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Seismic hazard analysis for Sutami Dam using probabilistic method

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Abstract. One of the largest structures in Malang is Sutami dam. It was built in 1964 to 1973 and began to be operated in 1977. Considering the age of the dam which is over 40 years and the high risk of earthquake in this area, it is necessary to analyze its seismic hazard using an updated data. The probablilistic seismic hazard analyses (PSHA) was employed to obtain peak ground acceleration (PGA). The deagregation was conducted to obtain the most influencing magnitudes (M) and and distance (R) values affecting the dam. The result indicates that the area of the dam has the PGA of 0.261 for 500 years return period, 0.41 for 2500 years return period and 0.586 for 10,000 years return period of eartquakes. The magnitude of 5.93-6.17 for the distance of 22-44 km are considered as the most influencing earthquake for the dam. Due to the lack of ground motion data for Sutami dam, the ground motion from other earthquake might be utilised such as Morgan Hill earthquake 1984, Whittier Narrow earthquake 1987, Chalfant Valley earthquake 1986, Georgia USSR earthquake 1991, Northridge earthquake 1994, or San Fernando earthquake 1971.

1 Introduction

The island of Java is located in the Pacific ring of fire zone. It is a home of some active volcanoes and also near to the subduction zone between the Indo-Australia and Eurasian plates. Some active faults are also encountered in the island. The situation in this area makes the infrastructures vulnerable to volcanic and tectonic earthquakes. Planning process and evaluation of structure and infrastructure in the area must consider the risk of high seismicity. One of the large structures in this area is the Sutami dam located in Malang, east Java, and built from 1964 to 1973 and began operation in 1977. Malang is surrounded by some volcanoes; Mount Bromo and Semeru in the eastern part, Mount Kawi, Arjuno, Welirang and Mount Kelud in the western part. It is also relatively close to the subduction zone located in the southern part of Java. The seismic activity in Malang is also influenced by the existence of faults such as Tulungagung, Lumajang, and Banyu Putih faults. Some historical seismic was encountered such as earthquakes with M 6.7 in 1958, M 6.2 in 1967, M 6.3 in 1998, and M 6.2 in 2011 [1-2]. Geographical and seismotectotic locations of the Malang Regency, makes it one of the regions with high risk of earthquakes. The geographical location of the dam is illustrated in Fig. 1.

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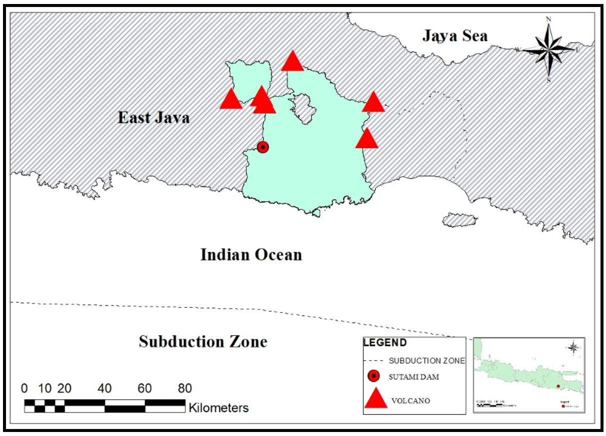

Fig. 1. Geographical location of Sutami dam.

With the age of the dam which is more than 40 years and the high risk of earthquakes in this area, it is necessary to analyze its earthquake hazard. The seismic hazard analysis has been carried out using Probabilistic Seismic Hazard Analysis (PSHA) with three earthquake return period of 500, 2500 and 10,000 years.

2 Probabilistic seismic hazard analysis

Earthquake hazard analysis with a total probabilistic method (PSHA) refers to the concept of probability developed by Cornell [3]. This analysis is based on the assumption that an earthquake event with magnitude (M) and distance (R), is a continuous independent random variable. The probabilistic seismic hazard analysis has four stages; identification of earthquake sources, characterization of seismic source, selection of attenuation functions, and earthquake hazard calculations [4]. The steps of analyses are presented in Fig. 2.

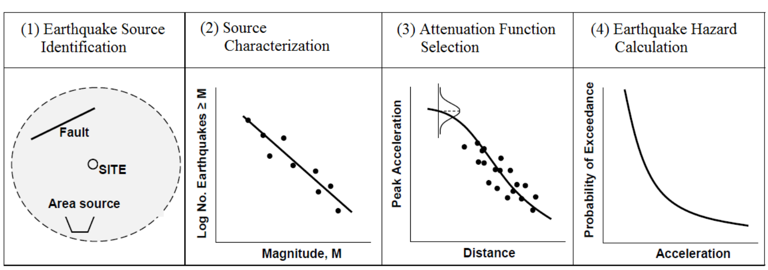

Fig. 2. Four steps of PSHA.

The basic equation for PSHA as shown in the Eq. 1 below [5].

$$\lambda\left(a>a^{*}\right)=\sum_{i=1}^{ns} v\left(m>m_{0}\right)\sum_{j=1}^{nm}\sum_{k=1}^{nr} P\left[a>a^{*} \mid m_{j} r_{k}\right] P\left[M_{i}=m_{j}\right] P\left[R_{i}=r_{k}\right] \tag{1}$$

where $\lambda\left(a>a^{*}\right)$: Annual rate of exceedance of particular PGA, v ($m>m_0$): Annual occurrence rate of earthquake exceed particular magnitude, P [$a>a^{*} \mid m_j\, r_k$]: probability of the ground-motion parameter to exceed level of a^* for a specific magnitude m at a distance r, P [$M_i=m_j$]: Magnitude distribution function, P [$R_i=r_k$]: Distance distribution function.

The analysis is carried out using three different return periods; 500, 2500, and 10,000 years for the location of the earthquake. The result of the earthquake analyses may be further utilized for dynamic studies of the dam referring to Design Base earthquake (DBE) and Safety Evaluation Earthquake (SEE) for 2500 and 10,000 years return periods as recommended by ICOLD 2016 [6].

2.1 Earthquake catalog

The seismic risk analysis uses a uniform magnitude scale for all earthquake record data. To homogenize the magnitude scale of all earthquake record data, the correlation equations are utilized as presented in Table 1 [7]

Table 1. Correlation of magnitude scale conversions for the Indonesian region.

Correlation	Range Data	(R^2)
$Mw = 0{,}143\ Ms^2 - 1{,}051Ms + 7{,}285$	$4{,}5 \le Ms \le 8{,}6$	93.9 %
$Mw = 0{,}114\ Mb^2 - 0{,}556\ Mb + 5{,}560$	$4{,}9 \le Mb \le 8{,}2$	72.0 %
$Mw = 0{,}787\ M_E + 1{,}537$	$5{,}2 \le M_E \le 7{,}3$	71.2 %
$Mb = 0{,}125\ M_L^2 – 0{,}389\ M_L + 7{,}285$	$4{,}5 \le M_L \le 8{,}6$	56.1 %
$M_L = 0{,}717\ M_D + 1{,}003$	$4{,}5 \le M_D \le 8{,}6$	29.1 %

Earthquake record was obtained from several earthquake data catalogs including Advanced National Seismic System (ANSS), United States Geological Survey (USGS), and International Seismological Center (ISC). The analysis was conducted using earthquake record from 1900 to 2018 with a distance of 500 km from the location of the dam (-8.152 lat, and 112.455 long). As the magnitude of less than 4 does not cause significant the damage, the only earthquakes of M > 4 and focal depth of 300 km were selected. The number of earthquake record data obtained from the catalogs are presented in Table 2.

The earthquake data was analyzed as the independent earthquake record data (mainshock) so that the decluttering process for the earthquake record data is obtained [3]. Declustering is the process of identifying and separating earthquake-dependent data as foreshock and aftershock from the main earthquake (mainshock). After the declustering process, 1143 main earthquake record data is obtained.

Table 2. Earthquake record data from each catalog.

No	Catalog	Number of data
1	ANSS	2744
2	ISC	6129
3	USGS	2818
Total		11,691

2.2 Data completenes analysis

The incompleteness of earthquake data will cause the generated parameters to become overestimated or underestimated. The Step's method has been utilized to overcome this condition [4]. To find out the period in which an earthquake catalog is used is quite complete, the frequency of independent earthquake events for several ranges of magnitudes is plotted against the calculated time, from the time of the last observation back. Complete data retrieval is based on visual observations of graph results. Data that is considered complete when it makes a constant slope as shown in Fig. 3 as follows.

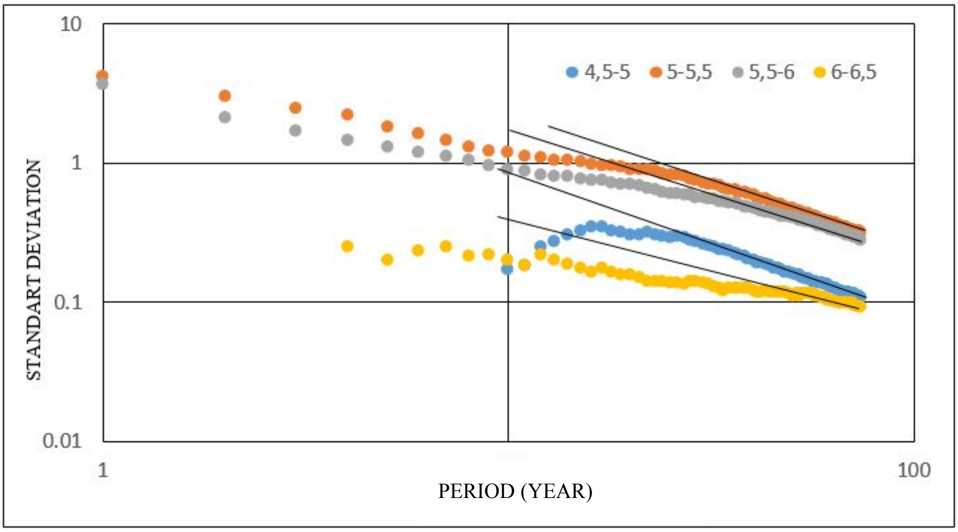

Fig. 3. Graph of completeness test results.

From visual observations of the completeness analysis, the interval of the year for the complete data is shown in Table 3.

Table 3 Earthquake record result from data completeness test

Magnitude Interval	4.5-5	5-5.5	5.5-6	6-6.5
Starting from (year)	1991	1980	1977	1959
Number of year	27	38	41	59

2.3 Earthquake sources modeling

Modeling of earthquake sources was categorized according to the depth of the source; 0-50 km for shallow crustal (including subduction and fault), 50-175 km and 175-300 km for a deep background. Each category was grouped by a means of area sources (segments) as illustrated in Fig. 4 and each segment in that figure consists of a group of earthquake source with the same category.

The earthquake source modeling produces some seismic earthquake parameters such as maximum magnitude (M_{max}), earthquake activity rate (λ), and ab-value as proposed by Gutenberg & Richter [9].

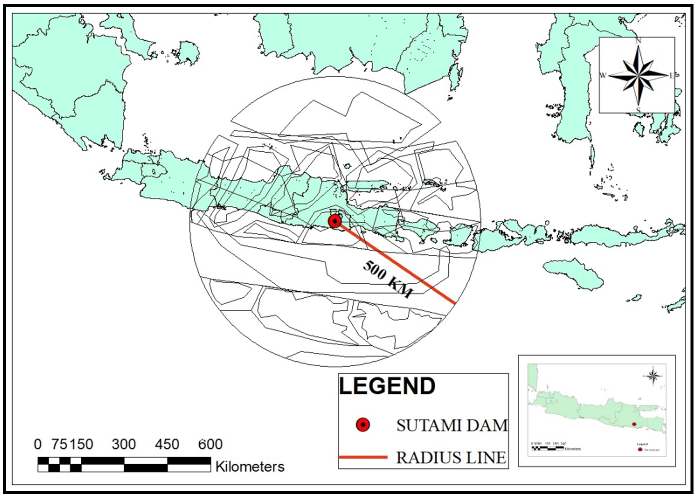

Fig. 4. Earthquake source modelling.

2.4 Attenuation function

The attenuation function is a very important formulae for describing the relationship between magnitude (M), intensity, and distance (R). The selection of this function is determined by the earthquake mechanism, epicenter distance and the local soil conditions. In this study, the attenuation function referred to the 2017 Indonesian Earthquake Earth Source and Hazard Map [6] and according to Irsyam [4], logic tree concept must be employed for weighting of each functions for each source of the earthquake model, as shown in Table 4.

Table 4. Attenuation function and weighing for the analyses.

Source	Attenuation function	Weight
Fault	Boore-Atkinson NGA [10]	1/3
	Campbell-Bozorgnia NGA [11]	1/3
	Chiou-Youngs NGA [12]	1/3
Subduction *Interface*	BCHYDRO [13]	1/4
	Atkinson-Boore BC *rock and global source subduction* [14]	1/4
	Zhao et al. *with variable Vs30* [15]	1/2
Deep background	AB *interslab seismicity* Cascadia *region* BC-rock *condition* [14]	1/3
	Geomatrix slab seismicity rock, 1997 *srl* July 25 2006 [16]	1/3
	AB 2003 *interslab seismicity world wide data region* BC-rock *condition* [14]	1/3

3 Results and discussion

3.1 The result of peak ground acceleration

Seismic analysis was carried out to cover the area of the study of 500 km distance from the dam. The result of hazard for 500, 2500, and 10.000 years return period are presented in Fig. 5, Fig. 6 and Fig. 7 which shows the intensity of the dam at 0.261, 0.41, and 0.58 g.

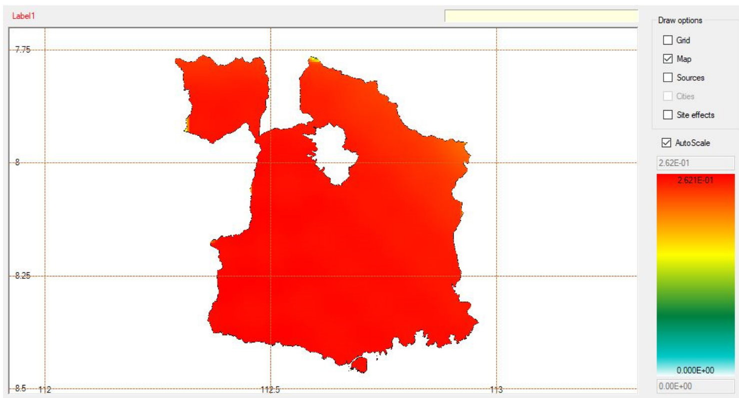

Fig. 5. The hazard maps of Malang for 500 years return period.

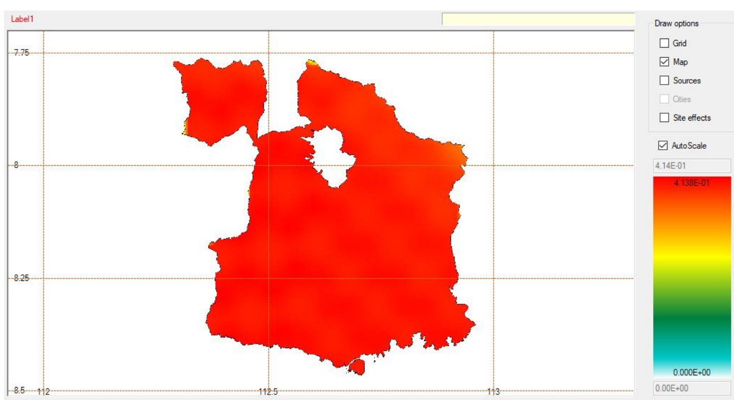

Fig. 6. The hazard maps of Malang for 2500 years return period.

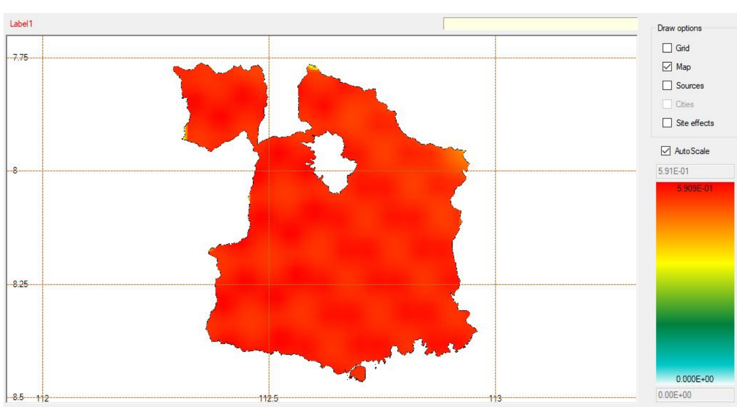

Fig. 7. The hazard maps of Malang for 10000 years return period.

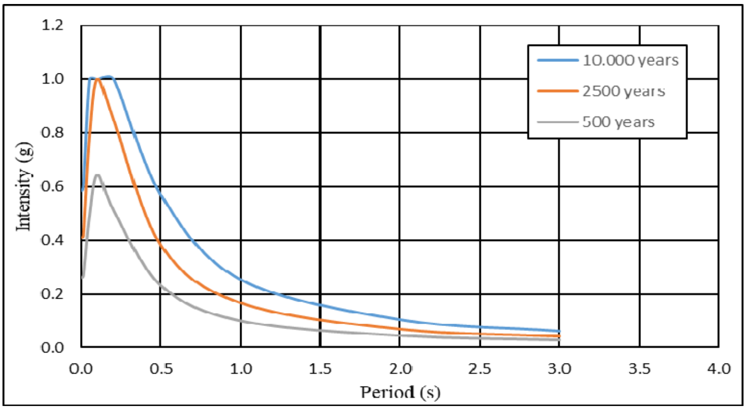

Fig. 8. Spectra graphs on all return period.

The spectra graph of all return periods are shown in Fig. 8 and it can be concluded that the increase in the value of the peak ground acceleration is directly proportional to the increase in the earthquake return period. The 500-year return value is the smallest value and the 10,000-year return period has the greatest value.

3.2 Exceedance probability

Exceedance Probability for Hazard Maps is a constant exceedance probability for all hazard maps that will produce intensity results. Calculation of exceedance probability for each earthquake event is presented in Eq. 2.

$$Exceedance\,probability = 1 - \exp^{\left(-\frac{time\,frame}{return\,period}\right)} \tag{2}$$

The value of each exceedance probability at each return period of the earthquake can be seen in Table 5.

Table 5. The value of exceedance probability for all return periods.

Return period (years)	Exceedance probability (%)
500	9.51
2500	1.98
10000	0.49

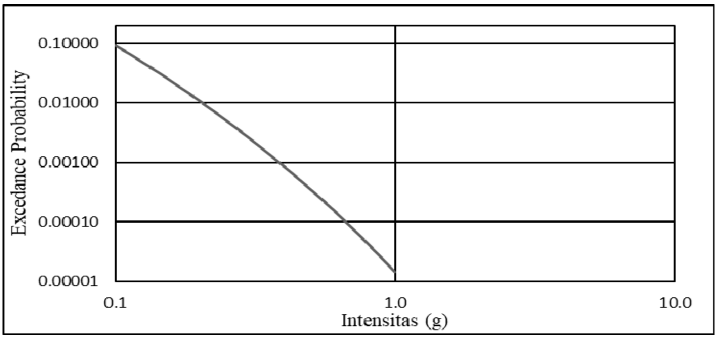

Fig. 9. Exeedance probability curve for the location of the dam.

The results of the probability analysis shows that along with an increase in intensity, it will be accompanied by a decrease in the probability of exceedence and the greater the intensity, the less likely the occurrence. The Exceedance probability curves can also be used to determine the value of an intensity by pulling the line up to the intensity in the Fig. 9.

3.3 Deaggregation

The PSHA is basically a method used in estimating an earthquake threats based on the collection of results of all earthquake events that might occur in the future however, a possible earthquake event cannot be seen clearly in PSHA. With this condition, the PSHA becomes less complete, providing information about the earthquake M and R parameters. To complete the method, deaggregation is needed for each earthquake source modeled. Deaggregation results in controling magnitude ($M_{controling}$) and the earthquake distance control ($R_{controling}$) provide the greatest contribution to the probabilistic seismic hazard analysis. An example of the result for 10,000 years return period is shown in **Fig. 10**. It shows that the most influencing earthquake for the Sutami dam is the earthquake with a magnitude of 5.93-6.17 and a distance of 22-44 km.

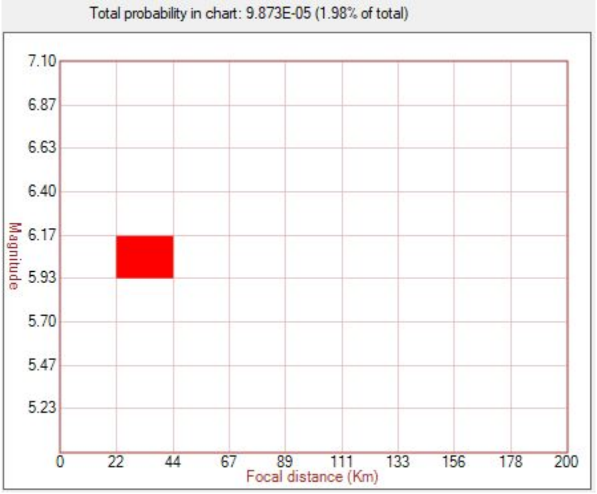

Fig. 10. The result of deagregation for 10,000 year return period.

3.4 Ground motion

Due to the record data of ground motion for the Sutami dam been unavailable, the ground motion from other locations with similar properties might be utilised. For this, the data of the focal distance (R) and magnitude (M) obtained from the deaggregation process for the Sutami dam was sent to the Pacific Earthquake Engineering Research (PEER) website. This institution has many ground motion database across the world with a wide variation of R and M. According to PEER, some ground motion records to be utilised for the Sutami dam includes; Morgan Hill earthquake 1984, Whittier Narrow earthquake 1987, Chalfant Valley earthquake 1986, Georgia USSR earthquake 1991, Northridge earthquake 1994, and San Fernando earthquake 1971.

4 Conclusions

Based on the PSHA, it can be concluded as follows. The peak ground accelerations (PGA) for the Sutami dam are 0.261 for a 500-year return period, 0.41 for a 2500-year return period and 0.586 for a 10,000-year return period. Deaggregation process indicates that the most influencing magnitude M and distance R for Sutami dam are 5.93 - 6.17 and 22 - 44 km respectively. Due to the lack of ground motion data for Sutami dam, the ground motion from other earthquake might be utilised such as the Morgan Hill earthquake 1984, Whittier Narrow earthquake 1987, Chalfant Valley earthquake 1986, Georgia USSR earthquake 1991, Northridge earthquake 1994, or San Fernando earthquake 1971.

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