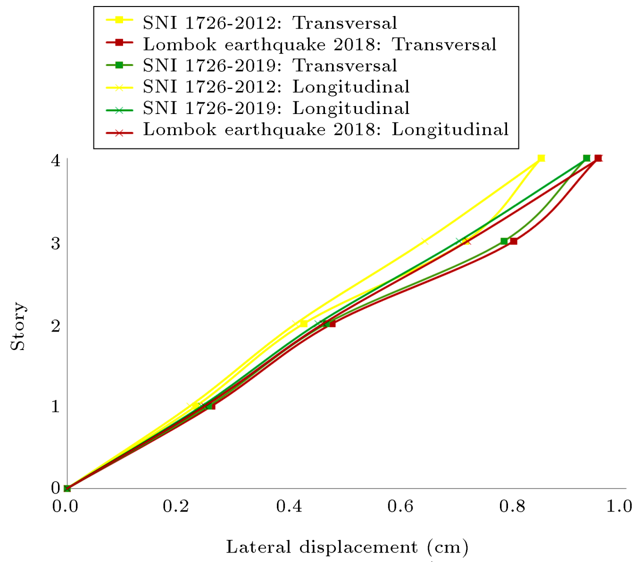


(a) Medium soil, SD

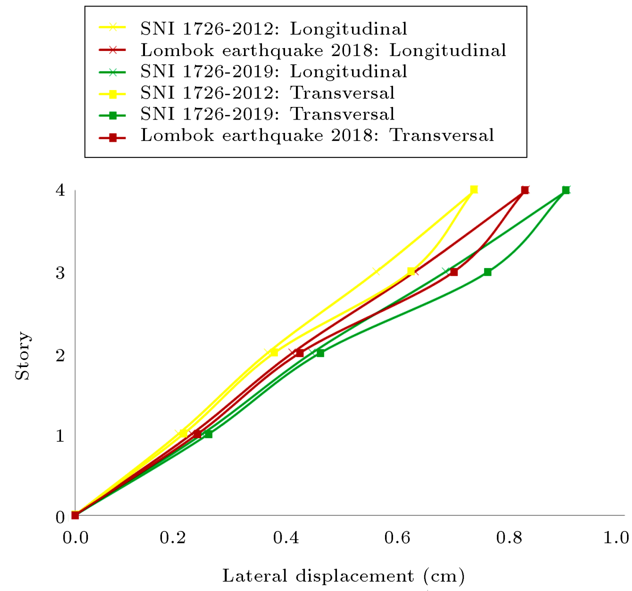


(b) Soft soil, SE

Figure 10. Lateral forces of the overviewed frame section.



(a) Medium soil, SD



(b) Soft soil, SE

Figure 11. Lateral displacement of the overviewed frame section.

as illustrated in Figure 10(a), the most significant lateral force occurs when calculated based on the acceleration of the PSHA results associated with the 2018 Lombok earthquakes.

Minor lateral forces are obtained when calculated by the old code, namely SNI 2012. The lateral force calculated based on the spectral acceleration of the 2018 Lombok earthquake is also more remarkable than that calculated based on SNI 1726-2019. This difference ranges from 2.3% to 5.4%, depending on the story height and direction of the building reviewed.

However, in the case of soft soil (Figure 10(b)), the largest lateral forces are found using SNI 1726-2019 compared with the lateral force calculated based on the acceleration of the PSHA results due to the 2018 Lombok earthquake. This value is 8%–9% greater depending on the story height and direction of the building reviewed. Soft soil generates a long-period response greater than medium soils [38]. Therefore, the lateral force in the case of SNI 1726-2019 is more significant because the spectral acceleration of soft soil in SNI 1726-2019 is greater than the spectral acceleration of soft soil due to the 2018 Lombok earthquake.

A similar phenomenon occurs in the building response in the form of lateral displacement, as shown in Figure 11. On medium soil (Figure 11(a)), the most significant lateral displacement occurred in the calculation with the 2018 Lombok earthquake. However, in soft soil (Figure 11(b)), the lateral displacement value calculated by the SNI 2019 response design spectrum

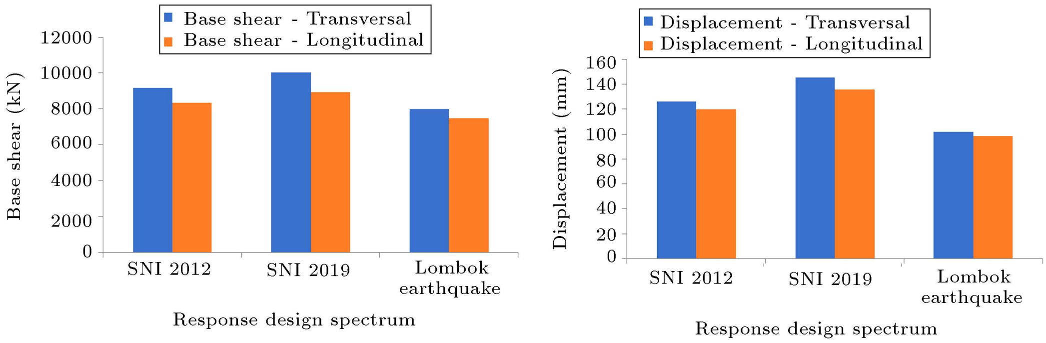


Figure 12. Performance point for base shear and displacement.

was the greatest. Meanwhile, the smallest building lateral displacement was found based on the 2012 response design spectrum.

The seismic response of buildings on medium soil was found to be greater if the response design spectrum for the PSHA results of the 2018 Lombok earthquake was used in the calculation compared to the two seismic codes in Indonesia.

Furthermore, the performance-based design evaluated using pushover analysis was added in order to present the building capacity. According to the analysis, upon the application of the three-response design spectrum of the medium soil, clearly SNI 2019 determined higher base shear and displacement. However, according to the performance level illustrated in Figure 12, the three-response design spectra exhibited the same performance level, called immediate occupancy. Immediate occupancy implies that the structure remains safe and only sustains minimal damage during the occurrence of an earthquake. Strength and stiffness are approximately equal to those in pre-earthquake conditions. In addition, the vertical and lateral structural resisting systems are still capable of sustaining earthquake load [36].

All efforts made to reduce earthquake damage and risk need to be carried out with preventive measures for disaster management. One of the efforts made is updating the Earthquake Hazard Map, which is usually updated every year or after such a strong earthquake stroke. For Indonesia, the updating attempt is made no later than every five years [26]. In this paper, although there is only a 4% increase in the short-period bedrock acceleration, it is necessary to update the map because it has existed for five years. Moreover, using the PSHA results obtained from the Lombok earthquakes, the design response spectrum increases the seismic building responses. In addition, some new fault characterizations have been studied following the sequence of the Lombok 2018 earthquakes [39,40]. Therefore, updating of the earthquake map is suggested for the next Indonesian code in this area to improve seismic mitigation. Seismic code updates provide preparation measures for new buildings and strengthen the existing one to ensure better structural seismic responses to future earthquakes. Other studies have made similar recommendations concerning the reduction of seismic disaster risk in this area [5,6,30,31,41].

4. Conclusions

The bedrock acceleration in the short period (S_S) in the order of the greatest to the smallest was obtained at 1.143 g based on the Probabilistic Seismic Hazard Analysis (PSHA) results from the 2018 Lombok earthquakes, 1.1 g from the SNI 1726-2019 seismic map, and 0.966 g based on the SNI 1726-2012 earthquake map. Meanwhile, the highest value of the bedrock acceleration in the long period (S_1) was found in the case of SNI 1726-2019. The outdated code, SNI 1726-2019, provided the lowest bedrock acceleration.

In principle, the typical shape of the response spectrum between both codes and the 2018 Lombok earthquake ground motion is similar. In both medium and soft soils, Lombok earthquake PSHA results had a higher spectral acceleration value in the short period, while SNI 1726-2019 had a prominent presence for the long period on the response design spectrum curve.

Given the effect of the higher value of S_{DS} on either medium or soft soil, the determined seismic response coefficient, C_S, due to the PSHA results of the 2018 Lombok earthquake was slightly more significant than the determined C_S analyzed by SNI 1726-2019. In addition, the building seismic response in terms of lateral forces and displacements on medium soil was greater when analyzed using the response spectrum due to the PSHA results obtained from the Lombok earthquakes. Furthermore, it is essential that the seismic codes be updated by considering the effect of the Lombok 2018 earthquake to support reducing the risk of earthquake disasters in the future.

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