Journal of Geological Resource and Engineering 6 (2018) 105-111
doi:10.17265/2328-2193/2018.03.002

Generation of Synthetic Ground Motion

Hari Ram Parajuli[1] and Rajesh Kumar Shrestha[2]

1. Dept. of Civil Engineering, Pulchowk Campus, Tribhuwan University, Nepal

2. Dept. of Civil Engineering, Thapathali Campus, Tribhuwan University, Nepal

Abstract: The main target of the study is to generate artificial earthquake time histories which are compatible with real earthquakes. A simple frequency-domain method for generating time histories from the given response spectrum is presented in this research. Weighted average response spectra are generated using three attenuation relationships developed for the subduction zonesuitable for Barpak M7.8 earthquake records at TU, Kirtipur. The ground motions are simulated with consideration of source, site, and path. The simulation work is started from noise generation work with windowing, Fast Fourier Transform (FFT) and spectra matching (target and generated) to obtain simulated time history using MATLAB programming language. Simulated ground motions can be utilized as input ground motions for the dynamic analysis and design of new structures as well as retrofitting of existing structures.

Key words: Artificial earthquake, weighted average response spectrum, attenuation relationship, Barpak, Fast Fourier Transform.

1. Introduction

Nepal lies in seismically vulnerable region. This region has high chance of tectonic earthquakes. A real evidence can be recent M7.8 Barpak earthquake [5] followed by M7.3 aftershock in Dolakha that has suffered lots of human, socioeconomic and environmental damages. During field observation it was found that local geology, local seismic site effect, lack of codal considerations during design along with poor construction quality were the main reasons for the massive damage.

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. Hence, the most important parameter in site specific hazard analysis is the generation of time histories. A realistic ground motion representation for a specific site may be considerably different from the stipulated in the codes, which are basically developed for general purpose of design of structures distributed in a larger region. Although contemporary codes consider site effects, they usually do so by lumping groups of similar soil profiles together so that their provisions apply to broad ranges of soil conditions within which the local conditions of a particular site are expected to fall. Because of this, design ground motions developed from code provisions are usually more conservative.

2. Methods of Time Histories Simulation

Mainly there are two methods for the simulation of ground motion.

2.1 Generation of Synthetic (Artificial) Time History in the Time Domain

In this method, the non-stationary nature of ground motion time histories in the time domain is obtained by: (1) multiplying the stationary random time series by a non-stationary envelop function that describes the buildup and subsequent decay of ground motion amplitude and; (2) by changing the frequency content of artificial accelerograms as a function of time to account for temporal variations in the frequency composition of the accelerogram. A target spectrum in probabilistic format is estimated then generation of a synthetic time history will be performed so that time

Corresponding author: Hari Ram Parajuli, Ph. D, associate professor of Civil Engineering, research fields: earthquake engineering, structural engineering, lifeline risk management.

history generated response spectrum and target response spectrum compare well.

2.2 Generation of Synthetic (Artificial) Time History in Frequency Domain

Frequency domain methods are particularly useful for generating motions that are consistent with target response spectra. The method initially assumes initial Fourier amplitude and phase spectra, and then iteratively adjusts the ordinates of the Fourier amplitude spectrum until a motion consistent with the target response spectrum that is produced.

Ongoing through literatures, most of the researches on the generation of ground motion are based on the historical earthquakes regarding the parameters used are based on the recorded accelerograms. Some of the methods are based on random vibration theory to simulate artificial ground motions in time domain or in frequency domain. The motion is generated in time domain whose properties may not be controlled in frequency domain and vice versa in the sense of input energy of ground motion to the structures. Therefore, it is necessary to use the method for simulating earthquake time histories whose properties are controlled in the time domain as well in frequency domain. Hence, frequency domain method is selected for this study to simulate spectrum compatible time history. Flow chart for the simulation procedure is as shown in Fig. 1.

3. Selection of Suitable Attenuation Relationship and Target Response Spectrum

Attenuation relationships provide the relationship between level of ground shaking and distance from the

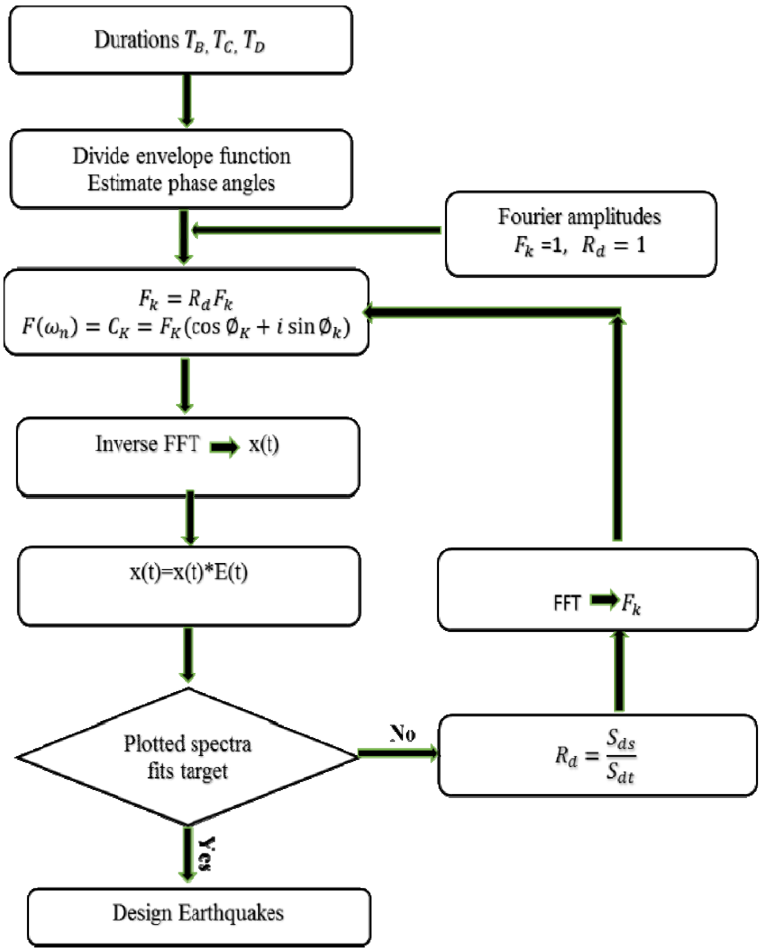

Fig. 1 Flowchart for simulation process.

earthquake source for varying magnitude. These laws, in general, are derived from strong ground motion records for a particular region. Out of several attenuation relationships derived for subduction zone earthquake, equation proposed by Youngs et al. [6] is the best one if no other alternatives are found. In addition, Department of Mines and Geology has also found based on the observed value of acceleration in seismic station that the attenuation law of Youngs et al.[2] is suitable for our country.

When ground motions are generated using spectral values given by Gregor et al. [1] they seem to be closer to the real earthquake time histories. Response spectral values as well as the time histories values given by Kanno et al. [4] are in slightly higher range. Hence more weightage is given by the Youngs et al. [2] and Gregor et al. [3]. Brief description of attenuation laws for horizontal response spectral acceleration (5% damping) followed in this research is highlighted below.

3.1 Youngs et al. [2] (For Soil)

$$\ln(Y) = -0.6687 + 1.438M + C_1 + C_2(10 - M)^3 + C_3 \ln(r_{rup} + 1.7097e^{0.617M}) + 0.00648H + 0.3643Z_T \quad (1)$$

where,

Y = Spectral acceleration in g;

M = Moment magnitude;

r_{rup} = Source to site distance (km);

H = Focal depth (km);

C = Coefficients determined by regression analysis;

Z_T = Source type (0 for interface and 1 for intra slab).

3.2 Gregor et al. [3] (For Soil)

$$\ln(Y) = C_1 + C_2M + (C_3 + C_4M) * \ln[R + \exp(C_5)] + C_6(M - 10)^3 \quad (2)$$

where,

Y = Peak ground parameter in g;

C_1-C_6 = Coefficients;

R = Closest distance to rupture (km);

M = Moment magnitude.

3.3 Kanno et al. [4] (For Focal Depth Less Than 30 km)

$$\log(Y) = a_1M_W + b_1X - \log(X + d_1 10^{0.5M_w}) + c_1 + e_1 \quad (3)$$

where,

Y = Spectral acceleration in cm/s^2;

M_W = Moment magnitude;

X = Epicentral distance (km);

a_1, b_1, c_1, d_1, e_1 = Constants.

Data used:

Data used to generate response spectrum for TU, Kirtipur Soil site are:

Moment magnitude = 7.8 M_W (Barpak Earthquake);

Epicentral distance = 80 km;

Focal depth = 8.3 km;

Significant duration = 45 sec;

Weightages given are:

Youngs et al. [2] = 40% = 0.4;

Gregor et al. [3] = 40% = 0.4;

Kanno et al. [4] = 20% = 0.2;

From the above recorded data at soil site, spectral acceleration values are calculated using earlier mentioned attenuation relationships. Each of the spectral values obtained by the equation proposed by Youngs et al. [2] and Gregor et al. [3] equation is multiplied with coefficient 0.4 and Kanno et al. [4] by coefficient of 0.2. Thus obtained values for different structural periods are summed up to get weighted average response spectrum. Weighted average response spectrum for Barpak earthquake is as shown in Fig. 2.

4. Duration Time and Envelope Function

Duration of earthquake is the function of magnitude and epicentral distance. Thus each earthquake has separate duration. Duration time is related with the time required for the fault to complete rupture. Duration of strong ground motion increases in increasing earthquake magnitude. Total time duration T_D of earthquake is divided into three parts as shown in

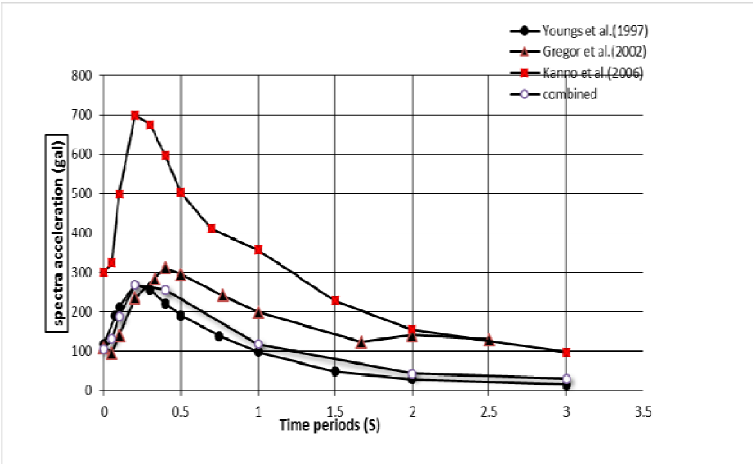

Fig. 2 Weightage average response spectrum for Barpak earthquake.

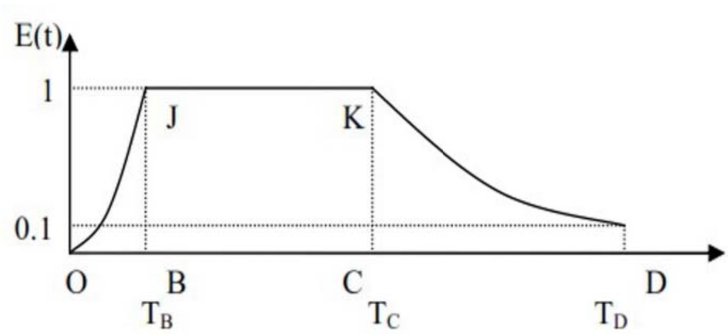

Fig. 3 Envelope function.

Fig. 3. In the first part up to T_B, acceleration will be ascending, between T_B to T_C, it is almost constant and after T_C, it starts descending. T_B and T_C are calculated using equation given by Osaki [6] and T_D is calculated using equation given by Kempton and Stewart [7].

$$T_B = [0.12 - 0.04(M - 7)]\,T_D \quad (4)$$

$$T_C = [0.50 - 0.04(M - 7)]\,T_D \quad (5)$$

$$\ln T_D = \ln\left[\frac{\left(\dfrac{\exp(b_1 + b_2(M-6))}{10^{1.5M+16.05}}\right)^{-1/3}}{4.9*10^6\beta} + c_2 r + c_1 s\right] \quad (6)$$

where, b_1, b_2, c_1, c_2 are coefficients equal to 2.79, 0.82 ,1.91, 0.15 respectively, β is shear wave velocity equal to 3.2 km/sec, s is soil type and equal to one for soil, and zero for rock, M is magnitude of earthquake and r is epicentral distance.

Transient character of real earthquakes can be obtained by the envelope function. The steady state motions are multiplied by deterministic envelope function to make artificial earthquakes compatible with real earthquakes. Typical types of envelop functions are boxer, trapezoidal, exponential and trapezoidal combined with exponential.

Envelope function $E(t)$ can be evaluated using following equations:

$$0 \le t \le T_B : E(t) = (t/T_B)^2 \quad (7)$$

$$T_B \le t \le T_C : E(t) = 1 \quad (8)$$

$$T_C \le t \le T_D : E(t) = \exp\left(\frac{\ln 0.1}{T_D - T_C}(t - T_C)\right) \quad (9)$$

5. Generation of Artificial Ground Motions

There are many methods available for the generation of artificial ground motions. In this study, one used is to express the acceleration time history in terms of following expression as:

$$C_K = \sum_{K=0}^{N} F_K (\cos\phi_k + i \sin\phi_k) \quad (10)$$

where, C_K is the acceleration, F_K is the kth Fourier amplitude, $\emptyset_K$ is the kth Fourier phase angle, n is number of cycles.

In reality, the earthquake gradually increases its magnitude, holds its maximum magnitude for some time, and then decreases. Therefore, to generate more realistic characteristics of earthquake acceleration, an envelope function $E(t)$ needs to be considered. If artificial time histories are multiplied by the function $E(t)$, then Eq. (10) can be redefined as follow:

$$C_K = E(t)\sum_{K=0}^{N} F_K (\cos\phi_k + i \sin\phi_k) \quad (11)$$

The envelope function approximately envelops the time history of the entire earthquake records. Total duration T_D of time history is divided into N number of small divisions Δt ,

$$\Delta t = \frac{T_D}{N} \quad (12)$$

R_d, is ratio of ordinates of simulated spectra (S_{ds}) to target spectra (S_{dt}) and is calculated by:

$$R_d = \frac{S_{ds}}{S_{dt}} \quad (13)$$

The envelope plot is divided into small increments Δt . Using Eqs. (7)-(9), the ordinates of envelope function E (t) are calculated. For each increment cumulative value is determined and normalized by final sum to obtain probability density function. Phase angle for each time step is determined randomly from probability density function over the range [0, 2π]. For the first iteration, Fourier amplitude F_K is assumed as unity. Fourier transform C_K is evaluated following equation:

$$C_K = F_K (\cos\phi_K + i \sin\phi_K) \quad (14)$$

Acceleration at each interval of time is obtained from Inverse Fourier transform. In order to make simulated ground motions similar to real earthquakes, accelerations are multiplied by envelope function. Using the calculated accelerations, response spectra were determined and compared with original spectra called target spectra. Ratio of simulated spectra to target spectra at each interval is obtained by Eq. (13). New Fourier amplitude is then calculated multiplying old amplitude by obtained ratio, R_d. Again Fast Fourier Transform (FFT) is calculated and accelerations are determined. The iteration process is repeated until the simulated spectra and target spectra match.

6. Numerical Study

Durations obtained from empirical Eqs. (4)-(6) are T_B = 3.6 s, T_C = 19.2 s and T_D = 41 s for Barpak earthquake. Then, envelop function is determined using Eqs. (7)-(9). Spectrum compatible acceleration time history is generated by using the steps as shown in flowchart given in Fig. 1. MATLAB program is used for the generation of artificial ground motion for the weightage average target spectrum. This program is capable of producing response spectrum compatible acceleration time history for more than 1,024 (2 N) numbers of data points easily. The program can simulate the time history of any duration for 5% damping value. Iteration continues until the error between simulated spectra and target spectra falls within 0.0005.

The set of phase angle is kept constant for all iterations only changing Fourier amplitude. Matching of simulated response spectrum depends upon the modified (new) Fourier amplitude and consequently, modified Fourier amplitude depends upon the set of random phase angles taken. The method gives response compatible time history for a particular set of phase angles, may be in first iteration or second. If simulated response spectrum is not well fitted with target spectra (weightage average) within second iteration, the method is repeated using another different set of phase angles till the simulated response spectrum fits with target response spectrum i.e. R_d defined by Eq. (13) becomes constant.

7. Results

Following the iterative procedures, final time history is obtained after fifth iteration for weightage average target response spectrum of Barpak earthquake. Considering total duration of earthquake as 55 seconds and to make real time history comparable with simulated earthquake, acceleration after 60 seconds is assumed noise since accelerations are small. Comparison of the simulated time history with real earthquake (Barpak earthquake) after removing noise is made in Fig. 4 which shows that the simulated ground motion is closer to the real earthquake after removing the noise. In Fig. 5 significant duration [3] of Barpak earthquake is taken as 45 seconds, there no significant change in the simulated time history is obtained from the duration calculated by empirical relationships. In real earthquakes, accelerations start from zero, increase gradually, attain peak values and decrease to zero finally. Simulated earthquake also looks like real earthquake. Maximum value of acceleration time history after fifth iteration is 225 gal at 16 seconds which is nearly equal to 230 gal for the

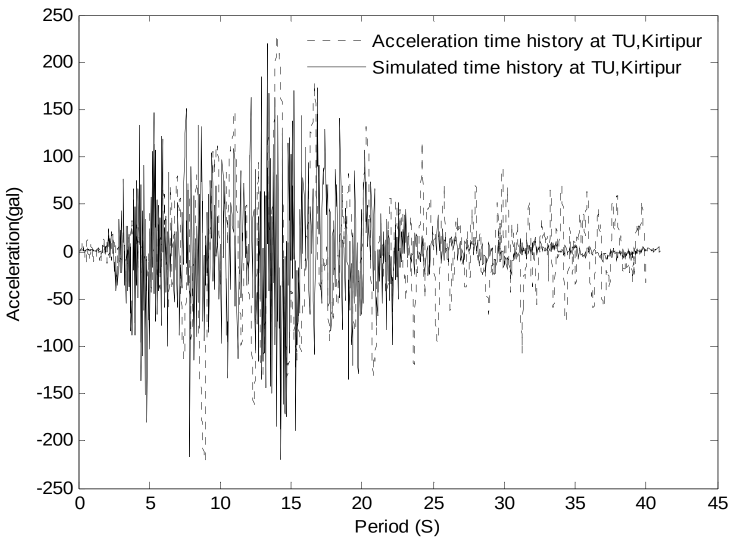

Fig. 4 Comparison of simulated time history with real earthquake after removal of noise.

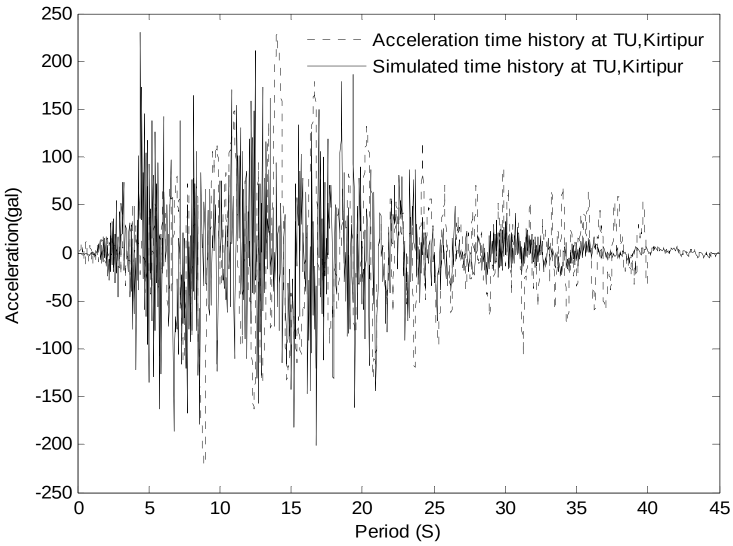

Fig. 5 Comparison of simulated time history with real earthquake for significant duration 45 sec.

M7.8 real earthquake. Shape of acceleration time histories may completely vary for real earthquake and simulated earthquake since the amplitude and nature of earthquake totally depend on the target spectrum. However maximum amplitude of acceleration in both cases is almost equal.

8. Conclusions

Following conclusions can be drawn based on this study:

(1) Artificial ground motions generated from this work can be utilized as an input ground motion for the dynamic analysis of structures which is useful for design of new structures as well as retrofitting of existing structures;

(2) Duration time and envelope function are key parameters for generation of synthetic ground motions. So appropriate value and function should be taken to best represent the more realistic records of real earthquake time histories;

(3) Nature and total duration of acceleration time histories may completely vary with real earthquakes. However the maximum amplitude of acceleration in both cases is almost equal;

(4) Attenuation relationship given by Youngs et al. [2] is the best in case no alternative is found for the region of Nepal. Other attenuation relationships proposed by Gregor et al [3] and Kanno et al [4] can also be used when suitable weightage is given;

(5) From above results, it can be concluded that a simple mathematical expression for these three attenuation relationships can be:

$$C = 0.4 * Y + 0.4 * G + 0.2 * K$$

where, C is the combined spectral acceleration values, Y, G and K are the spectral acceleration values for Youngs et al. [2], Gregor et al. [3] and Kanno et al. [4] respectively.

Acknowledgments

I would also like to thank Mrs. Sunita Ghimire and Mr. Avishek Shrestha for their support in research work.

References

[1] USGS, n.d. http://pubs.usgs.gov/gip/dynamic/undertanding.html,http://earthquake.usgs.gov/regional/world/world_deaths.php. s.l., s.n.

[2] Youngs, R. R., Chiou, S. J., Silva, W. J., and Humphrey, J. R. 1997. "Strong Motion Attenuation Relationship for Subduction Zone Earthquakes." *Seismological Research Letters* 68 (1): 58-73.

[3] Gregor, N. J., Silva, W. J., Wong, I. G., and Youngs, R. R. 2002. "Ground-Motion Attenuation Relationships for Cascadia Subduction Zone Mega Thrust Earthquakes Based on a Stochastic Finite-Fault Model." *Bulletin of Seismological Society of America* 92 (5): 1923-32.

[4] Kanno, T., Narita, A., Morikawa, N, N., Fujiwara, H., and Fukushima, Y. 2006. "A New Attenuation Relationship for Strong Ground Motion Based on Recorded Data." *Bulletin of Seismological Society of America* 96 (4): 879-97.

[5] Parajuli, H. R. 2009. "Dynamic Analyses of Low Strength Masonry Houses Based on Site Specific Earthquake Ground Motions." Kyoto University, Japan.

[6] Osaki, Y. 1994. "Introductory Book for Spectral Analysis of Earthquakes Motion," Kajima Institute of Publishing Co. Ltd.

[7] Kempton, J. J., and Stewart, J. P., 2005. "Prediction Equations for Significant Duration of Earthquake Ground Motions Considering Site and Near-Source Effects." *Earthquake Spectra: November 22 (4): 985-1013.*

[8] Han, J., Liu, L., Yang, O., and Yang, C., "Simulation of Earthquake Ground Motions Compatible with Multi-Damping-Ratio-Spectra Based on Genetic Algorithms." *13th World Conference on Earthquake Engineering, August 1-6, 2004 Paper No. 151.*

[9] Kramer, S. L. 1996. *Geotechnical Earthquake Engineering.* Delhi, India: Pearson Education Pvt. Ltd.