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Assessment of Seismic Loss in Surakarta School Buildings

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Abstract Surakarta is a relatively small yet is categorized as a densely populated city. There are a lot of types of public buildings, such as hospitals, supermarkets, government infrastructures, and school buildings. The city has more than 1100 school buildings threatened by many potential earthquakes. The possibility of an earthquake hitting Surakarta may be fatal and cause significant losses of buildings. However, studies on seismic hazard of the city are still very rare and need more attention. This paper presents a recent study on the seismic loss assessment of school building in Surakarta. The survey has been conducted by a team to visit, check, record and document all the required information to obtain exposure, combined with the information from google map application, while the seismic hazard analysis was carried out using the event-based stochastic method. An open-source application, OpenQuake, was utilized to assess the seismic loss and the results were presented here. The elaborated analysis is presented concluding that the exposure and vulnerability of school buildings are very important factors to determine a risk of loss. It indicates that the wooden school building contributes a highest risk of loss, whereas the confined masonry ones give a lowest risk. Among the whole sub districts in Surakarta, it is assessed that Laweyan suffers the biggest seismic loss of 2.36 million USD due to 500 years return period earthquake and 5.39 million USD due to 2500 years return period earthquake. These results of this study are valuable information for government in order to overcome disaster mitigation policy of Surakarta.

Keywords Event-Based Method, Exposure, Seismic Hazard, Loss Assessment, School Buildings

1. Introduction

The Java Island is one of most seismically active areas in Indonesia. Each year, the region was impacted by more than 20 mediums to large magnitude of earthquakes. The earthquake sources of Java come from active faults which are scattered from the west to the east along the island itself. Some active faults were identified in West Java such as Cimandiri fault, Lembang fault, Cirebon fault and Baribis fault. A lot of faults were found in the Central Java such as Opak fault, Merapi-Merbabu fault, Rawapening fault, Muria fault, Semarang fault and Lasem. In the East Java, there are Pasuruan fault, Probolinggo, and Baluran [1-4]. Java is also threatened by a subduction zone between Australian plate and Eurasia Plate, a larger earthquake potential source located along the southern coast of Java. It has been recorded that within the last 25 years two big earthquakes have been produced from this subduction zone; Pacitan earthquake in East Java (Mw = 7.8, 1994) and Pangandaran earthquake in West Java (Mw = 7.8, 2006) [5, 6]. It can be said that every place and city in this island is threatened by earthquake (either small or large magnitude).

Surakarta city is located at the center of Java Island, (Figure 1). The city is surrounded by some potential earthquake sources such as Opak fault in the west with the slip rate of 5 mm/year, Merapi-Merbabu fault in the southwest with the slip rate of 1 mm/year, Rawapening fault in the north with the slip rate of 0.1 mm/year, and the subduction zone in the south with the movement rate of 5-7cm/year [7, 8]. Unfortunately, more than 500,000 people are living in Surakarta while its area is relatively small (only 46 km^2), resulting in the population density of Surakarta almost 11,000 people/km^2, higher than Semarang, the capital city of Central Java. A lot of private and public infrastructures laid on Surakarta, such as hospitals, supermarkets, schools, and government buildings. This study is focusing on school building loss assessment, whereas other results are presented in other publications. According to Indonesia Statistical Central Bureau, BPS 2021, there are 49 Vocational Senior High schools, 35 Senior High Schools, 73 Junior High Schools, and 267 Elementary Schools, giving the total number of 424 schools in Surakarta [9]. Generally, each school has more than one building, so that the total number of school buildings may reach thousands.

Considering that Surakarta has a large number of school building threatened by potential earthquake, the study on seismic hazard mitigation and earthquake risk on those buildings is required. The aim of this study is to analysis a seismic hazard and seismic risk of school building in Surakarta. The study includes the economic loss assessment for a certain scenario of earthquake.

2. Previous Study

The comprehensive study of earthquake engineering needs the understanding of wide range of sciences such as the vibration theory, seismology, geology, dynamics soil properties, ground motion analysis, probability theory, seismic hazard analysis, wave propagation, and ground response analysis [10]. These branches of science help the engineers to obtain the information of the seismicity of a particular place. Basically, when the earthquake engineers deal with the seismicity of a place, they have to make two main analyses; seismic hazard and seismic risk. Within the last two decades, the engineers have not only been involved in seismic hazard, but also begun to develop a seismic risk. The latter is actually the combination of seismic hazard, vulnerability and exposure [11]. The seismic risk is fundamentally dealing with the probability of loss or damages of the human environment when they are exposed to seismic hazard [12].

Figure 1. The location of Surakarta

The attempt to study the seismic hazard of Surakarta has been conducted by several researchers. Firstly, the analysis of peak ground acceleration (PGA) of Surakarta has been studied using Gumbel method [13] and probabilistic seismic hazard analysis [14-16]. The study was then continued to develop a hard soil surface map of Surakarta based on standard penetration test (SPT) from bore hole data [17] followed by the updating the previous seismic site class map based on standard penetration test using the additional of bore hole data [18]. The information of the wave propagation from bedrock to soil surface has been studied using ground response analysis and indicates that the soil layer of Surakarta tends to amplify the ground motion of the earthquake wave. The geophysics study using microtremor analysis was later reported that the location of bed rock surface of Surakarta is at a depth variation of 145 m to 185 m [19]. The result of the geophysics studies also provided the information of shear wave velocity at a depth of 30 m from the surface and the variation of seismic site class map of Surakarta [20].

The studies of seismic risk across the world are still very rare. In European countries, the study has been conducted in a few European countries, such as Greece [21], Italy [22], Spain [23], and Turkey [24]. In Indonesia, the study of seismic risk assessment is also still very rare. So far, the Indonesia engineers have just conducted the study of seismic risk only for the city of Jakarta, [25] and Semarang [26]. However, the estimated economical loss for both studies has not taken into account yet.

3. Method

Basically, there were four main stages for conducting this seismic loss study: 1) seismic hazard analysis, 2) exposure analysis, 3) development of vulnerability curve, and 4) loss assessment analysis.

3.1. Seismic Hazard Analysis

Seismic hazard analysis was conducted to obtain surface maximum ground acceleration. It can be calculated either using classical probabilistic seismic hazard analysis (classical PSHA) or event-based probabilistic seismic hazard analysis. The analysis needs the determination of source model, ground motion prediction equation (GMPE), and site specific parameter. The difference between the first and the second method is in the calculation of hazard on the surface of bed rock. In the second method, the calculation hazard on the bedrock is not required anymore, instead it uses the stochastic event set of earthquakes.

The initial stage of this research requires data preparation, including earthquake source data about sources of subduction earthquakes, active fault earthquake sources, and background earthquakes with a radius of about 300 km from the city of Surakarta. Earthquake source data is taken from the earthquake catalog. National factors include the source of the megathrust earthquake in the south of the island of Java, an active fault from Cirebon in the west to the Blumbang fault in the east. To analyze the acceleration of earthquakes on the surface, GMPE is adjusted to the earthquake mechanism of each source.

GMPE is an equation correlating the magnitude of the earthquake and the peak ground acceleration. In PSHA, the uncertainty in calculation of seismic source and GMPE was anticipated using logic tree concept for estimating hazard [27]. The weightings on GMPE logic tree following to previous studies of hazard analysis in Indonesia in updating of National Hazard Map 2017 are shown in Figure 2 [28, 4].

A GMPE is a mathematical model that relates the ground motion parameter of interest to one or more parameters of earthquake source, wave propagation path and local site conditions. The general Formula of GMPE is expressed as:

$$\ln Y = f_1(M) + f_2(R) + \varepsilon \qquad (1)$$

$$\ln Y = f_1(M) + f_2(R) + f_3(F) + f_4(HW) + f_5(S) + f_6(D) + \varepsilon \qquad (2)$$

where ln Y is natural log of ground motion, f_1 (M) is earthquake magnitude term, f_2 (R) is source-site distance term, f_3 (F) is style-of-faulting term, f_4 (HW) is hanging-wall term, f_5 (S) is shallow site conditions term, f_6 (D) is sediment depth term [29-31].

Site specific parameter for the seismic hazard is shear wave velocity at 30 m layer thickness from the ground surface (Vs30). This parameter was obtained from indirect methods by correlation of standard penetration test (SPT) of the bore hole and Vs30 as shown in Eq. (3) [32]. In this study, the value of this parameter was also adapted from Vs30 from USGS database [33]. The basin effect was determined by calculating Z1.0 and Z2.5. based on correlation with shear wave velocity at 30 m depth from ground surface.

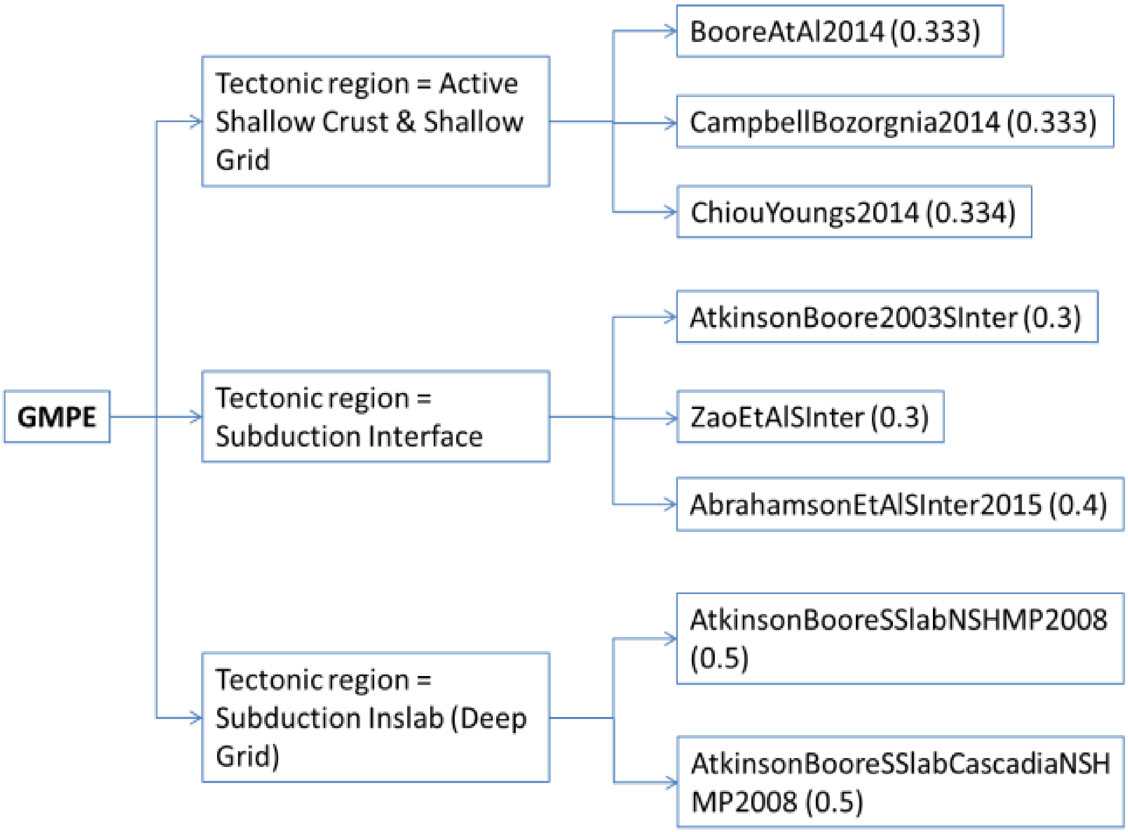

Figure 2. Logic tree of GMPE

$$\mathrm{Vs30} = 85.3 \text{ x } (\text{N-SPT})^{0.341} \text{ (m/s)} \qquad (3)$$

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

$$\ln Z_{2.5} = 7.089 - 1.144 \ln Vs_{30} (\text{km}) \qquad (5)$$

Where:
Z1.0: depth of rock with shear wave velocity 1000 m/s
Z2.50: depth of rock with shear wave velocity 2500 m/s

Event-Based PSHA basically performs the Monte Carlo integration where the calculation was conducted through random sampling from a magnitude pdf (probability density function) to get a single magnitude. Furthermore, from the magnitude, the earthquake probability is calculated using the earthquake recurrent model (Guttenberg Richter (GR) and/or Characteristic (CH) model. The next step was to calculate the length and width of the rupture based on the magnitude and mechanism of the earthquake using the scaling law. This method determines the moment magnitude considering to ruptures and displacement per event [34].

The rupture centroid is determined randomly, which is not outside the outer boundary of the rupture. Furthermore, the probability of each event and rupture can be estimated as a hazard by considering site amplification according to its specific site.

In the stage of hazard analysis, the rate of exceeding a given ground motion value $\lambda(GM > gm)$ in a region with Ns seismic sources:

$$\lambda(GM > gm) = \sum_{i=i}^{N_s} \nu_i \int M \int R \, P[GM > gm|m,r] f_M(m) \, f_R(r|m) dm \, dr \qquad (6)$$

where ν_i stands for the average rate of magnitude exceedance threshold for source i, $P[GM > gm|m,r]$ can be derived from the ground motion prediction model, $f_M(m)$ represents the probability density function for magnitude, and $f_R(r|m)$ stands for the probability density function for the source-to-site distances conditional on a magnitude m [35].

The final step of hazard analysis was calculating the hazard using stochastic event set (SES). The calculation was then conducted using OpenQuake software [36]. As per SNI 8460-2017, the Indonesian code of Geotechnical Design Requirement that earthquake load for building and non-building with service live of 50 years must comply the return periods of 2500 years or probability of exceedance of 2%, (PoE = 2%) [37]. However, in this study, the return periods of 500 years or the probability of exceedance of 10% (PoE = 10%) was also presented.

3.2. Exposure

Exposure is the element at risk that is exposed to the hazard [37]. In this study, the exposure data of all school buildings in Surakarta were collected through a field survey supported by Google map. The exposure data includes identity of school, location coordinate (longitude, latitude), year built, building taxonomy, material use, number of building, number of story and replacement cost. The determination of building types followed Global Earthquake Model (GEM) taxonomy using the GEM-IDCT application (Inventory Data Capture Tools), whereas the replacement cost was calculated based on local unit price.

The physical information of all school buildings in all five sub districts in Surakarta; Pasar Kliwon, Jebres, Serengan, Laweyan, and Banjarsari has been obtained. The survey was conducted by a team to visit, check, record and document all the required information for more than 1 month. The survey was supported by the information from google map application. The team has collected and identified the information of 163 school buildings in Pasar Kliwon, 253 buildings in Jebres, 128 buildings in Serengan, 337 buildings in Laweyan, and 291 buildings in Banjarsari. They give the total number of 1172 school buildings. Other than that, the team has also collected the information of 284 buildings of universities across Surakarta.

3.3. Vulnerability Curve

The vulnerability function was derived from empirical methods where losses from past events at a given location are related to level of ground motion intensity. In this study the secondary data from vulnerability of previous building vulnerability studies were obtained from building taxonomy.

The vulnerability factor of the building is an important part of the earthquake risk analysis. To obtain earthquake risk in the form of building structural losses, a building vulnerability function is used, which is the relationship between the ratio of losses to the level of earthquake intensity.

The vulnerability model can be derived through empirical methods where losses from past earthquake events at a particular location are related to the intensity level of ground motion at the related location, or obtained by combining the fragility function and the consequence function. The fragility function describes the probability of exceeding the performance limit of the structure at a certain level of damage to the level of intensity measure. The fragility function can be derived by expert opinion, empirically (using observed data), or numerically by modeling the typological behavior of a given asset when experiencing an increase in ground motion. While the consequence function is a function that describes the distribution of the probability of loss at a given level of performance. This function is generally derived empirically.

In this study, the vulnerability function uses secondary data from previous studies, adjusts for the taxonomy of buildings in the exposure data. The vulnerability model used in the calculations is taken from https://platform.openquake.org/vulnerability/ [36]. Figure 3 shows an example of the vulnerability curve for various taxonomies of confined masonry buildings for variation PGA.

Building taxonomy of the assets was distributed as MCF (Confine Masonry) and MUR (Unreinforced Masonry) buildings with height of 1 to 3 stories. For those buildings, intensity measure level of PGA, SA (0.3) was considered, whereas for CR (Reinforced Concrete) buildings with height of 4 to 5 stories, SA (0.6) in the risk analysis was employed [37].

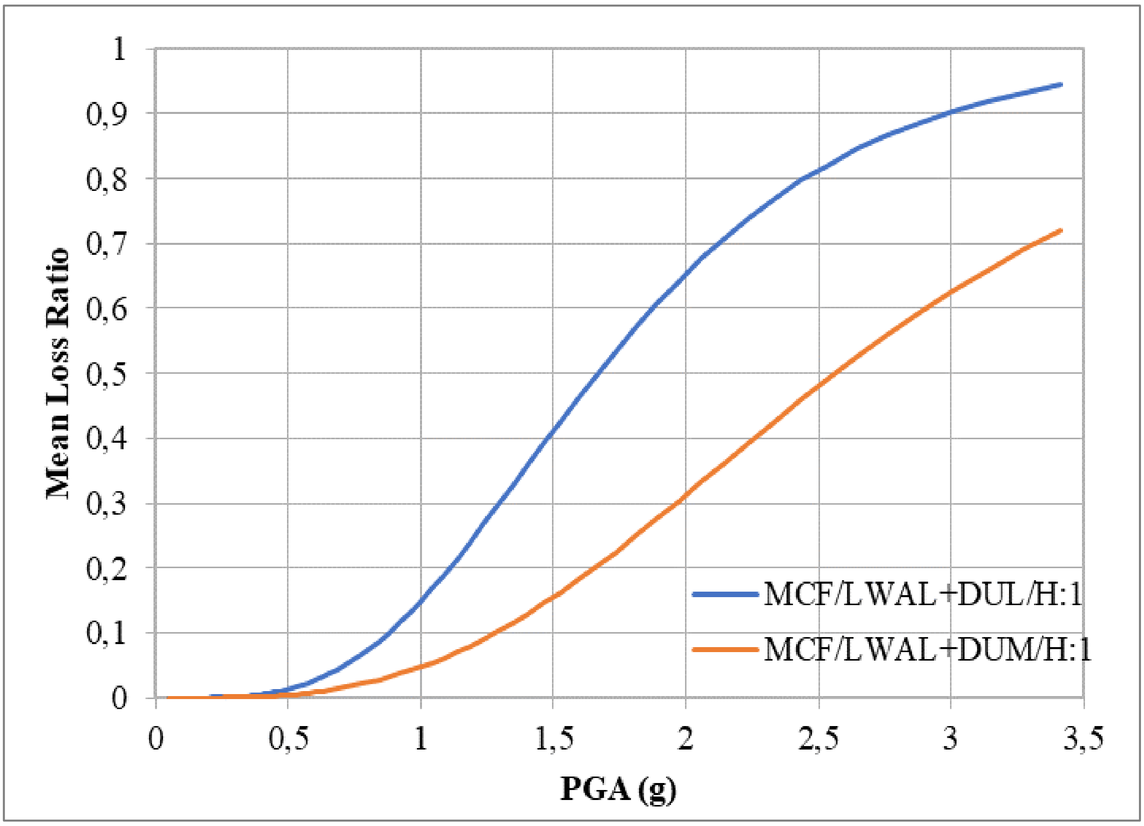

Figure 3. Vulnerability curve for various taxonomy of reinforced concrete buildings for spectral acceleration for 0.6 second (SA 0.6).

3.4. Losses Assessment

Risk analysis in terms of loss was conducted using Event-Based Risk Analysis. This method in principle uses the stochastic event set and the related ground motion field (gmf) that was produced from hazard analysis to calculate the loss curve exceeded for each asset contained in the exposure model consider to the vulnerability function of the building type.

In each gmf, the level of intensity measurement at a given location is combined with a vulnerability function, wherein the loss ratio is sampled randomly for each asset contained in the exposure model. The loss ratios sampled for assets that are given a taxonomic classification in different locations are considered to be independent or fully correlated. The distribution of loss occurrences for a particular asset is calculated using all ground motion fields, which leads to a loss ratio histogram which is then converted to a cumulative histogram, by calculating the cumulative number of events for each loss ratio interval. The exceeded rate of each loss ratio is calculated by dividing the cumulative number of events by the number of stochastic event sets multiplied by the length of each event set. Assuming a Poisoning distribution of the event model, the probability of exceeding each loss ratio is calculated [38].

$$\lambda(L > l) = \sum_{i=i}^{N_s} v_i \int M \int R \int GM\, P[L > l|gm] f_{GM}(m|r)\, f_M(m) f_R(r|m) dgm\, dm\, dr \tag{7}$$

$\lambda(L > l)$ is the annual rate of exceeding a set of loss levels which is calculated from hazard curves combined with the vulnerability functions of the associated assets. $f_{GM}(m|r)$ stands for the probability density function of the ground shaking at the location of the asset, conditional on a magnitude m and distance r.

Another important risk metric in probabilistic earthquake loss assessment is the average annual loss (AAL) [35].

$$AAL = \sum_{i=i}^{N_s} v_i \int M \int R \int GM \int L\; P[L > l|gm] f_{GM}(m,r)\, f_M(m) f_R(r|m) dl\, dgm\, dm\, dr \tag{8}$$

The outputs of earthquake risk analysis using the Event-Based approach included the Aggregated Loss Table and the Aggregated Loss Curve. Aggregated Loss Table is a table of building structural losses based on the type of material analyzed within 1 year of risk investigation. While the Aggregated Loss Curve is the loss value of the building structure due to the earthquake in a certain return period. In this study, the loss curve is presented based on the type of structural material, per sub-district. Furthermore, the total loss map for 500-year and 2500-year return period was produced based on total loss which is derived from loss curves.

4. Result and Discussion

4.1. Seismic Hazard Map

Shear wave velocity at 30 m layer thickness from the ground surface (Vs30) was indirectly from N-SPT of bore holes scattered throughout the city of Surakarta combined with the Vs30 from USGS. Figure 3 shows the location of 32 bore holes (black circle) and grid points of USGS.

Vs30 map is shown in the Figure 4, indicating that the shear wave velocity in the northeast of Surakarta tends to be larger than that in the southern part.

For a reliable statistic result, seismic hazard was analyzed using Event-Based PSHA method with SES (stochastic event set) 200,000 years [39]. The hazard curves of acceleration spectrum in 0 second (PGA), 0.3 second SA (0.3) and 0.6 second SA (0.6) are shown in Figure 5, Figure 6 and Figure 7 and 8 respectively. Ground acceleration for PGA is about 0.25 g to 0.5 g for return periods of 500 years and 2500 years, respectively. It has deviation standard of about 0.073 and 0.146. Seismic intensity for SA (0.3) are around 0.5 g to 1.0 g, respectively. It has deviation standard of about 0.143 and 0.296. Whilst ground acceleration for SA (0.6) are about 0.4 g to 0.9 g for PoE = 0.2% (500 years return period) and PoE = 0.04% within 1 year (2500 years return period), respectively. It has deviation standard of about 0.116 and 0.255

Hazard maps for PGA presented in Figure 8 and 9, show that for PoE = 0.2% and PoE = 0.04% within 1 year, the ground acceleration is 0.25 g in the northern part to 0.28 g in the southern part of Surakarta. Whilst for PoE = 0.2% and PoE = 0.04% within 1 year, the ground acceleration is 0.4 g in the northern part to 0.52 g in the southern part. From those two maps, it showed that the ground acceleration is increasing from the northern part to the southern part gradually due to site specific of the soil. (See Figure 4.)

Epistemic uncertainty is shown in the hazard curve. The smaller the intensity measure level, the less uncertainty due to quite a lot of data. Meanwhile, there is significant uncertainty at large seismic intensities due to the lack of recording data.

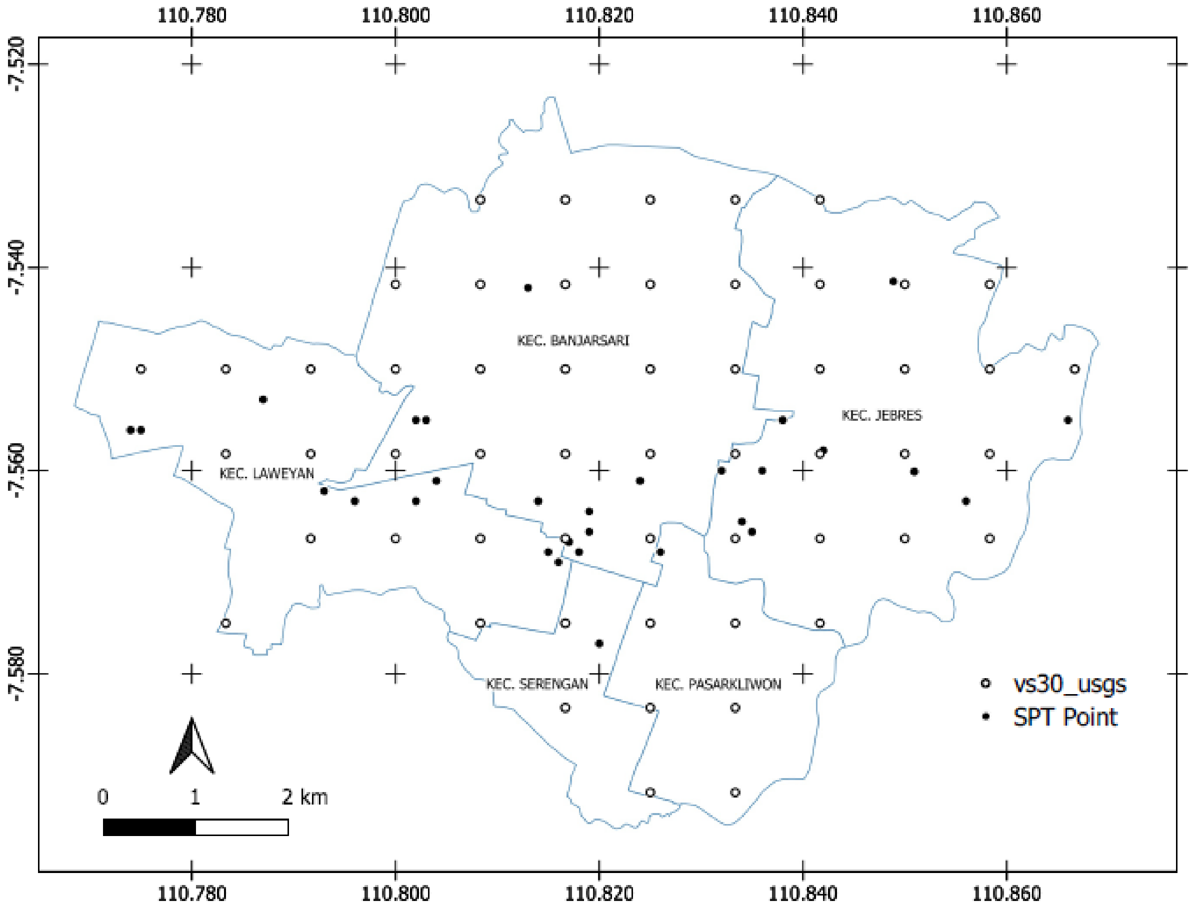

Figure 4. Location of bore hole

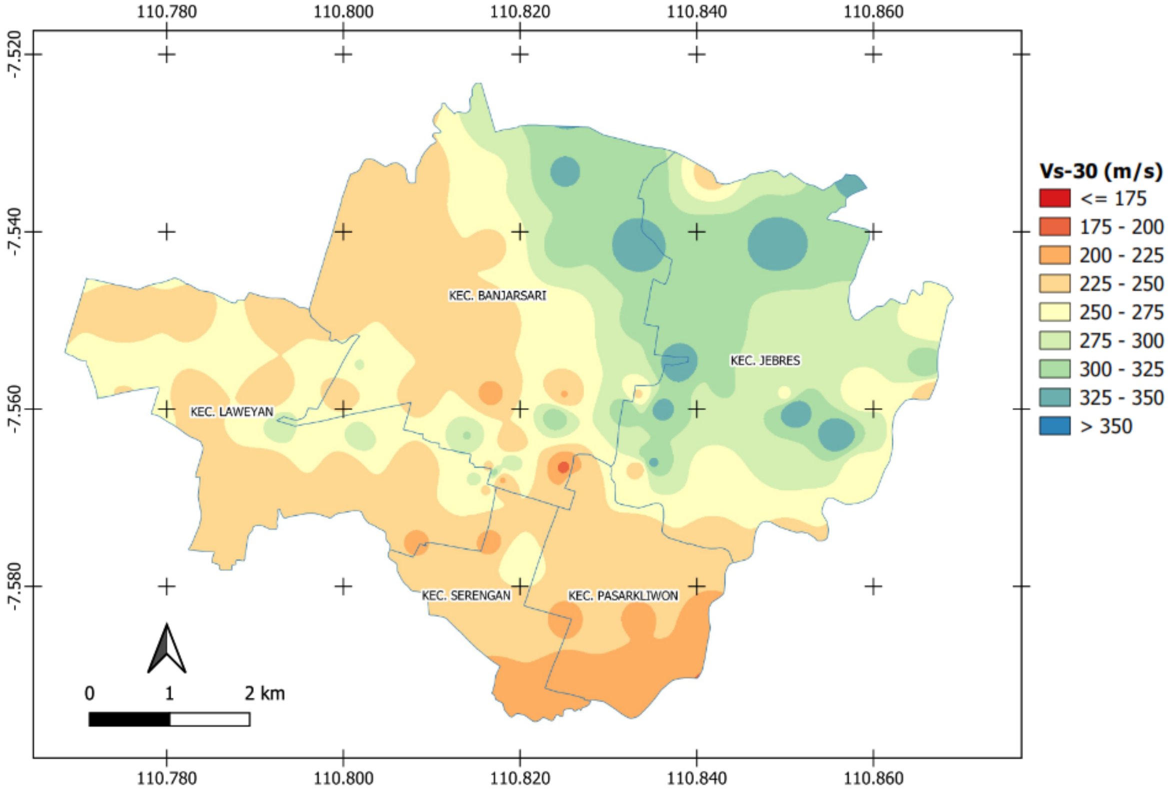

Figure 5. Vs30 map of Surakarta

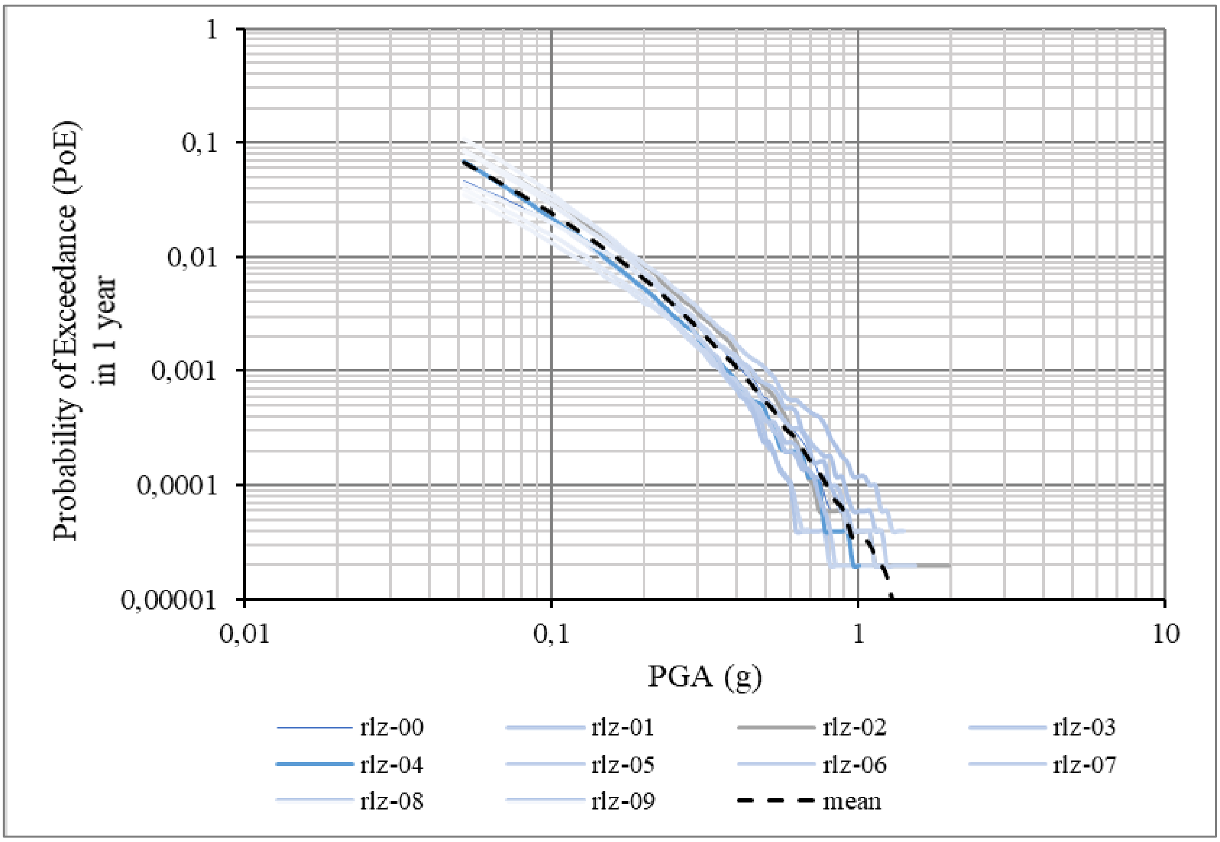

Figure 6. Hazard curve of PGA of a site in Surakarta

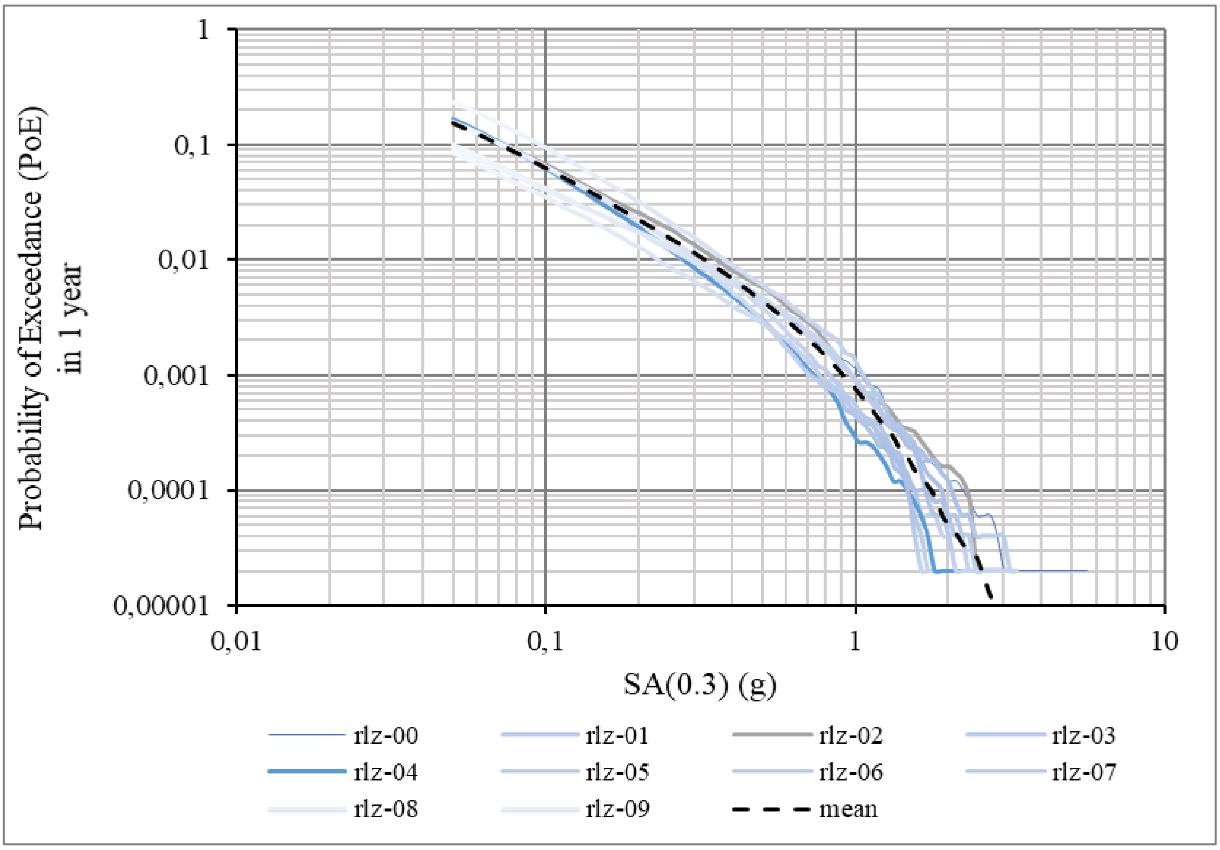

Figure 7. Hazard curve of SA (0.3) of a site in Surakarta

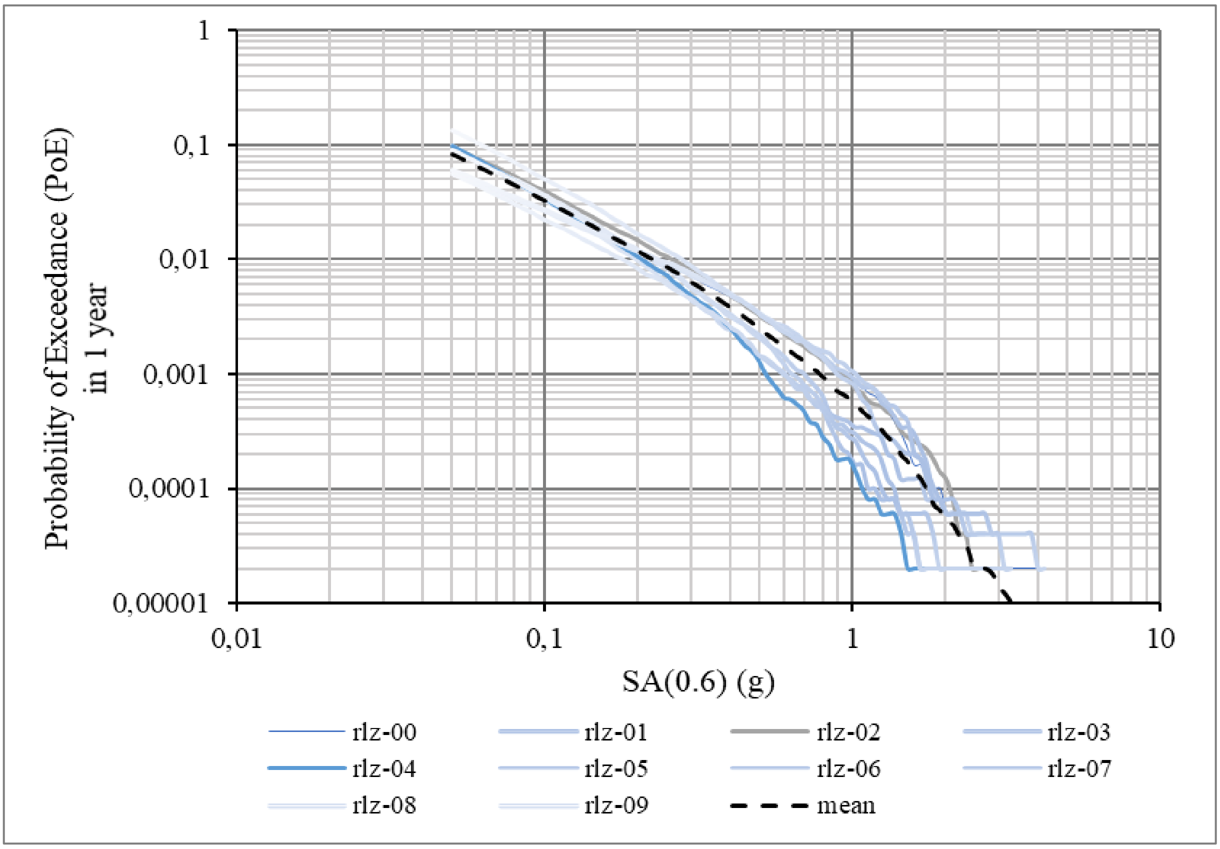

Figure 8. Hazard curve of SA (0.6) of a site in Surakarta

Table 1. Specific data of Column/Row

Sub-district	**Material**	**Loss Value (USD)**	**Exposed Value (Mill USD)**	**Loss ratio (%)**
Pasar kliwon	CR	7,655.27	28.08	0.027
Pasar kliwon	MCF	188.08	7.50	0.003
Jebres	CR	9,928.40	38.85	0.026
Jebres	MCF	795.21	14.13	0.006
Jebres	MUR	23.70	0.05	0.049
Jebres	W+WLI	27.19	0.03	0.093
Jebres	W+WO	76.0	0.08	0.094
Serengan	CR	6,669.53	24.08	0.028
Serengan	MCF	166.06	6.05	0.003
Serengan	W+WLI	12.81	0.01	0.106
Laweyan	CR	16,008.13	65.80	0.024
Laweyan	MCF	564.66	20.60	0.003
Laweyan	MUR	145.83	0.27	0.055
Laweyan	W+WLI	6.13	0.01	0.097
Banjarsari	CR	1,2616.07	57.44	0.022
Banjarsari	MCF	301.76	14.88	0.002
Banjarsari	W+WLI	80.23	0.08	0.101
Banjarsari	W+WO	24.72	0.03	0.097
Total		5,5289.73	277.95	0.020

4.2. Seismic Loss Analysis

The result of loss analysis was the aggregated loss table which describes the loss value of a number of buildings based on building material type in exposure data per sub-district. (Table 1).

It can be seen from the table that the loss ratio of wood/light wood (W+WLI) and wood/other wood school building has the highest loss ratio, 0.1 %. Meanwhile the confined masonry (MCF) school buildings have the lowest loss ratio of 0.002%. Loss ratio is a comparison of loss value/expose value.

Aggregated Loss Curve is the loss value of the building structure due to the earthquake in a certain return period. Some of the Aggregated Loss Curve is presented in Figure 10, Figure 11 and Figure 12.

It is shown in Figure 10 to 12 that for PoE = 2 %, the loss of CR Buildings is around 70 billion IDR (4.7 million USD), MCF buildings is around 3 billion IDR (200,000 USD) whilst the loss of W+WLI buildings is around 0.6 billion IDR (40,000 USD).

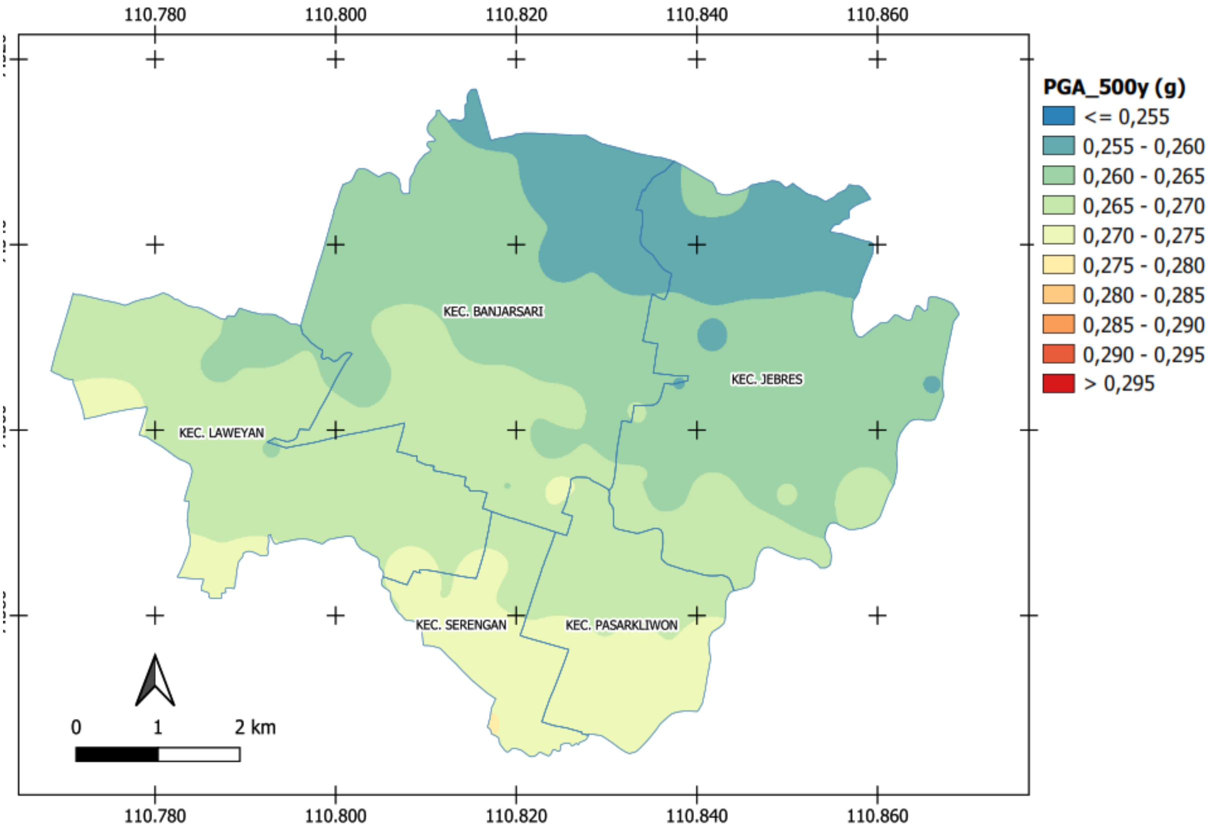

Figure 9. Seismic hazard map for PGA PoE = 10% within 50 years

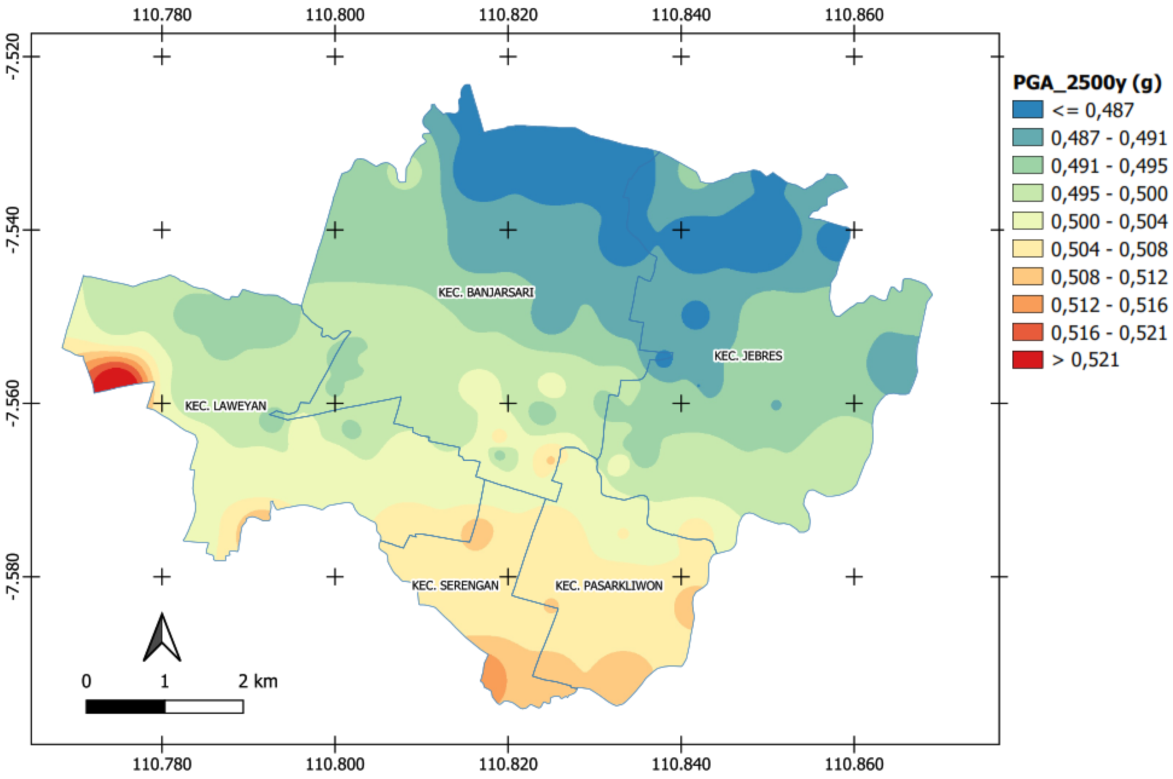

Figure 10. Seismic hazard map for PGA for PoE = 2% within 50 years

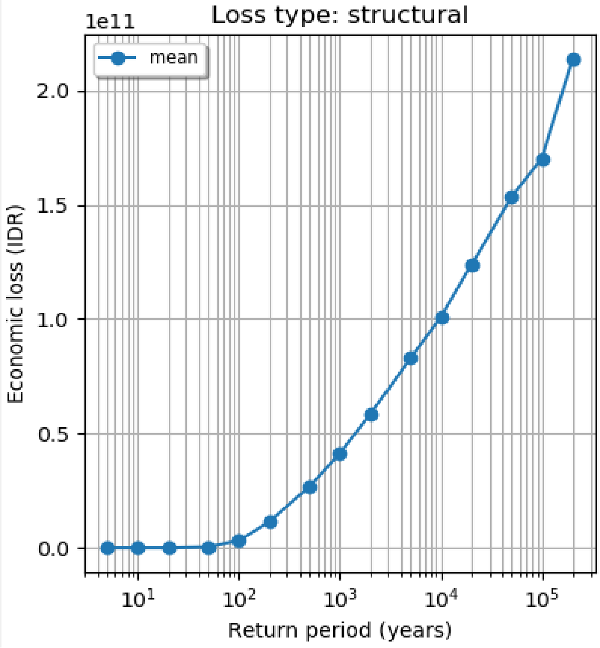

Figure 11. Aggregated Loss Curve for Reinforced Concrete Buildings (RC) in Banjarsari sub-district

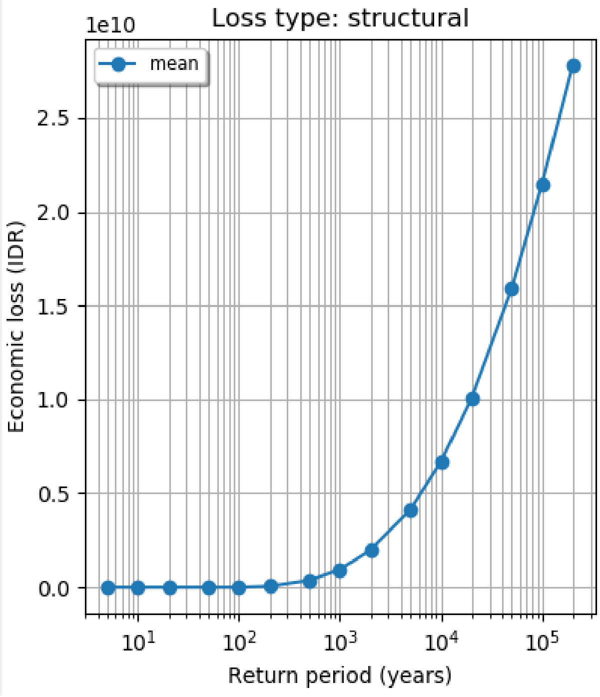

Figure 12. Aggregated Loss Curve for Wood+Light Wood (W+WLI) Buildings in Banjarsari sub-district

Furthermore, the total loss of school buildings computed for PoE = 10% and PoE = 2% are presented in Figure 13 and 14. Within 50 years, PoE = 10%, the highest total loss of school buildings is in Laweyan sub-district, around 35.4 billion IDR (2.36 million USD), and the lowest one is in Serengan, about 14.4 billion IDR (960,000 USD). For PoE 2%, the highest total loss of school buildings is in Laweyan sub-district, around 80.9 billion IDR (5.39 million USD), and the lowest one is in Serengan, about 33.2 billion IDR (2.2 million USD).

For whole school buildings in Surakarta, the total loss of school buildings for PoE = 10% is 7.79 million USD, wheres for PoE = 2% is 17.9 million USD. Based on source loss table presented in Figure 16, in terms of Subduction mechanism, the potential earthquake sources are East Java and West Central Java Megathrusts, while the potential sources of shallow faults are Opak, Purwodadi, Demak, Rawa Pening, Cepu, Merapi Merbabu, and Pati faults respectively.

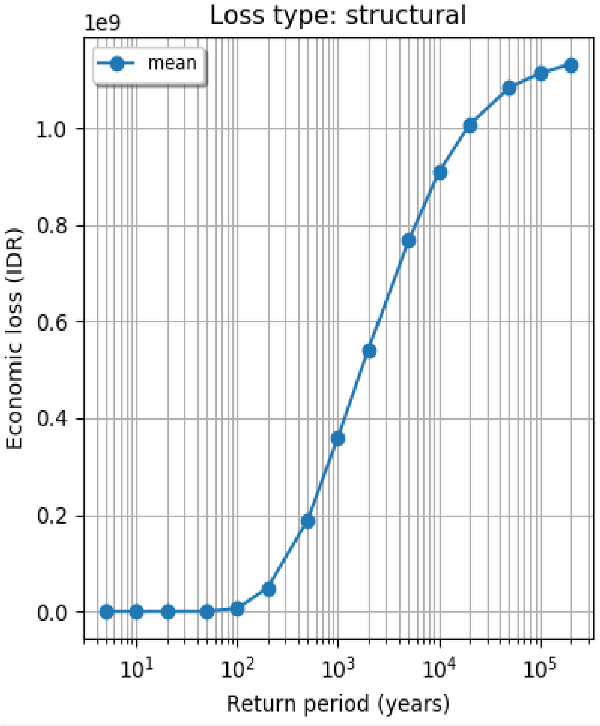

Figure 13. Aggregated Loss Curve for Wood+Light Wood (W+WLI) Buildings in Banjarsari sub-district

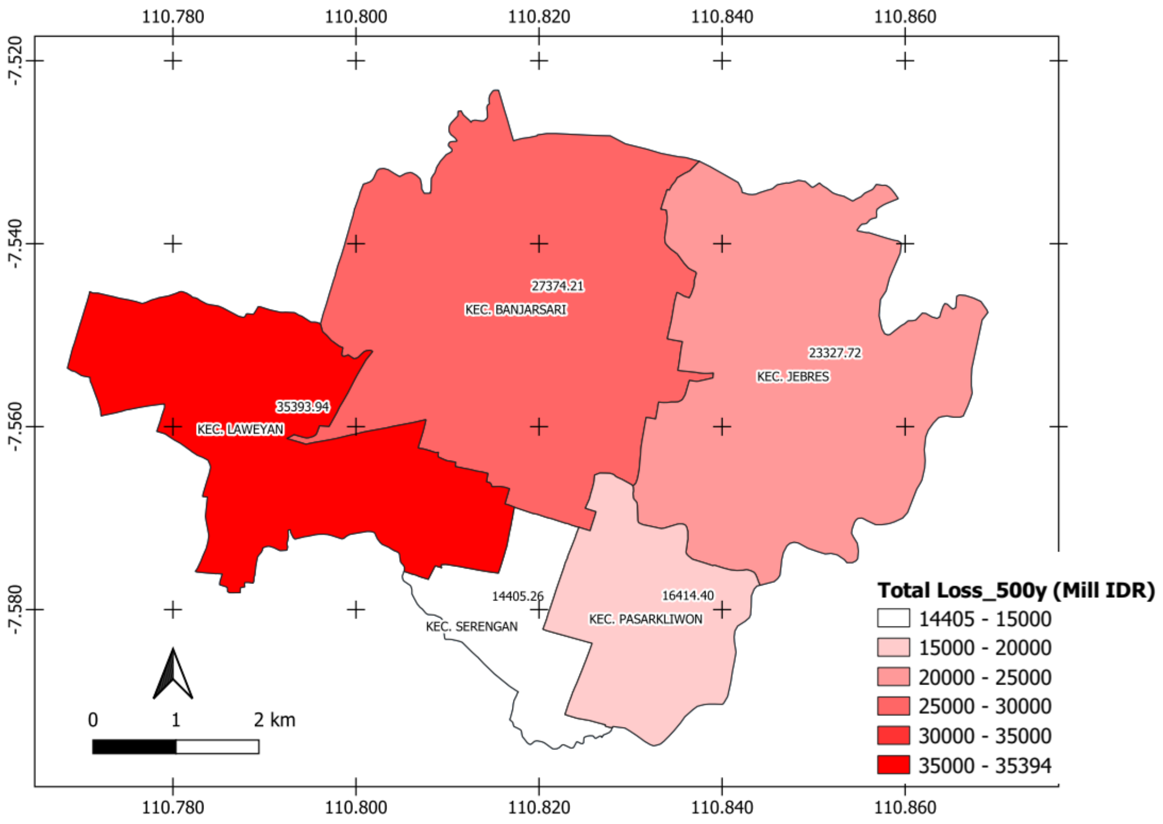

Figure 14. Total Loss Map of School Building (structural) in Surakarta for PoEs = 10% within 50 years

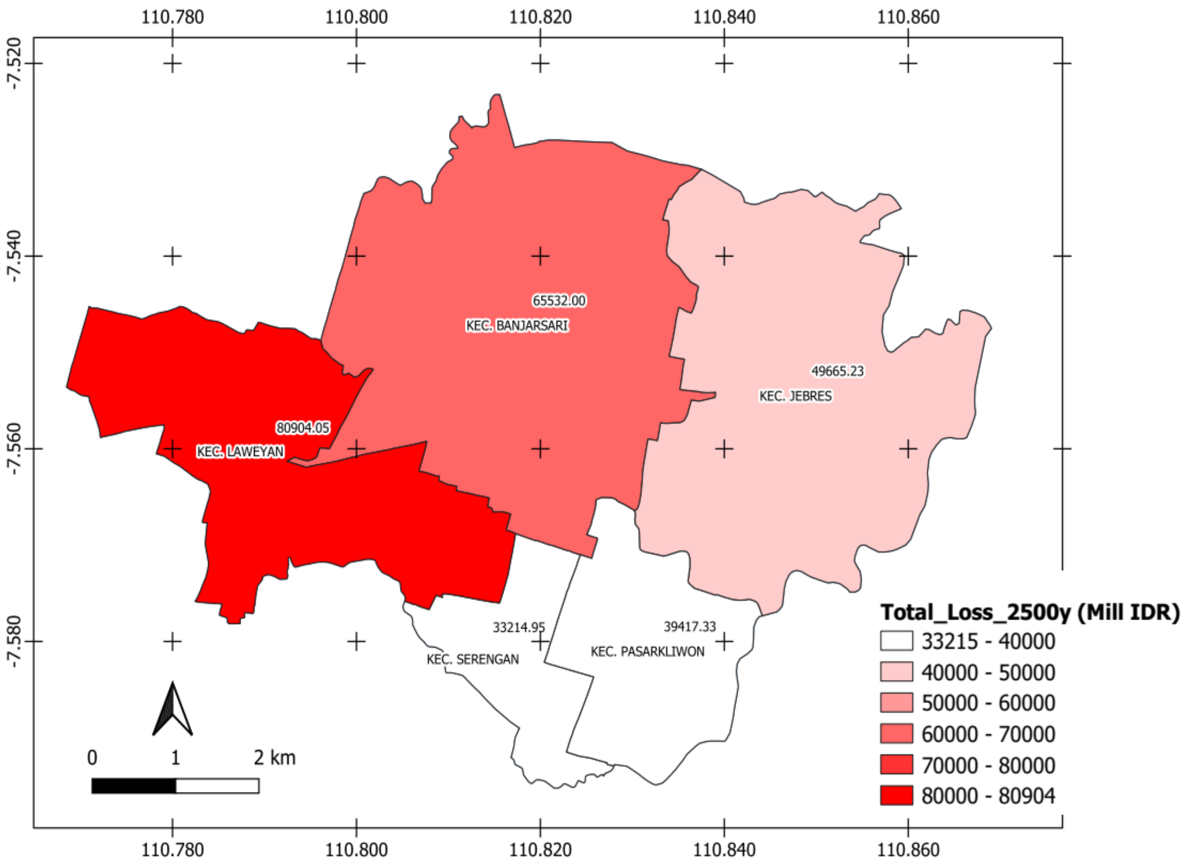

Figure 15. Total Loss Map of School Building (structural) in Surakarta for PoEs = 2% within 50 years

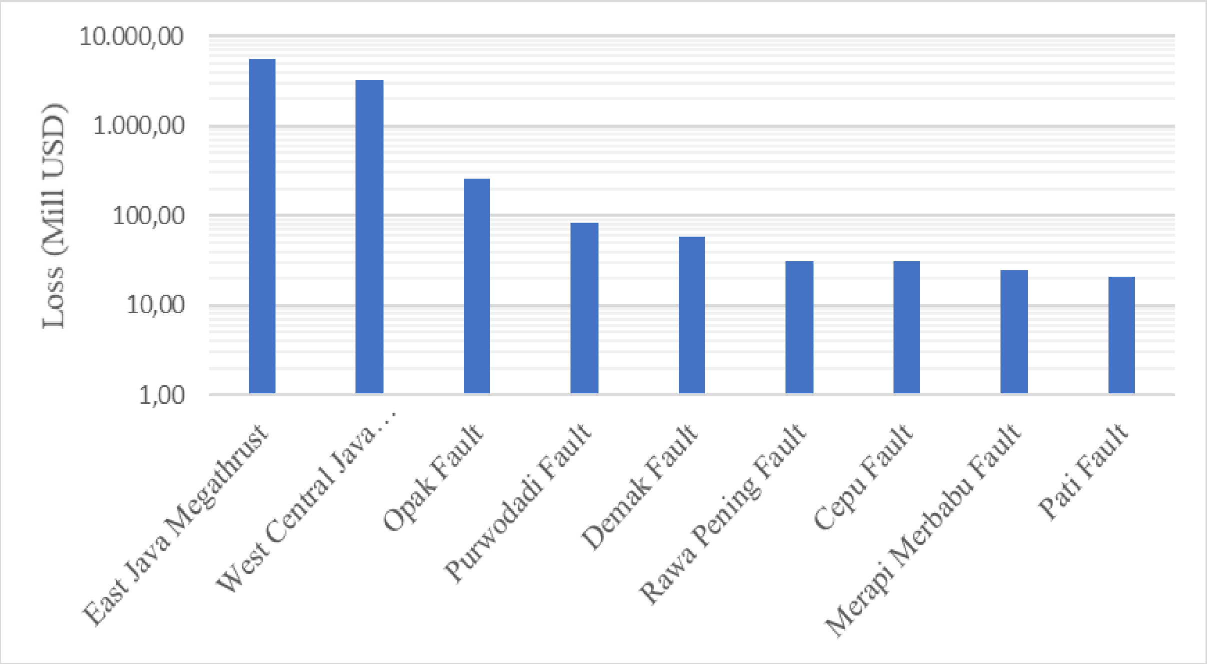

Figure 16. Potential earthquake sources

5. Conclusions

1. The ground acceleration of Surakarta is gradually increasing from the northern part to the southern part due to the site specific of the soil where in the southern part the PGA is softer than in the northern part.
2. The exposure and vulnerability of school buildings are very important factors to determine a risk of loss. It indicates that the light wooden school building shows a highest risk of loss, whereas the confined masonry ones give a lowest risk.
3. Among the whole sub districts in Surakarta, it is assessed that Laweyan suffers the biggest seismic loss of 2.36 million USD due to 500 years return period earthquake and 5.39 million USD due to 2500 years return period earthquake.
4. The total seismic loss of school buildings across Surakarta due to 500-year return period earthquake is 7.79 million USD, while due to 2500-year return period earthquake is 17.9 million USD.

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