STUDIES ON THE SEISMIC BEHAVIOUR OF THE LEANING TOWER OF PISA

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SUMMARY

Acceleration time histories for certain location exhibit specific geological condition and specific earthquake parameters such as the value of maximum ground acceleration, duration, and frequency content for that location. Because there are no earthquake ground motions recorded near Jakarta, generation of unique artificial ground motions for bedrock of Jakarta is therefore considered necessary.

The generation is based upon tectonic setting, seismic hazard, and estimated response spectra at bedrock of Jakarta. The seismic sources cover the earthquake potential to a depth of 200 km beneath Java and South-eastern Sumatra. They include the Great Semangko Fault, shallow crustal surrounding Jakarta and subduction zones of Sumatra and Java. The seismic hazard is conducted for 10% probability of exceedence in 20 years and 50 years. Two attenuation relations are chosen to represent surficial fault and subduction zone for determination of maximum acceleration and response spectra at bedrock. Attenuation relation proposed by Boore et al., (1997) is selected for the Great Semangko Fault, and shallow crustal and attenuation relation proposed by Youngs et al. (1997) for subduction environments of Java and Sumatra.

INTRODUCTION

Indonesia is surrounded by four major tectonic plates of the earth; Eurasian, Australian, Pacific, and Philippine plates which caused Indonesia region is one of the most seismically active zones; at the same time it has a leading position from the view of active and potentially volcanoes. This has caused Indonesia as one of the earthquake prone countries in the world. Based on the list of Indonesian earthquakes, which have been compiled by national and international foundations showed that the total number of earthquakes that occurred during 1897-1992 with magnitude, $M_s \geq 5$ is approximately 8237 and 5% from that number occurred around Java Island. Epicenter locations of the above earthquake can be seen in Figure 1.

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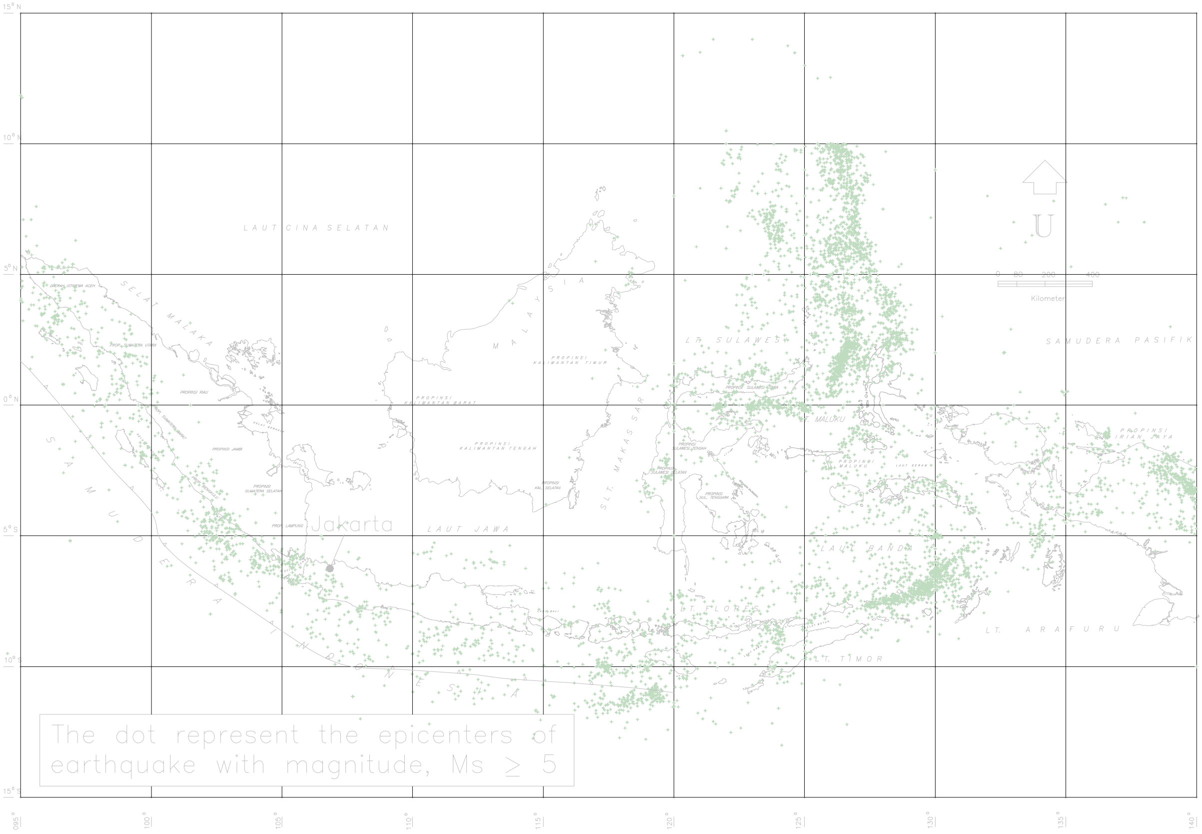

Figure 1. Indonesian seismic activity.

Based upon the Directorate of Environmental Geology, earthquake is one of the largest disasters in Indonesia. The 1992 Flores earthquake, for example, that struck a relatively remote island registered at 6.8 on Richter has inflicted more than 2000 fatalities, hundreds of grave injuries, thousands of destroyed houses and damaged buildings (Irsyam, et. al, 1994,1997).

Acceleration time histories for certain location exhibit specific geological condition and specific earthquake parameters such as the value of maximum ground acceleration, duration, and frequency content for that location. Unfortunately, there are no earthquake ground motions recorded near Jakarta. Therefore generation of unique artificial ground motions for bedrock of Jakarta as a Capitol City of Indonesia is considered necessary.
The list of Indonesian earthquakes to be used in this study has been compiled primarily from the following four sources:

1. Earthquake listings held by National Earthquake Information Center (NEIC), U.S. Geological Survey (USGS) of the United States, which is a compilation of several catalogs from sources such as: The Bureau Central International de Seismologie (BCIS), the International Seismological Summaries (ISSN), the International Seismological Center (ISC), the Preliminary Determination of Epicenters (PDE), and catalogs compiled by individual such as: Abe (1981, 1984), Abe and Noguchi (1983a, 1983b), Pacheco and Sykes (1992) and Guttenberg and Richter (1954).
2. Indonesia earthquake listing prepared by the Meteorological & Geophysical Institute, Jakarta, Indonesia.
3. Newcomb and McCann (1987) catalog where several large events in Indonesia have been relocated.
4. Pacheco and Sykes catalog (1992) where the earthquakes was corrected for heterogeneities caused presumably by changes in instrumentation, reporting and/or detection capabilities.

This paper presents the generation of synthetic ground motions for bedrock of Jakarta. The generation of artificial ground motions is developed for the 200 years and 500 years return period earthquake. The generation is based upon tectonic setting, seismic hazard, and estimated response spectra at bedrock Jakarta. Ground motion parameters and response spectra at bedrock Jakarta are evaluated based on the total probability theorem, and generation of artificial ground motion is developed based on random vibration theorem.

In order to generate the ground motion parameters, the following work is performed: 1) reviewing and researching literature on available regional geologic and tectonic setting to identify the regional earthquake activity and to prepare a seismic source model for use in the seismic hazard analysis, 2) seismic hazard analysis to estimate ground acceleration for Indonesia based on 200 years and 500 years return period earthquake, 3) estimation of response spectra at bedrock Jakarta based on 200 years and 500 years of return period of earthquake, and 4) generation of artificial ground motions that match target response spectra.

REGIONAL SEISMICITY AND SEISMIC SOURCES

List of regional seismicity from the NEIC database within the radius of 200 km and magnitude of M_s > 5 indicates that nearly all of the events occurred along the Sunda Arc region and Sukabumi fault. One large event (M_s=7.5) occurred on April 16, 1957 in the Java Sea with epicenter distance of 170 km from Jakarta. However, when this data was examined more closely, it was discovered that it was a deep event with depth of 546 km. The largest shallow event within 200 km from Jakarta occurred on June 24, 1949 (M_s=7.2). The epicenter of this event which is originally reported to occur at (5.8^0S, 106.1^oE) was relocated further south by Newcomb and McCann (1987) to (6.24^oS, 105.39^oE) which is in the Sunda Strait. Only three small shallow earthquakes have been recorded within radius of 100 km from Jakarta area in the last 92 years. The first event occurred on November 2, 1969 with M_s=5.2, depth equal to 57 km and the epicenter distance of 48 km from Jakarta. The second event occurred on February 9, 1975 with M_s=5.6, depth equal to 27 km and the distance of 58 km. The third event occurred on February 10, 1982 with M_s=5.3, depth equal to 39 km and the distance of 76 km. This observation suggests that the shallow depth seismicity of Jakarta is at best moderate.

In comparison, there are only three small intermediate earthquakes have been recorded within radius of 100 km from Jakarta area in the last 92 years. The first event occurred on July 12 1963 with M_s=5.2, depth equal to 133 km and the epicenter distance of 70 km from Jakarta. The second event occurred on November 24, 1964 with M_s=5.3, depth equal to 130 km and the distance of 88 km. The third event occurred on October 9, 1985 with M_s=5.9, depth equal to 103 km and the distance of 67 km. Similar to shallow earthquake, this observation suggests that the intermediate depth seismicity of Jakarta is moderate.

By contrast, earthquake lists shows that there are neither shallow nor intermediate depth earthquakes occur in the Java Sea in the last 92 years. Accordingly, regional seismicity observation suggests that Jakarta area is relatively stable which is consistent with the finding that the uppermost sediments of Sunda Shelf are not faulted. It is expected that the large event that has significant effects on building structures in Jakarta might occur on Sumatra or Java segments which are located more than 200 km southwest or southward of Jakarta. Based on the evaluation of regional seismicity, it is appropriate to assign maximum magnitude M_s=6.0 for background seismicity in the seismic hazard analysis to estimate ground acceleration for Jakarta.

List of Indonesia Earthquake occurring before 1963, i.e., prior to the establishment of the World Wide Seismograph Network (WWSN), occur much more frequently than the events since 1963. This heterogeneity has been investigated by Perez and Scholz (1984), who concluded that the apparently greater activity rates for the earlier large shocks are not real, and these rates are overestimated relative to recent activity rates because of (1) the nonuniformity of magnitude determinations throughout the 20^{th} century, and (2) changes in the type and numbers of seismographs deployed. For example, the earthquake that occurred on February 27, 1903 approximately 220 km south of Jakarta was originally estimated by Guttenberg and Richter (1954) as M_s=8.1 event. This magnitude is about 0.7 units larger than the values of surface-wave magnitudes (M_s) computed by Abe (1981, 1984) and Abe and Noguchi (1983). This event was recomputed by Abe and Noguchi (1983) to have a surface magnitude M_s=7.4, and again was recomputed by Newcomb and McCann (1987) to have a surface magnitude M_s=7.6.

In order to differentiate seismic sources, earthquake source zones are classified into subduction and transform fault. Earthquakes that occurred near convergent boundaries where an oceanic plate is being subducted under an island arc or continent are classified into subduction zones. Thrust fault earthquakes along the interface, normal faulting events seaward of them along the outer arc high and in the trench, and reverse and strike-slip faulting events in the upper plate are taken to fall within this classification as long as they are near a convergent margin of the subduction zone. The strike-slip events along clearly defined fault in the frontal arc area such as Sumatra Fault is classified as transform fault.

The gross configuration of the subduction zone was investigated by mapping in detail to determine the location of the Sunda Arc subduction zone along portions of the Sumatra and Java segments adjacent to Sunda Strait. Spatial distribution of earthquakes were constructed for four segments along the Sunda Arc by projecting the seismicity onto vertical plane perpendicular to the strike of the arc using the regional seismicity data recorded since 1900. Tectonic features that affected Jakarta region is then further divided into three different Classifications as shown in Figure 2. Although all segments are seismically active, only Sumatra segment has experienced a great earthquake ($M_w \geq 8.5$) during the last two centuries. The locations of the segments are shown in Figure 2.

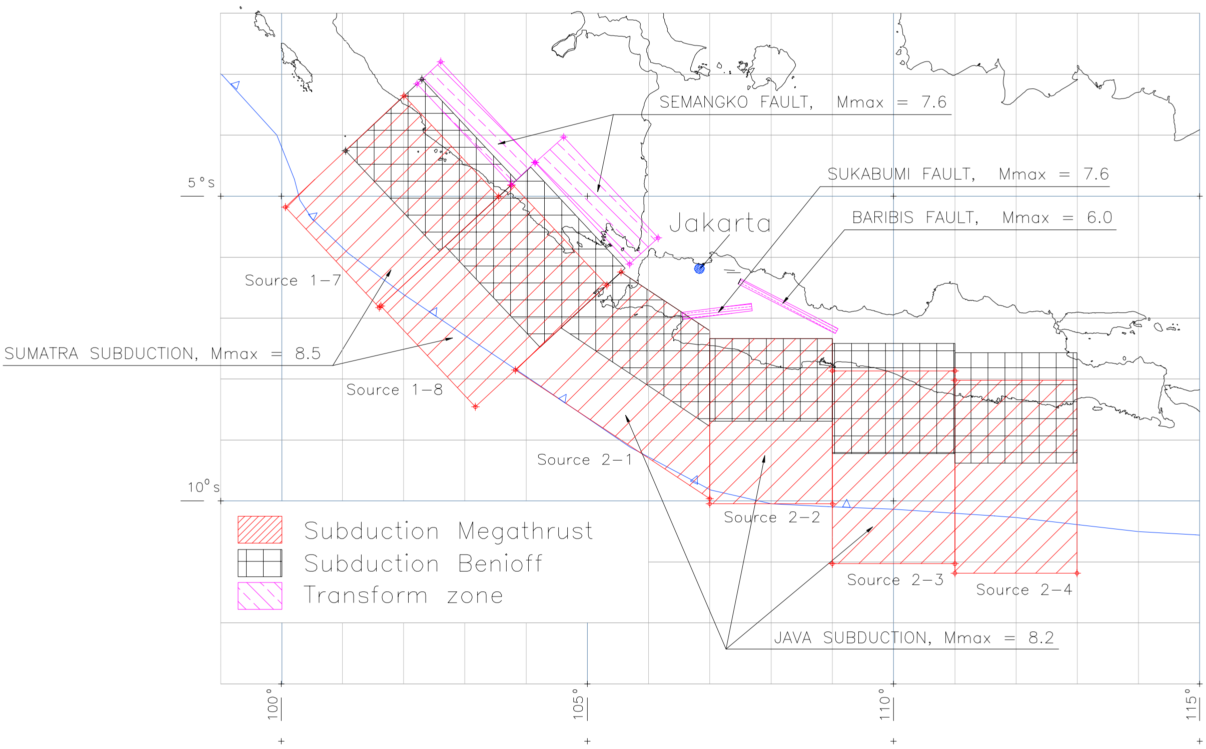

Figure 2. Earthquake source modelling for Jakarta

ANALYSIS OF SEISMIC HAZARD

Evaluation of Seismic Hazard Parameters

Seismic hazard parameters are needed to fully describe earthquake activity within the earth crust in a certain region. A seismic source model provides a description of potential future earthquake in terms of their spatial variations, rupture sizes and frequency of occurrences. There are three basic steps involved in source characterization: 1) identify regional geologic structures within the earth's crust that are potential sources for future earthquake, 2) determine maximum size of future earthquakes for each source, and 3) estimate the recurrence rate of various size earthquakes for each source.

Estimation of the seismic hazard parameters in the frequency-magnitude has been the subject of several papers and research efforts since Guttenberg and Richter first put fort the equation in 1954. A method for developing unbiased recurrence relationship which are consistent with the available geological, historical and instrumental occurrence information which was developed by Dong et. al. (1984) is used in this study. Dong et al. showed that the probability density function f(m) is:

$$f(m) = \frac{\lambda_1 \cdot e^{-\lambda_1 (m - m_o)}}{1 - e^{-\lambda_1 (m_u - m_o)}} \qquad m_o \leq m \leq m_u \qquad (1)$$

where m_o is the threshold magnitude of engineering interest (in this study $m_o = 5$) and m_u is the upper magnitude above which a source cannot generate any bigger earthquake.

Maximum Magnitude

A realistic risk analysis must admit a regional maximum possible magnitude, eventhough it may not yet be possible to estimate this magnitude reliably. In this study, the maximum magnitude for each seismic source has been estimated independently by using historical data, geophysical consideration, and seismic moment listed in Pacheco & Sykes catalog's (1992).

The maximum magnitude, which can occur in a region, can be inferred from geophysical consideration of crustal structure and dynamics. The maximum magnitude for subduction zone can be estimated from the expression for the seismic moment that is combined with Kanamori's (1977) moment-magnitude formula. In this study, rigidity of the rock, μ, is taken to be $\mu = 5 \times 10^{11}$ dynes cm^{-2} (Newcomb and McCann, 1987). It is assumed that the thickness of seismic lithosphere is 35 km with a dip angle of 40^0, and the length of rupture is calculated using the relationship proposed by Slemmons and Chung (1982).

Ground Motion Attenuation Relationship

An essential factor to be considered in the probabilistic seismic hazard assessment is the modeling of the decay with the distance of seismic waves from the earthquake focus. The attenuation relationships for rock for subduction earthquake developed by Young's et al. (1997) and for shallow crustal earthquake developed by Boore et al.(1997) are selected.

a. Attenuation Relationship for Subduction Zones

Attenuation relationship for subduction – related earthquake, in general can be divided into two categories: relationship for the interface and intraslab events. Interface earthquakes represent low angle thrust events occurring at the interface between the downgoing and overriding plates in subduction zone. Intraslab events are usually high angle normal faulting events that occur within the subducting oceanic plate at depths typically greater than 50-km (Youngs et al., 1997). One of the relationships that was proposed recently for rock and deep soil is that of Youngs et al. (1997);

$$\ln(PGA) = 0.2418 + 1.4 \cdot M - 2.552 \cdot \ln(R + 1.7818 \cdot e^{0.554M}) + 0.00607H + 03846 \cdot Zt \quad (2)$$

b. Attenuation Relationship for Crustal Earthquakes

There has been an increase in the number of attenuation relationship in the last decade since there has been a great number of additional ground motion data that have been recorded during more recent earthquakes. The newer models are expected to be more sophisticated in their functional forms and analytical techniques, as more information about ground motion and factor affecting it become available. One of the relationship that was proposed recently for several types of soil is that of Boore et al. (1997). It has the following equation:

$$\ln(PGA) = b_1 + 0.527(M - 6) - 0.778 \cdot \ln(R) - 0.371 \cdot \ln \frac{V_s}{1396} \quad (3)$$

Maximum Peak Ground Acceleration at Bedrock of Jakarta

Maximum Peak Ground Acceleration (PGA) with 10% of not being exceeded in a life time of 20 years and 50 years (T_R = 200 years and T_R = 500 years) for Jakarta is calculated using the modified version of EQRISK (1976) and based on probability of seismic hazard analysis. The calculation result can be seen in Figure 3. The PGA at bedrock of Jakarta for 200 years and 500 years return period are 129 gal and 175 gal respectively.

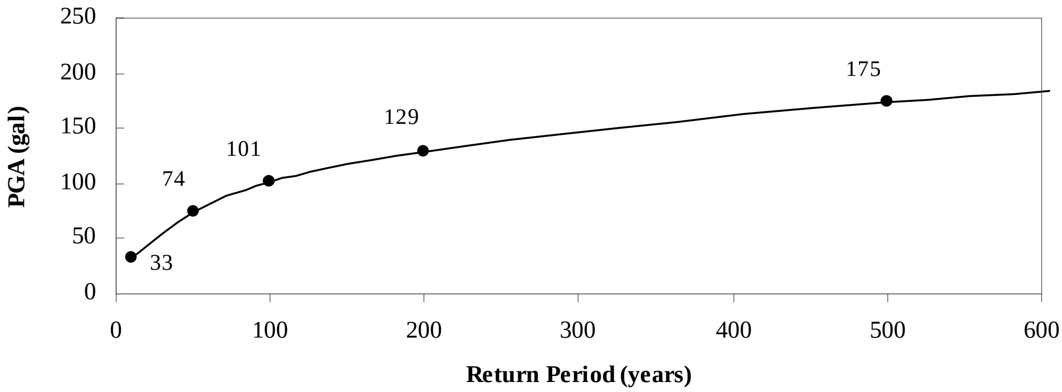

Figure 3. Peak Ground Acceleration at bedrock of Jakarta for several return periods

DEVELOPMENT OF SYNTHETIC GROUND MOTIONS

There are several procedures that can be used to select earthquake ground motions at bedrock. These procedures include: (1) utilization of motions previously detected near the site; (2) Utilization of motions previously recorded at other locations during similar size earthquake and at distance comparable to those under consideration; (3) estimation of a target spectrum and then generation of a synthetic time history whose spectral ordinates provide a reasonable envelope to those of the target spectrum. Procedure number (1) can not be conducted for Jakarta because there are no strong motions detected near the site. Procedure number (2) is difficult to utilize at most locations because the number of recorded motions is not extensively enough to cover a sufficiently wide range of possibilities. Procedure (3) is therefore selected to generate synthetic ground motions.

Target Spectrum

Target spectrum is required to generate a synthetic time history. The spectrum can be obtained from seismic hazard analysis by using attenuation relationships for response spectrum. The attenuation relationships for rock site developed by Youngs et al. (1997) and developed by Boore et al.(1997) are selected for subduction earthquakes and for shallow crustal earthquakes respectively. Youngs divides subduction earthquakes into two categories; interface and intraslab events. The relationship that was proposed by Youngs et al. (1997) for target spectrum can be seen in equation (4).

$$\ln(PGA) = 0.2418 + 1.414 \cdot M + C_1 + C_2(10 - M)^3 + C_3 \ln\left(r_{rup} + 1.7818 e^{0.554M}\right) + 0.00607H + 03846 \cdot Z_T \quad (4)$$

Attenuation relationship proposed by Boore et al. (1997) for shallow crustal is presented in equation (5).

$$\ln(PGA) = b_1 + 0.527(M - 6) - 0.778 \cdot \ln(R) - 0.371 \cdot \ln\frac{V_s}{V_A} \quad (5)$$

Seismic hazard analysis is then conducted by applying the above equations to obtain target spectrum at bedrock of Jakarta. The result of hazard analysis using the modified version of EQRISK (McGuire, 1976) is presented in Figure 4.

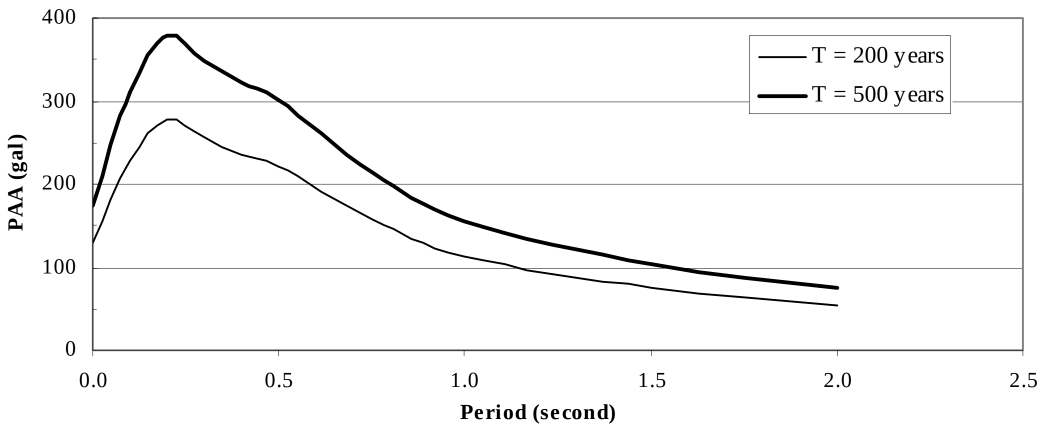

Figure 4. Target spectra at bedrock of Jakarta for 200 years and 500 years return period.

Synthetic Earthquake Ground Motions

Procedure for generating synthetic ground motion based on random vibration theorem has been described by Gasparini and Vanmarcke (1976). This procedure requires the following information; maximum ground acceleration, target spectrum, duration and envelope intensity function.

Maximum accelerations and target spectrum at bedrock of Jakarta have been describes in the previous sections. The duration and envelope intensity function are needed in order to simulate the transient character of real earthquakes. There are three different intensity envelope functions available such as trapezoidal, exponential, and compound. In this study, duration and envelope intensity function are calculated based on a procedure proposed by Kuda (Newject Inc, 1996).

Synthetic ground motions for 200 and 500 years return period at bedrock of Jakarta is then generated by using SIMQKE program (Gasparini and Vanmarcke, 1976). The calculation result is shown in Figure 5 and Figure 6.

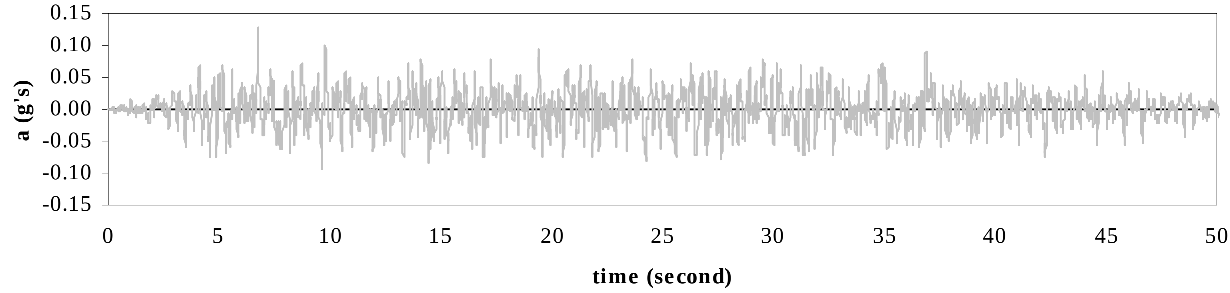

Figure 5. Earthquake ground motion at bedrock of Jakarta for 200 years return period

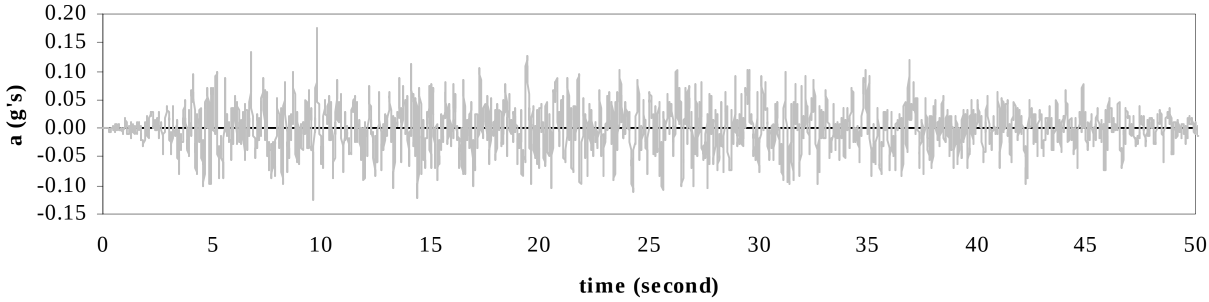

Figure 6. Earthquake ground motion at bedrock of Jakarta for 500 years return period

CONCLUSION

Because there are no earthquake ground motions recorded near Jakarta, generation of unique artificial ground motions for bedrock of Jakarta is therefore considered necessary. The ground motions exhibit specific geological condition and specific earthquake parameters such as the value of maximum ground acceleration, duration, and frequency content for that location. The generation is conducted by estimation of a target spectrum and generation of a synthetic time history whose spectral ordinates provide a reasonable envelope to those of the target spectrum.
In order to differentiate seismic sources, tectonic features that affects the region of Jakarta are classified into three different earthquake source zones. They include subduction megathrust, subduction benioff, and transform zones. Attenuation relationships proposed by Youngs et al. (1997) and Boore et al. (1997) are selected to represent subduction zone and surficial fault respectively. The above relationships are used in seismic hazard analysis to determine maximum acceleration and response spectra at bedrock of Jakarta.

Maximum Peak Ground Acceleration (PGA) with 10% of not being exceeded in a life time of 20 years and 50 years (T_R = 200 years and T_R = 500 years) for bedrock of Jakarta has been performed by using the modified version of EQRISK (1976). The calculation result shows that the PGA for 200 years and 500 years return period are 129 gal and 175 gal respectively.

Generation of synthetic ground motion requires the information of maximum ground acceleration, target spectrum, duration and envelope intensity function. Target spectrum at bedrock of Jakarta for 200 and 500 years return period has been obtained by using attenuation relationships proposed by Youngs et al. (1997) and Boore et al. (1997) for response spectrum. Duration and envelope intensity function were obtained based on a procedure proposed by Kuda (1996). Synthetic ground motions for bedrock of Jakarta were then generated based on random vibration theorem.

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