Proceedings of the 6th Asia-Pacific Structural Engineering and Construction Conference (APSEC 2006), 5 – 6 September 2006, Kuala Lumpur, Malaysia

DEVELOPMENT OF SYNTHETIC TIME HISTORIES AT BEDROCK FOR KUALA LUMPUR

Azlan Adnan[1], Hendriyawan[2], Aminaton Marto[3], Masyhur Irsyam[4]
Structural Earthquake Engineering Research
Faculty of Civil Engineering-Universiti Teknologi Malaysia
Structure and Material Laboratory D-04, Tel. 07 5531748
azlan@seer.org.my[1]; hendri@seer.org.my[2]

ABSTRACT: Acceleration Time-histories of earthquake ground motions are required for analyzing the structural performances and response of soil deposits under seismic loading. Selection of appropriate time-histories for specific geological and seismological conditions plays an important role for obtaining accurate results. Due to lack of representative strong motion data recorded in Malaysia, synthetic ground motions were generated in the frequency domain by using spectral matching analysis and random vibration theory. The uniform hazard spectra (UHS), which are required for developing synthetic time histories, were obtained from probabilistic seismic hazard analysis using attenuation relationships for response spectrum. In this study, two UHS were developed for 10% and 2% Probability Exceedance (PE) in design time period of 50 year or correspond to return period of approximately 500 and 2,500 years, respectively. Two time histories for each hazard level were generated in this study, which represent the most likely and mean contribution magnitude-distance combinations. Finally, the time histories were applied in using 1-dimensional shear wave propagation analysis to obtain peak acceleration and amplification factor at the surface of Kuala Lumpur. The results indicate that the selection of appropriate time histories is one of the most critical in ground response analysis. The accelerations at the surface could be different up to about 35%.

Keyword: synthetic time histories, uniform hazard spectra, probabilistic seismic hazard analysis

1. INTRODUCTION

Acceleration time-histories are the most detailed representation of earthquake ground motion and contain a wealth of information about the nature of the ground shaking. The data are required by engineers or researchers for analyzing the performance of new or existing structures located at a specific site and the response of layered soil deposits under seismic loading. It has been known for many years that selection of time-histories appropriates for specific geological and seismological conditions play an important role for obtaining accurate results (e.g. USACE, 1999; Azlan et al, 2003).

The input ground motions to such analyses are usually selected to be either representative of earthquake scenarios that control the site hazard, or consistent with predefined, "smooth" target elastic response spectra. The two methods that can be used to select earthquake acceleration time-histories at bedrock (USACE, 1999): method 1 is by utilizing existing ground motion time histories recorded near the site and method 2 is by generating artificial ground motions time histories.

The advantage of procedure in method 1 is that the analysis uses natural motions that are presumably most representative of what the structure or site could experience. In this

---

[1] Assoc. Prof. and Head of SEER
[2] Ph.D Student, Faculty of Civil Engineering UTM
[3] Assoc. Prof., Faculty of Civil Engineering UTM
[4] Assoc. Prof., Faculty of Civil Engineering ITB

approach, simple scaling of individual accelerograms by a constant factor is done to improve the spectral fit, but the wave form and the relative spectral content of the accelerograms are not modified. This procedure is difficult to be applied on location in which a lack of representative recording time histories.

The scarcity of real recordings with the desired characteristics has often forced practitioners to generate artificial time histories. Generally, the methods for generating of artificial ground motions fall into two main categories: (1) modifying the existing time histories and (2) developing artificial time histories. A number of techniques and computer programs have been developed either to completely synthesize an accelerogram or modify a recorded accelerogram so that the response spectrum of the accelerogram closely fits or matches the design spectrum. Both of these methods require uniform hazard spectrum (UHS) as a target spectrum to generate the artificial time histories. This spectrum could be obtained from probabilistic or deterministic seismic hazard analysis.

This paper presents the development of synthetic time histories for Kuala Lumpur using spectral matching analysis and random vibration theory (RTV). Two UHS at bedrock of Kuala Lumpur for 10% and 2% probability exceedance (PE) in design time period of 50 years or correspond to return periods of approximately 500 and 2,500 years, respectively, were developed in this study using probabilistic method. Finally, the application of time histories for ground response analysis was also discussed in this paper.

2. TARGET SPECTRUM

Uniform Hazard Spectrum (UHS) is a spectrum of which each point has the same probability of being exceeded. Two basic approaches can be considered in developing UHS for bedrock using a PSHA (USACE, 1999): first is by scaling response spectral shape to PGA, and second is by estimating the entire spectrum on the basis of PSHA for response spectral values at a number of periods of vibration.

In the first approach, a PSHA is conducted to establish the relationship between PGA and frequency of exceedance. The design peak acceleration level is specified by selecting an appropriate frequency, return period, or probability level. A UHS is then constructed by scaling an appropriate spectrum shape to this acceleration level. The selected spectral is based on earthquake size and distance producing the hazard as well as the local subsurface conditions.

In the second approach, PSHA is conducted for response spectral values covering the range of vibrational periods of interest for the project. When the appropriate exceedance frequency or return period to use for design is specified, spectral ordinates are read off each hazard curve and are plotted against frequency. A smooth spectral shape is then drawn through these points to construct the equal-hazard spectrum (a spectrum that has the same probability of exceedance at each frequency).

In this research, the UHS were constructed by combining those two approaches. Two attenuation functions used for subduction earthquakes were developed only for predicting PGA (i.e. Petersen *et al.*, 2004 and Azlan *et al.,* 2005), and thus they cannot be used to generate spectral accelerations (SA). Therefore, attenuations proposed by Youngs (1997) and Campbell (2002) were used in this research to produced SA. The hazard calculations for developing SA for Kuala Lumpur were performed by using total probability theory which assumed the earthquake magnitude, M, and the hypocenter distance, R, as a continuous independent random variable (Cornel, 1968, Merz and Cornel, 1973). The UHS were then constructed by scaling the spectral accelerations to the PGA values. The UHS for 500 years and 2,500 years return periods of earthquakes are shown in Figure 1.

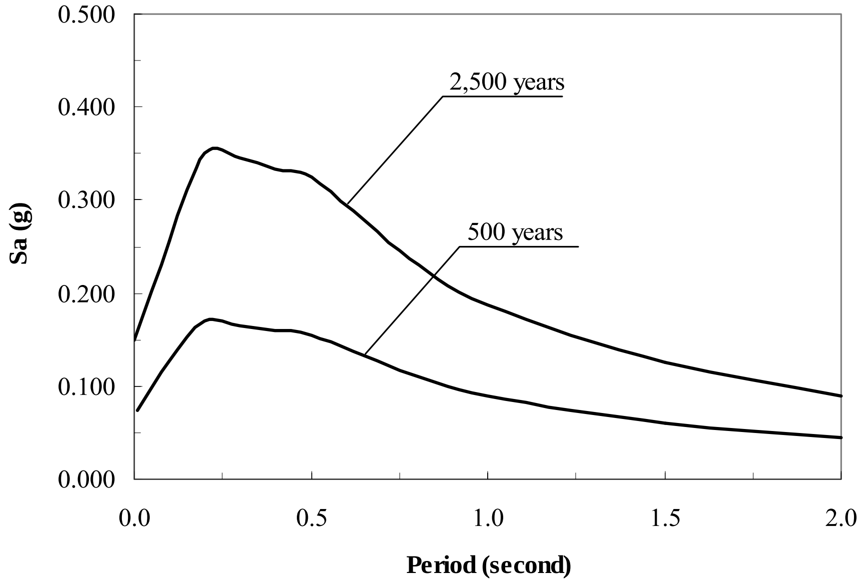


Fig. 1.Uniform hazard spectra at bedrock of Kuala Lumpur

3. DEAGGREGATION ANALYSIS

Consideration of earthquake size and distance is less straightforward in the PSHA than in a deterministic analysis. This is due to the hazard is the result of the possible occurrences of many different earthquakes of varying sizes and distances from the site. In order to generate synthetic time histories, the mean magnitude and distance of earthquakes that control the ground motions at particular response spectral frequencies require to be identified. Thus, the hazard analysis results must be examined to identify the major contributors to the hazard at the ground motion level of interest. This could be achieved through the deaggregation of the probabilistic seismic hazard (McGuire, 1995).

The deaggregation should be carried out for a target annual frequency of exceedance, typically the value selected for determining the design basis ground motion at the site. In order to determine which earthquakes are contributing most to the hazard in Kuala Lumpur, deaggregation analyses were performed to determine the sources that contribute at hazard levels of 500 and 2,500 year return periods. Results of this deaggregation are shown in Figures 2 to 5. The results are summarized in Table 1.

As shown in Figures 2 and 3, the deaggregation plot of PGA ($T \approx 0$ sec) for 10% PE in 50 years shows two overall peaks: one for relatively short distance earthquakes (325 km) and one for a bigger magnitude at about 775 km distance. The short distance earthquakes were probably contribution from Sumatra fault while the M_w, 9.25 was obviously from Sumatra Subduction zone. Generally, the mean contribution for this hazard level is given by magnitude, M_w 8.0 at a distance of 520 km.

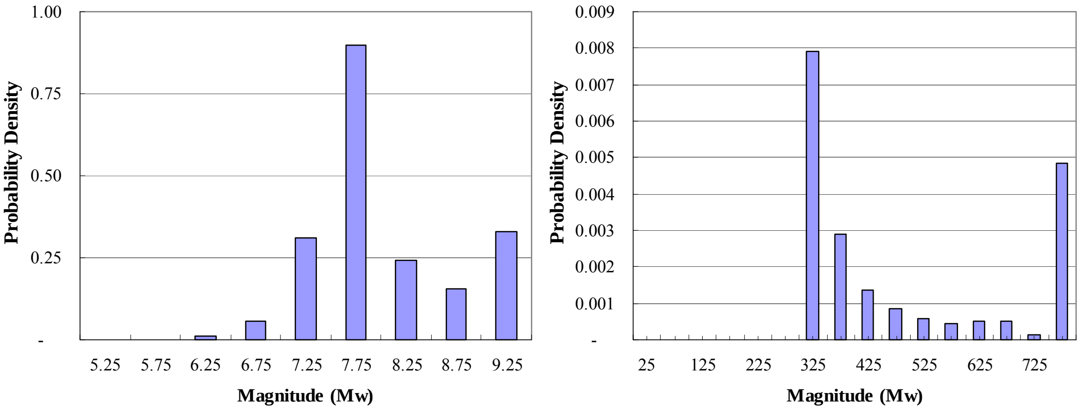


Fig. 2. Hazard contribution by magnitude and distance (for 500 year return period)

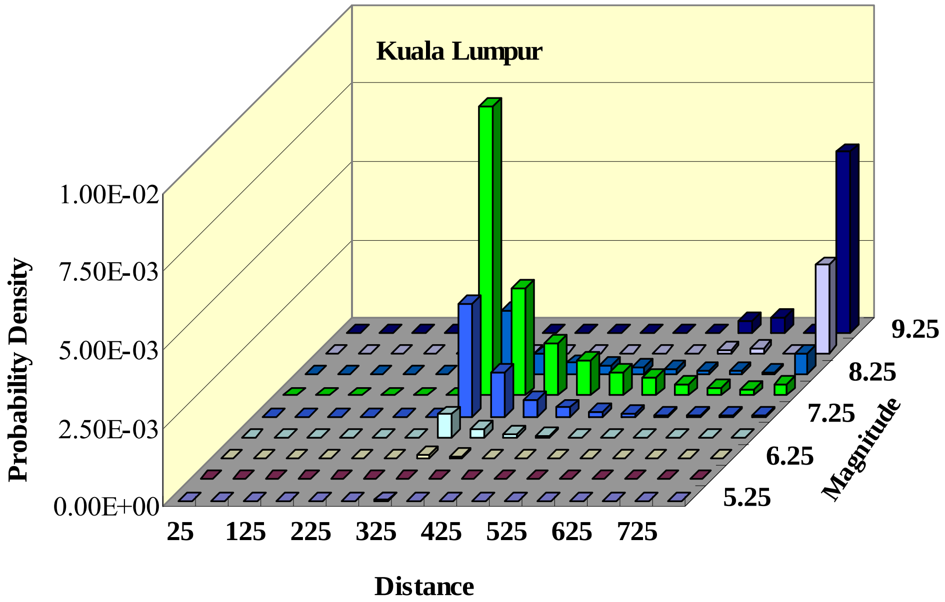


Fig. 3. The relative contribution to the PGA hazard as a function of magnitude and distance at a site in Kuala Lumpur (for 500 year return period)

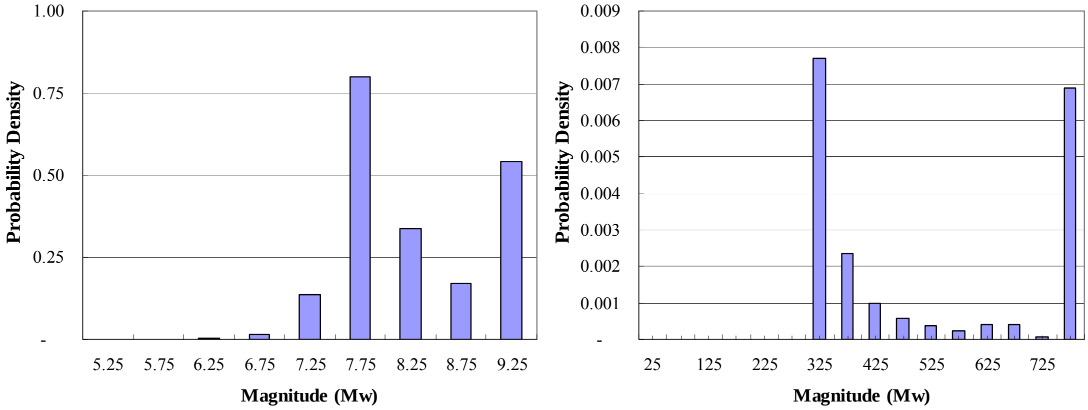


Fig. 4. Hazard contribution by magnitude and distance (for 2,500 year return period)

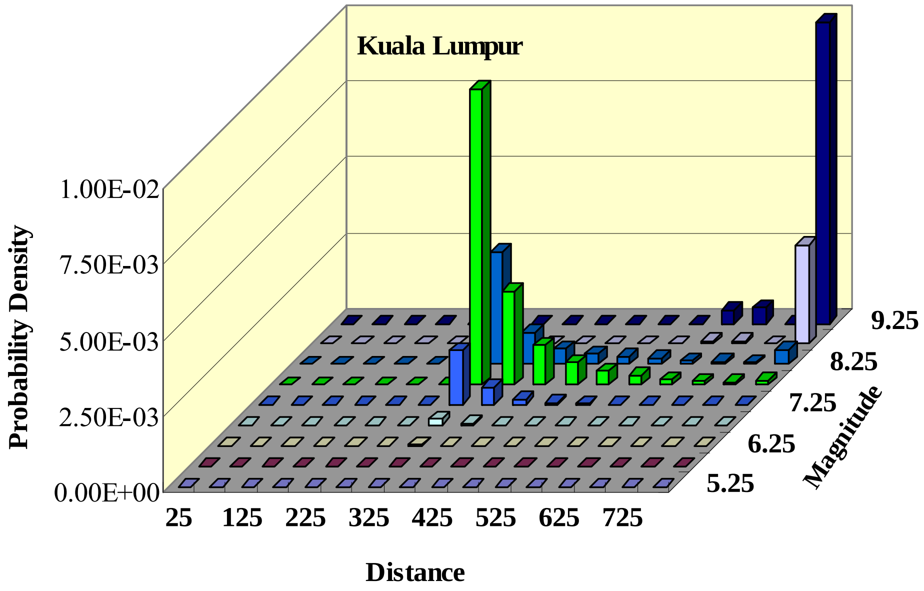


Fig. 5. The relative contribution to the PGA hazard as a function of magnitude and distance at a site in Kuala Lumpur (for 2,500 year return period)

The deaggregation chart for the 2,500 year ground motions shows as the return period is increased; more distant earthquakes with big magnitudes have more contribution to the hazard at a site. Figure 5 shows that the great earthquakes M_w 9.25 at a distance 775 km has a major contribution at a site for hazard level 2% PE in 50 years. The mean contribution for this hazard level is given by magnitude, M_w 8.3 at a distance of 560 km.

Table 1. Deaggregation analysis

No.	**Return Period (Year)**	**Target**		
		M_w	**Distance (km)**	**PGA (g)**
1	500	7.8	325	0.074
2		8.0	520	0.074
3	2500	9.3	775	0.149
4		8.3	560	0.149

4. SYNTHETIC TIME HISTORIES

4.1 Modifying the Existing Time Histories

In order to obtain sufficient records for analysis, it will often be required to use a relatively poor match with magnitude and/or distance. The records selected should then be scaled to compensate for the mismatch of magnitude, distance or other factors, or to obtain a better match with the design spectrum. Even if scaling is done on the basis of any Magnitude and distance mismatches, it will generally still be necessary to check the agreement or otherwise with the design spectrum. Generally, there are two methods for modifying the existing time histories to obtain a time histories that will have a response spectrum as close as desired to the target spectrum. These two methods are frequency domain and time domain.

Generally, a matching procedure in frequency domain does not have good convergence properties, particularly for multiple damping spectra (Takhirov *et al.*, 2005). An alternative approach adjusts the reference time history in time domain by adding wavelets to it. Kaul (1978) proposed a formal optimization procedure for this type of time domain matching that was extended to an algorithm to simultaneously match spectra at multiple damping values developed by Lilhanand and Tseng (1987 ,1988). This procedure has good convergence properties for several damping values, although it is more complex compared to frequency domain approach (Takhirov *et al.*, 2004).

The advantage of using this procedure is the modified time histories will have time-domain characteristics representative of actual ground motions (USACE, 1999). Therefore this method has account aleatory of variability. The existing time histories are primarily selected on the basis of two dominant parameters: magnitude and distance. The appropriate magnitude, M_w, and distance, R, for this formula can be obtained from deaggregation analysis.

There is one difficulty to use this procedure that is the number of recorded motions is usually not extensively enough to fulfill the requirements of certain magnitude and distance bins, especially for large magnitudes and long distances. In this case, the procedure proposed by Gasparini and Vanmarcke (1976) as described in the following section could be used to generate artificial time histories.

4.2 Development of Artificial Time Histories

It is well known that each accelerogram corresponds to a single response spectrum for a given damping ratio that can be defined relatively easy. On the other hand, on each response spectrum could correspond an infinite number of accelerograms. Gasparini and Vanmarcke (1976) originally proposed the method for generating synthetic ground motion based on random vibration theorem. This procedure is based on the fact that any periodic function can be expanded into a series of sinusoidal waves.

$$x(t) = A_0 + \sum_i A_i \cdot \sin(\omega_i t + \phi_i) \tag{1}$$

In Eq. (1) A_i is the amplitude and ϕ_i is the phase angle of the ith contributing sinusoidal. The amplitudes A_i are related to the (one side) spectral density function G (ω) in the following way:

$$A_i = \sqrt{2 \int_o^{\omega_i} G(\omega_i) \cdot d\omega} \tag{2}$$

A relationship between the response spectrum and the spectral density function of ground motion at site can be seen in the following equation.

$$G(\omega_n) = \frac{1}{\omega_n \left[\frac{\pi}{4\zeta_s} - 1 \right]} \left\{ \left(\frac{\omega_n \cdot Sv}{r_{s,p}} \right)^2 - \int_0^{\omega_n} G(\omega) d\omega \right\}^{1/2} \tag{3a}$$

where:

$$\zeta_s = \frac{\zeta}{1 - e^{-2\zeta \cdot \omega_n \cdot t}} \tag{3b}$$

$$r_{s,p} = \left[2 \cdot \log\left\{2n\left[1 - \exp(-\delta_y(s)\sqrt{\pi \cdot \log 2n}\right]\right\}\right]^{1/2} \tag{3c}$$

$$\delta_y(s) = \left(\frac{4\zeta \cdot t}{\pi}\right)^{1/2} \tag{3d}$$

$$n = \frac{-\omega_n \cdot t}{2\pi} \cdot \frac{1}{\log \cdot 0.368} \tag{3e}$$

In Eq. (3), S_v is a spectral velocity, ξ is a damping ratio, s is a duration, and ω_n is a natural frequency. The response spectrum in the equation (3a) is obtained from seismic hazard analysis by using attenuation relationships for response spectrum. The power of the motion produced by using equation (1) does not vary with time. To simulate the transient character of real earthquakes, the steady-state motions are multiplied by a deterministic envelope function I(t). The artificial motion X(t) becomes:

$$X(t) = a(t) = I(t)\sum_n A_n \cdot \sin(\omega_n t + \phi_n) \tag{4}$$

There are three different envelope intensity functions available such as trapezoidal, exponential, and compound (Gasparini and Vanmarcke, 1976). The procedure then artificially raises or lowers the generated peak acceleration to match exactly the target peak acceleration that has been computed by using seismic hazard analysis.

4.3 Time Histories for Kuala Lumpur

In this research, the synthetic time histories were developed using spectral matching analysis and random vibration theory (RTV). The spectrum matching analyses was performed using software EZ-FRISK™ from Risk Engineering Inc. This software provides Norm Abrahamson's time-dependent spectral matching method (Abrahamson, 1998) that has adopted and modified the procedure proposed by Lilhanand and Tseng (1987, 1988). The RTV proposed by Gasparini and Vanmarcke (1976) was also applied in this study to cover long distance earthquakes for certain magnitudes. This is due to there is some difficulties to get the existing time histories that suit with those characteristics. The procedures were performed using software SIMQKE (Gasparini and Vanmarcke, 1976).

The actual ground motions from worldwide earthquakes are selected based on their similarity of their characteristics such as magnitude, distance and site conditions and then the spectrums are scaled for matching them with the spectrums from probabilistic analysis.

The selection and generation of time histories are based on their similarity of their characteristic with the most likely and mean contribution magnitude-distance combinations to give the seismic hazard level 500, and 2,500 year return periods. Two time histories data recorded on the bedrock were selected as shown in Table 2.

Table 2. Selected Time Histories

No.	Return Period (Year)	Target			Sample			Result
		M_w	Distance (km)	PGA (g)	Earthquake Place and Date	M	Distance (km)	Record Name
1	500	7.8	325	0.074	Kocaeli (1999)	7.4	342.4	Synth-1
2	2500	8.3	560	0.149	Kocaeli (1999)	7.6	558.0	Synth-4

The earthquake data for spectral matching analysis (Synth-1 and Synth-4) were obtained from 1999 Kocaeli Earthquake. These records were downloaded from Pacific Earthquake Engineering Research (PEER) Strong Motion Database Record (http://peer.berkeley.edu/smcat/search.html). The results of spectral matching analysis and the synthetic time histories can be seen in Figures 6 to 9.

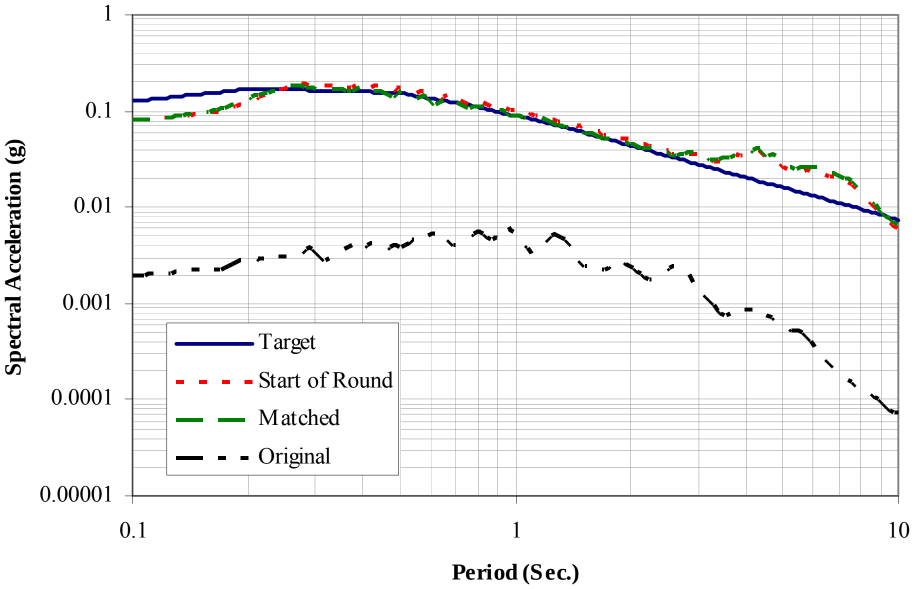


Fig. 6. Spectral matching result for Synth-1 (M_w7.8; R325 km)

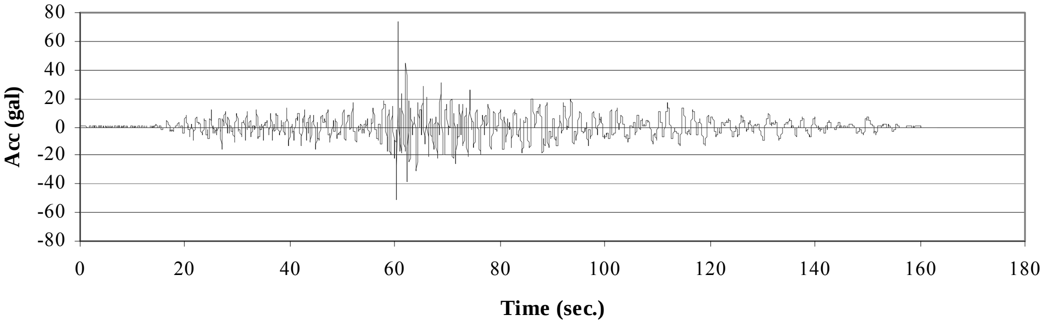


Fig. 7. Synthetic time histories Synth-1 (M_w7.8; R325 km)

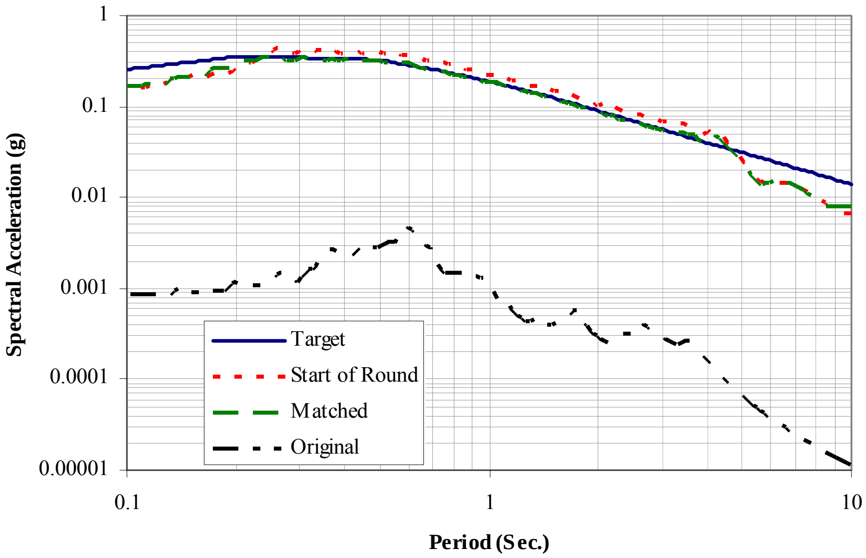


Fig. 8. Spectral matching result for Synth-4 (M_w8.3; R560 km)

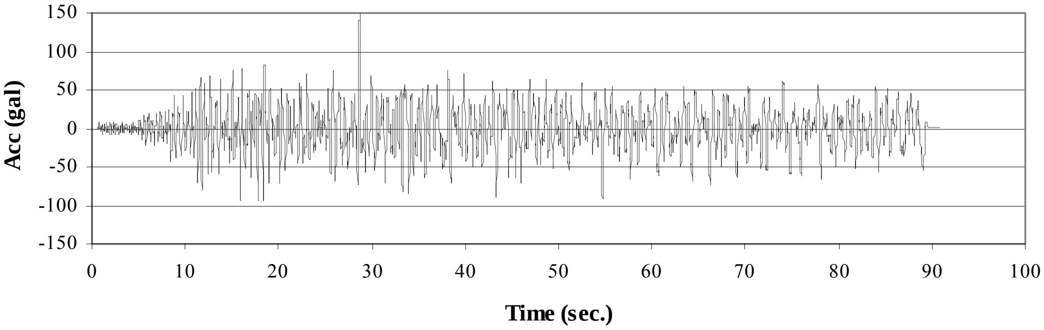


Fig. 9. Synthetic time histories Synth-4 (M_w8.3; R520 km)

Due to there is no record for other magnitude and distance combinations (no. 2 and 3 in Table 1), two time histories for those two combinations were generated synthetically using random vibration theorem (Gasparini and Vanmarcke, 1976). Two time histories are synth-2 and synth-3 that represent 500 and 2,500 years return period of earthquake, respectively. The results from RTV can be seen in Figures 10-13,

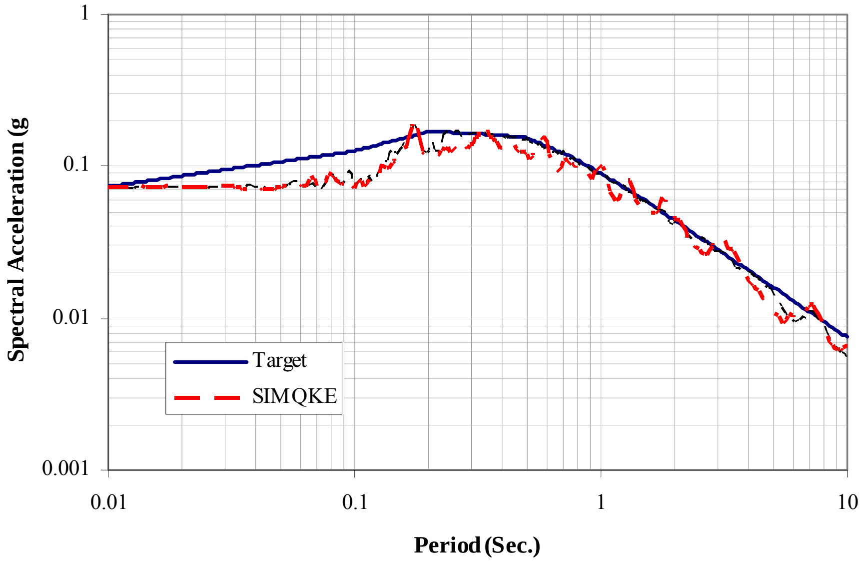


Fig. 10. Spectral Acceleration of Synth-2 (M_w8.0; R520 km)

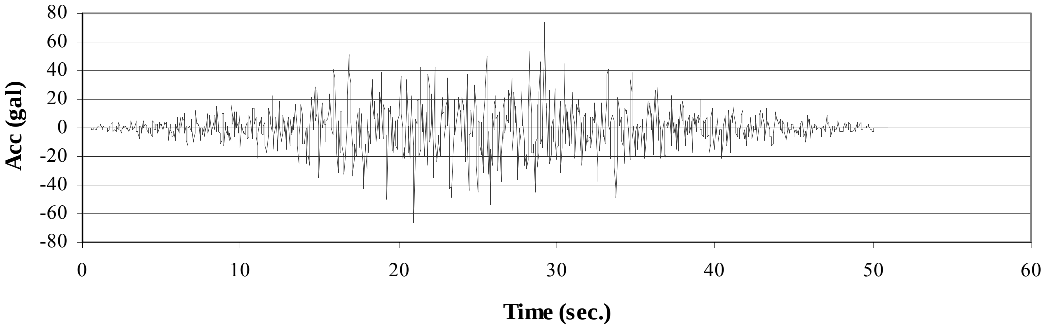


Fig. 11. Time histories of Synth-2 (M_w8.0; R520 km)

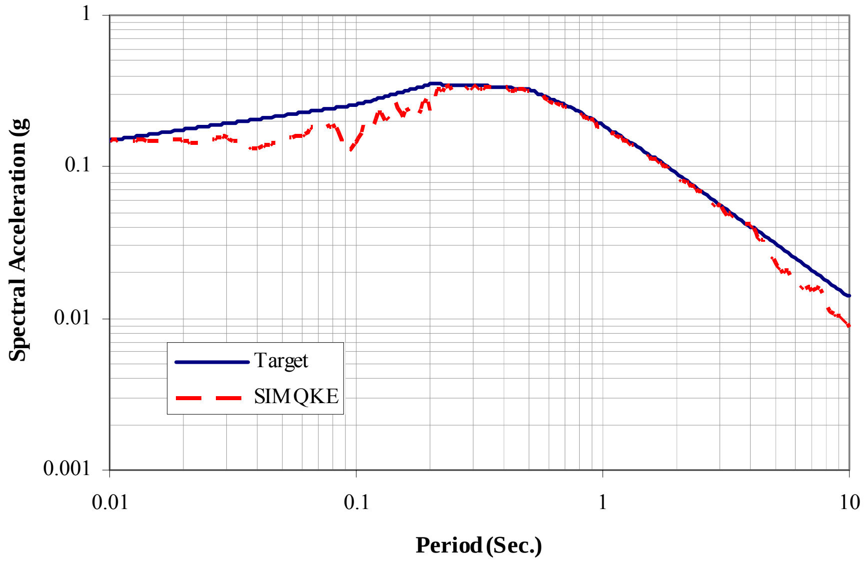


Fig. 12. Spectral Acceleration of Synth-3 (M_w9.3; R775 km)

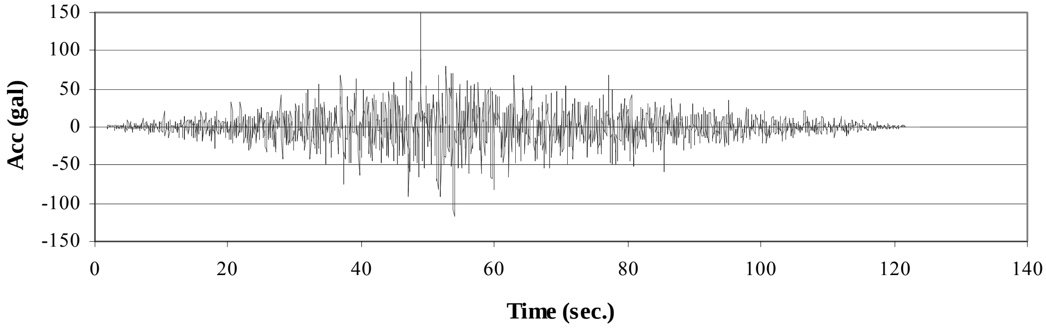


Fig. 13. Time histories of Synth-3 (M_w9.3; R775 km)

5. GROUND RESPONSE ANALYSIS

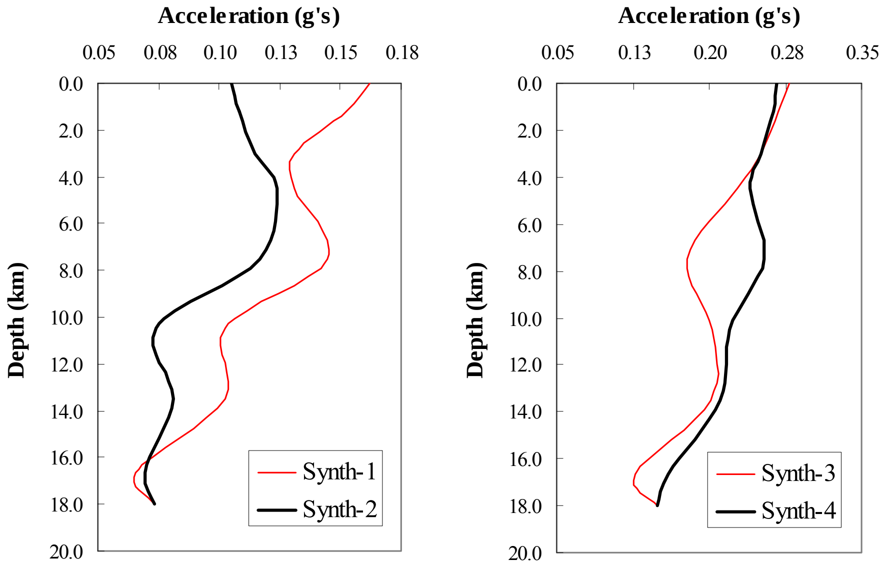
In order to know the effects of using difference time histories, ground response analyses were performed on several locations in Kuala Lumpur using 1-dimensional shear wave propagation analysis. Four time histories were used in the analysis: Synth-1, Synth-2, Synth-3, and Synth-4. Synth-1 and Synth-2 represent ground motion for 500 years return period (PGA=0.074 g), while Synth-3 and Synth-4 represent for 2,500 years return period (PGA=0.149 g). The analyses were performed using nonlinear approach in order to consider the actual nonlinear response of a soil deposit.

Table 3 shows the acceleration at surface and amplification factors on several locations in Kuala Lumpur area. These amplification factors show the ratio between acceleration at bedrock and at surface. Based on the results, most of the ground motions have been amplified at the surface. The results also indicate that the selection of appropriate time histories is one of the most critical in ground response analysis. The selection of time histories could change the results of accelerations at the surface significantly. The accelerations at the surface could be different up to about 35%. It can be seen in Figure 14, the time histories could also change the distribution of acceleration in soil deposits.

Time histories also influence the amplitude of spectral acceleration at the surface produced by ground response analysis as shown in Figures 15 and 16. It also can be seen in the figures, the frequency content of the spectrum is relatively not much different. In other hand, the figure 17 shows that the frequency content of the spectrum is more affected by the stiffness of the soil. According to the figure, soft soil deposits produce greater proportions of long period (low frequency) motions than stiff soil.

Table 3. Results of 1-D analyses for KLCC

No.	Location	PSA (g's)				Amplification Factor			
		Synth-1	Synth-2	Synth-3	Synth-4	Synth-1	Synth-2	Synth-3	Synth-4
1	Location-1	0.111	0.122	0.297	0.232	1.52	1.67	1.99	1.56
2	Location-2	0.158	0.146	0.238	0.245	2.16	2.00	1.60	1.65
4	Location-3	0.143	0.135	0.232	0.289	1.96	1.85	1.56	1.94
5	Location-4	0.112	0.087	0.154	0.169	1.53	1.19	1.03	1.13
6	Location-5	0.162	0.105	0.280	0.267	2.22	1.44	1.88	1.79
7	Location-6	0.160	0.113	0.221	0.223	2.20	1.55	1.48	1.50



a) 500 years *b) 2500 years*

Fig. 14. Distribution of acceleration vs. depth

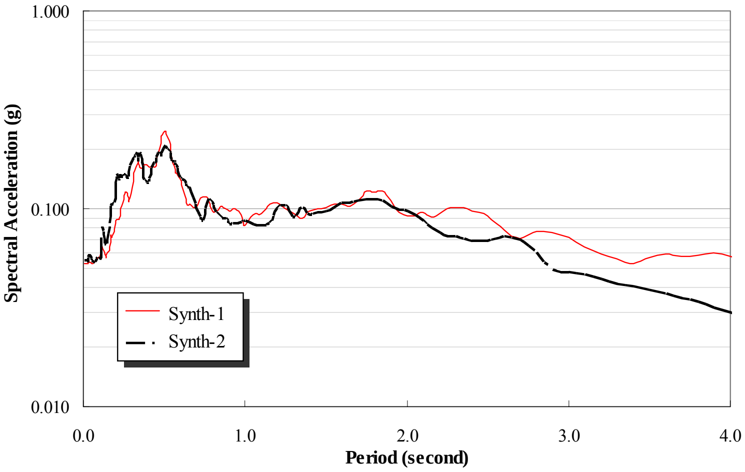


Fig. 15. Spectral acceleration at surface (for 500 years return period)

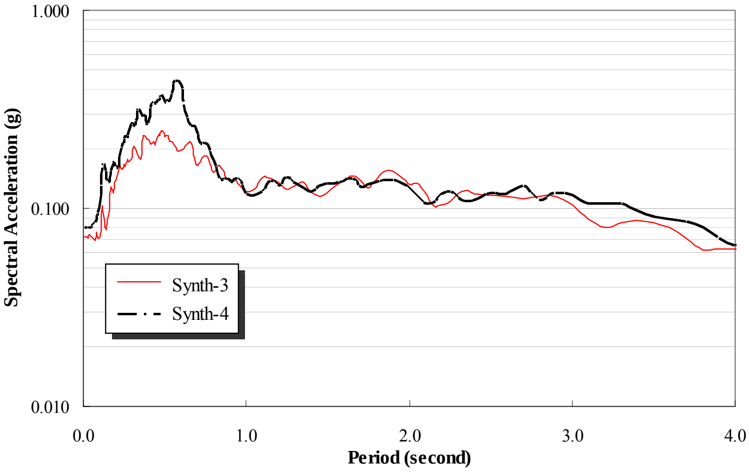


Fig. 16. Spectral acceleration at surface (for 2,500 years return period)

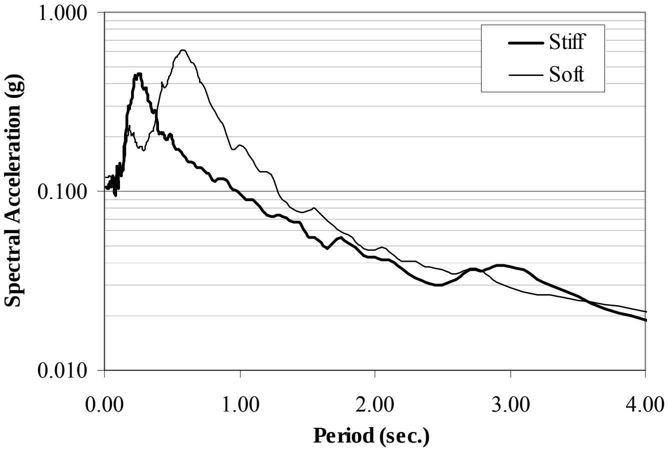


Fig. 17. Effect of soil stiffness

6. SUMMARY AND CONCLUSION

Time histories analyses were performed in this research to obtain a suitable ground motion time histories for Kuala Lumpur. Due to there is no representative data near the location, two methods for generating artificially time histories were applied: modifying the existing record and developing new record. Two time histories for each hazard level were generated in this study. This time histories represent the most likely and mean contribution magnitude-distance combinations to give the seismic hazard level 500, and 2,500 year return periods. These multiple accelerograms are required especially for nonlinear analyses because different accelerograms may have different pulse sequencing characteristics of importance to nonlinear response yet have essentially identically response spectra (USACE, 1999).

The results of ground response analysis show that both of time histories and local soil conditions (soil properties and stratigraphy) are critical to the results of ground response analysis. Generally, time histories affect the amplitude of spectral acceleration, whilst the soil conditions influence the frequency content of the spectrum. Therefore, these two subjects should be considered and determined carefully in ground response analyses.

7. ACKNOWLEDGMENT

The procedure described in this paper has been developed as part of a project funded by the Construction Industry Development Board (CIDB) Malaysia, entitled: "Seismic Hazard Analysis for Peninsular Malaysia for Structural Design Purposes”. This support is gratefully acknowledged.

8. REFERENCES

Abrahamson, N.A., 1998. *Non-Stationary Spectral Matching Program RSPMATCH.* PG&E Internal Report, February.

Azlan Adnan, Aminaton Marto, and Hendriyawan, 2003. The Effect of Sumatra Earthquakes to Peninsular Malaysia. *Proceeding Asia Pacific Structural Engineering Conference. August 26-28.* Johor Bahru, Malaysia.

Azlan Adnan, Hendriyawan, and Masyhur Irsyam, 2005. Selection and Development of Appropriate Attenuation Relationship for Peninsular Malaysia. *Proceeding Malaysian Science and Technology Congress 2005.* Mid Valley, Kuala Lumpur.

Campbell, K.W., 2002. Prediction of Strong Ground Motion Using the Hybrid Empirical Method: Example Application to ENA. *Bulletin of the Seismological Society of America.*

Cornel, C.A., 1968. Engineering Seismic Risk Analysis. *Bulletin of the Seismological Society of America*. Vol. 58, No. 5: 1583-1606.

Gasparini D.A Vanmarcke, E.H., 1976. *SIMQKE : User's manual and Documentation*. Dept. of Civil Eng. Massachusetts Institute of Technology.

Kaul, M.K., 1978. Spectrum-Consistent Time-History Generation. *ASCE J. Eng. Mech*. EM4:781-788.

Lilhanand, K. and Tseng, W.S., 1987. *Generation of Synthetic Time Histories Compatible with Multiple-Damping Response Spectra*. SmiRT-9. Lausanne, K2/10.

Lilhanand, K. and Tseng, W.S., 1988. Development and Application of Realistic Earthquake Time Histories Compatible with Multiple Damping Response Spectra. *Proceeding 9th World Conf. Earth. Engineering*. Tokyo, Japan. Vol. II: 819-824.

McGuire, R.K., 1995. Probabilistic Seismic Hazard Analysis and Design Earthquakes: Closing the Loop. *Bulletin of the Seismological Society of America*. Vol. 85: 1275-1284.

Merz, H.A. and Cornell, C.A., 1973. *Aftershocks in Engineering Seismic Risk Analysis*. Report R73-25. Massachusetts: Department of Civil Engineering, MIT, Cambridge.

Petersen, M.D., Dewey, J., Hartzell, S., Mueller, C., Harmsen, S., Frankel, A.D., Rukstakels, 2004. Probabilistic Seismic Hazard Analysis for Sumatra, Indonesia and Across the Malaysian Peninsula. *Journal of Tectonophysics*. Vol. 390: 141-158.

Risk Engineering (2005). *EZ-FRISK, Software for Earthquake Ground Motion: User's Manual*: Risk Engineering Inc.

Takhirov, S.M., Fenves, G.L., Fujisaki, E., and Clyde, D., 2005. *Ground Motions for Earthquake Simulator Qualification of Electrical Substation Equipment*. PEER Report 2004/07. Pacific Earthquake Engineering Research Center College of Engineering, UC. Berkeley.

U.S. Army Corps of Engineers, 1999. *Response Spectra and Seismic Analysis for Concrete Hydraulic Structures*. Engineer Manual 1110-2-6050. Washington, DC: Department of the Army.

Youngs, R.R., Chiou, S.J., Silva, W.J., Humphrey, J.R., 1997. Strong Ground Motion Attenuation Relationships for Subduction Zone Earthquake. *Seismological Research Letters*. Vol. 68, No. 1: 58-74.