Development of Artificial Earthquake Records in the Philippines using Specific Barrier Model Considering Local Site Conditions

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SUMMARY:
In pursuit of testing earthquake-resilient building models, ground motion records are necessary input in the analysis. Although using actual seismic records has many advantages, there is a lack of strong ground motion records in the Philippines. To compensate these shortcomings, available records in Japan and Taiwan were used to verify the seismological model that was applied in the simulation of the time-history records. A local earthquake record was used to determine the region-specific source parameters of this model to match the local site conditions of the country. Stochastic simulations were performed to generate acceleration time-history records for scenario earthquakes in West Marikina Valley Fault with different magnitudes and distances depending on the current seismic stations in Metro Manila. The peak acceleration produced by a M7.0 earthquake corresponds to the maximum PGA estimate of 0.5g in Metro Manila while the extreme scenario of M7.2 and M7.5 produced 0.57g and 0.63g, respectively.

Keywords: accelerogram, artificial, specific barrier model, local

1. INTRODUCTION

The economic and human loss resulting from recent damaging earthquakes in New Zealand, Haiti and China emphasize the call for evaluating potentially active faults in metropolitan areas. Metro Manila, the highly populated urban region of the Philippines, is subject to devastation from an earthquake on the nearby Valley Fault System (VFS) as well as on the distant plate-boundary faults (Philippine Fault Zone). Predictions of the time-history and maximum ground acceleration of a possible earthquake in VFS are needed to evaluate the current structural design practices and to provide necessary information and precaution for the inhabitants of the affected region. These predictions can be done through actual experiments or analytical modeling.

In the advent of experiment-based earthquake engineering in the Philippines due to the procurement of a shaking table (in the University of the Philippines), seismic ground motion records are necessity. Although we can use foreign earthquake data as input for our experiments, it is our responsibility to obtain data that can be used and simulate our own seismic scenarios in the country. Another reason is that earthquake events are region-specific; therefore records from other countries will not necessarily reflect the behavior of earthquakes here in the Philippines.

Strong ground motion records can be obtained from actual earthquake events through seismometers positioned in seismic stations. Another way of obtaining strong ground motion records is through synthesis of earthquake data using empirical relationships or physical models. Empirical approach is applied by gathering a large amount of actual ground-motion observations from different scenarios and with different characteristics, then constructing a mathematical model to describe those data using regression analysis. Empirical relationships have been developed and successfully implemented for regions where there are sufficient strong ground-motion data, such as California and Japan. It is obvious that the validity of this approach is basically dependent on the sufficiency of data. On the other hand, the second approach is concerned with physical modeling of the problem. In this way, much effort is made to describe the limited observations through physical modeling of the earthquake process. In this approach, limited observations are used just for the calibration of the physical model. Such models have usually been developed in the context of the stochastic modeling approach and random vibration theory (Zafarani et al, 2007).

In present time, there is a lack of available strong-ground motion records in the Philippines due to (1) inefficient recording system in the past especially during the 1990 Baguio earthquake and (2) occurrence of strong magnitude earthquakes after the improvement of seismic stations and network. Due to this fact, most of the seismic studies in the Philippines used earthquake records or just adapted values from the research of other countries.

Using stochastic methods to generate earthquake records, it is possible to simulate actual earthquake time histories, which are close to real data using geologic and seismic parameters. The Specific Barrier Model is one of the effective stochastic models to describe physical processes of earthquakes (Papageorgiou and Aki, 1982, 1983a,b; Papageorgiou, 2003). The advantage of using this model is that it uses relatively few parameters to generate records since it assumes an “average” earthquake and site behavior therefore, the inefficiency of data acquisition in the Philippines will not be a great problem.

This study aims to generate strong ground motion records for hypothetical scenario earthquakes in Marikina Valley Fault with different magnitudes and distances to provide awareness especially in Metro Manila. The results are expected to be close estimates of Philippine earthquakes based on the estimates of the region-specific parameters of Specific Barrier Model using the available earthquake records of the Philippine Institute of Volcanology and Seismology (PHIVOLCS).

2 METHODOLOGY

In this paper, physical modeling approach will be used to generate strong ground motion records. After the selection of the physical/seismological model to be used, simulations of actual records will be executed. A mathematical approach will then be used to verify the validity of the simulated records. Calibration of the model parameters using the available local earthquake record will be performed after the correlation of the actual and simulated data to verify the effectiveness of SBM. Using the calibrated values, time-histories of different scenario magnitude with varying distances will be produced. The magnitudes will be based on the study of seismicity of the Marikina Valley Fault System. The distances will depend on the current strong motion stations located in and near Metro Manila.

2.1 The Specific Barrier Model

The Specific Barrier Model (SBM), the physical model used in this study, provides the most complete, yet parsimonious, self-consistent description of the earthquake faulting processes that are responsible for the generation of the high-frequencies of ground motions (Papageorgiou and Aki, 1982, 1983a,b; Papageorgiou, 2003). SBM applies both in the “near-fault” and “far-field” regions, allowing consistent ground motion simulations over the entire frequency range and for all distances of engineering interest. Moreover, the SBM has been calibrated to shallow crustal earthquakes of three different tectonic regions: inter-plate, intra-plate, and extensional regimes (Halldorsson and Papageorgiou, 2005). For this reason, it lends itself useful for earthquake engineering applications that require the quantification of the seismic hazard at a site either in the form of time histories, response spectra or peak values of ground motion.

The Strong Ground Motion Simulation (SGMS), developed by Halldorsson (2004), implements the Specific Barrier Model to describe the earthquake source in the stochastic modeling approach. The program requires tectonic regime, magnitude, distance, ground motion type, seed number, soil type, spectra, and period as inputs to generate synthetic time-histories of the desired earthquake.

Aside from the comparison of the time-histories of the actual and simulated earthquake data, the frequency content will also be correlated using the Fast Fourier Transforms of each time-history.

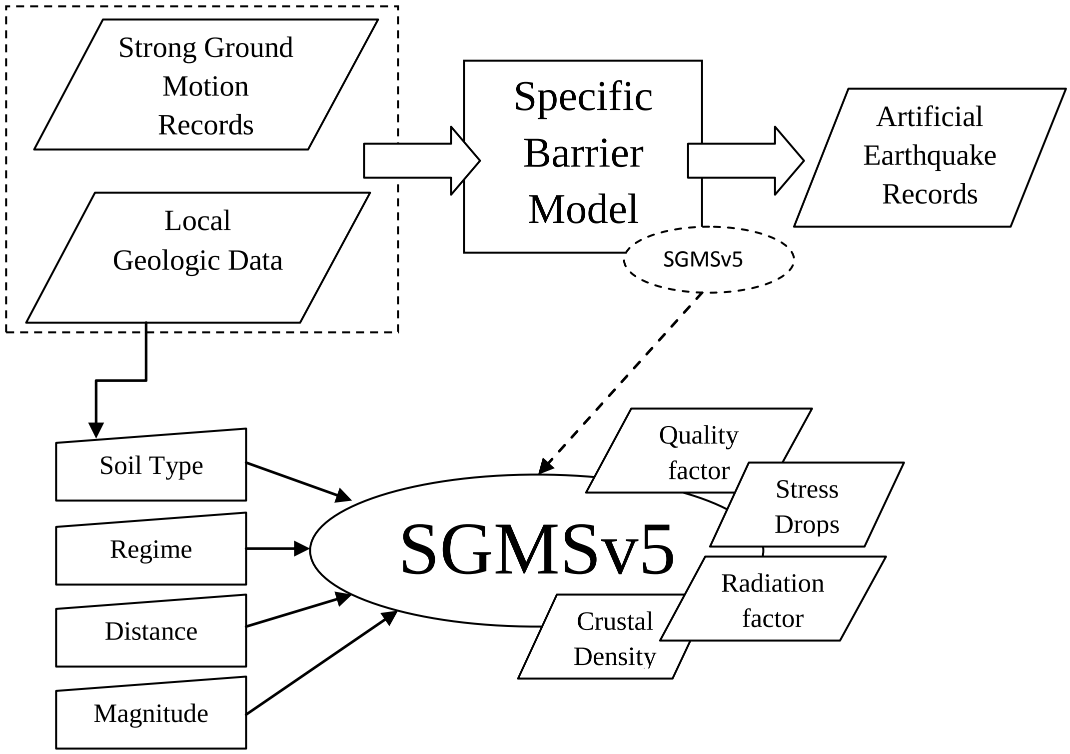

Figure 1. Conceptual Framework

2.2 Correlation of Actual and Simulated Data

Earthquake records from countries of the same plate boundary as the Philippines, e.g., Japan, Taiwan, was utilized for the correlation of data to verify the effectiveness of the model. In this paper, the M7.3 Tottori Earthquake which occurred last October 6, 2010 in Japan, the M7.6 Chichi Earthquake dated last September 21, 1999 in Taiwan, and the M6.5 Hermana Mayor Earthquake dated December 1999 in the Philippines are shown.

2.3 Calibration of Specific Barrier Model

The Specific Barrier Model used by the SGMS code was calibrated using the San Fernando, Loma Prieta and Hector Mine Earthquake data in California. Due to unavailable regional data for Philippines, this study will estimate the probable ideal model parameters for local site conditions.

Using the available information regarding the Hermana Mayor earthquake, SBM parameters will be adjusted to fit the simulated data to the actual earthquake record.

2.4 Generation of Artificial Earthquake Records

2.4.1 Valley Fault System

Based on the study of Rimando and Knuepfer (2005), empirical relations between rupture lengths and magnitudes of historic earthquakes in similar tectonic environments implies earthquakes of M 6–7 on the Marikina Valley Fault System. A fault length of 30 km on the northern half of WMVF is marked by young, fault-related landforms, which corresponds with M 6–7 earthquakes. Although a much longer section of the fault possibly ruptured during earthquakes as large as M 7.5, landforms suggesting repeated rupture of the west Marikina Valley fault southward beyond the Pasig River have yet to be identified. On the other hand, according to Director Renato Solidum, Jr., a M7.2 earthquake can hit Metro Manila anytime based on the study of PHIVOLCS.

2.4.2 Metro Manila Strong Motion Array (MMSTAR)

PHIVOLCS in cooperation with Japan International Cooperation Agency (JICA) launched a program to improve the seismologic and volcanic observation of the Philippines using state-of-the-art instruments to be provided by the government of Japan. MMSTAR is composed of 12-station network sited in different geologic conditions.

3 RESULTS AND DISCUSSIONS

3.1 Simulation of Actual Records

Among several actual records used in the correlation, the three records previously mentioned are shown in Figures 2-4. Corresponding spectral acceleration of the actual and synthetic data are shown (on the right of the figures) in straight and dash lines, respectively. These records were correlated without prior adjustments of the model parameters of SBM. This is to prove that SBM can closely simulate actual records using only the suggested global parameters.

3.1.1 Japan – 2010 Tottori Earthquake

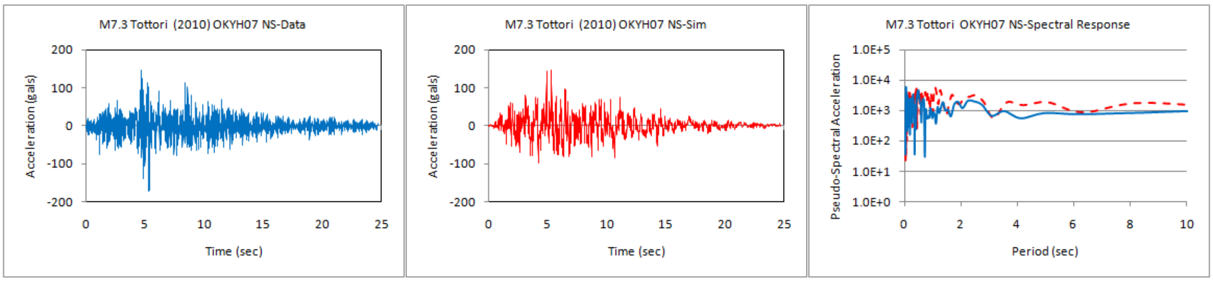

Figure 2. Acceleration time-histories recorded (left) and simulated (middle) in station OKYH07 of M7.3 Tottori Earthquake last October 2010.

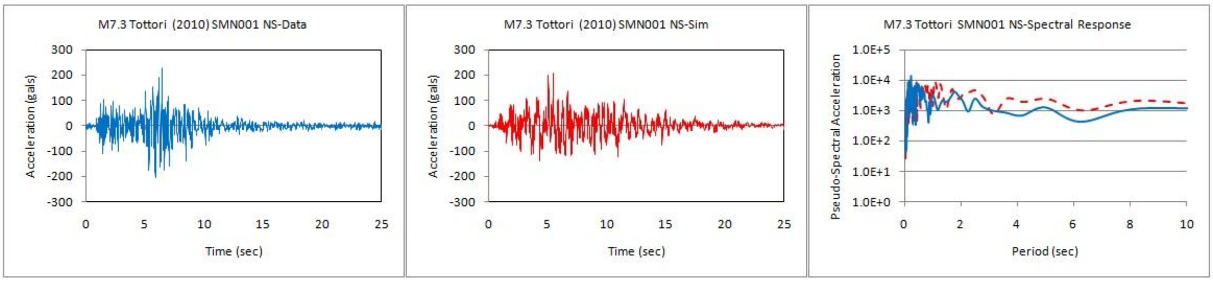

Figure 3. Acceleration time-histories recorded (left) and simulated (middle) in station SMN001 of M7.3 Tottori Earthquake last October 2010.

3.1.2 Taiwan – 1999 Chichi Earthquake

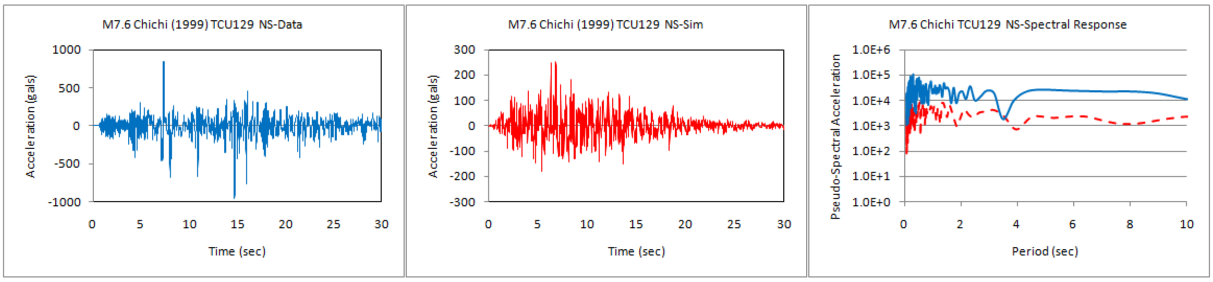

Figure 4. Acceleration time-histories recorded (left) and simulated (middle) in station TCU129 of M7.6 Chichi Earthquake last September 1999.

3.2 Calibration for Local Site Condition

The parameters are calibrated using the only available strong motion Hermana Mayor Earthquake in 1999. It is an interplate earthquake originated at Manila Trench. Using the two stations (MRK and PHV) which recorded the earthquake, model parameters will be adjusted until the simulated record fits the actual recordings on each station. The estimated distance from the epicenter to the stations is around 200 kilometers.

3.2.1 Philippines - MRK Calibration (1st)

Available digital data was acquired in MRK station which is lying on a soft soil. Frequency content of the actual and simulated data was compared.

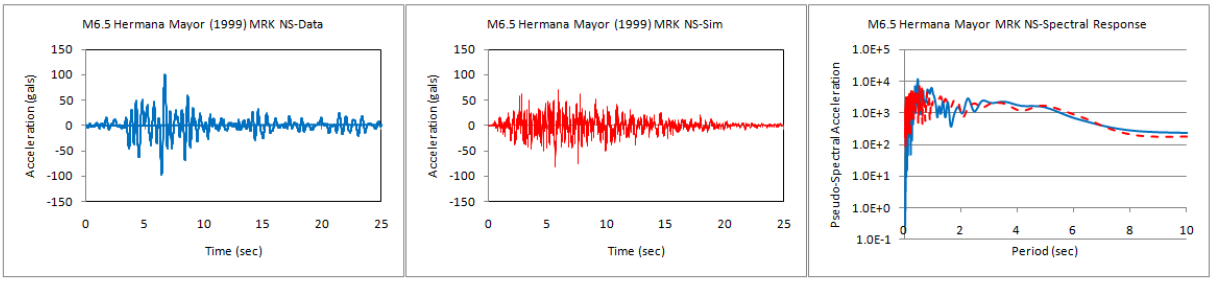

Figure 5. Calibration of SBM for local site parameters applied on the 1999 Hermana Mayor Earthquake in the Philippines recorded in MRK station. Acceleration time-histories recorded (left) and simulated (middle) in MRK and corresponding spectral acceleration where the actual and synthetic data are denoted in straight and dash lines, respectively (right).

Upon the adjustments of the model parameters of SBM, the frequency content closely-fit with the corresponding recorded ground motion.

Philippines - PHV Calibration (2nd)

The ground motion data recorded at the basement of PHIVOLCS main building will be used for the second calibration. Unfortunately, the digital record is not available.

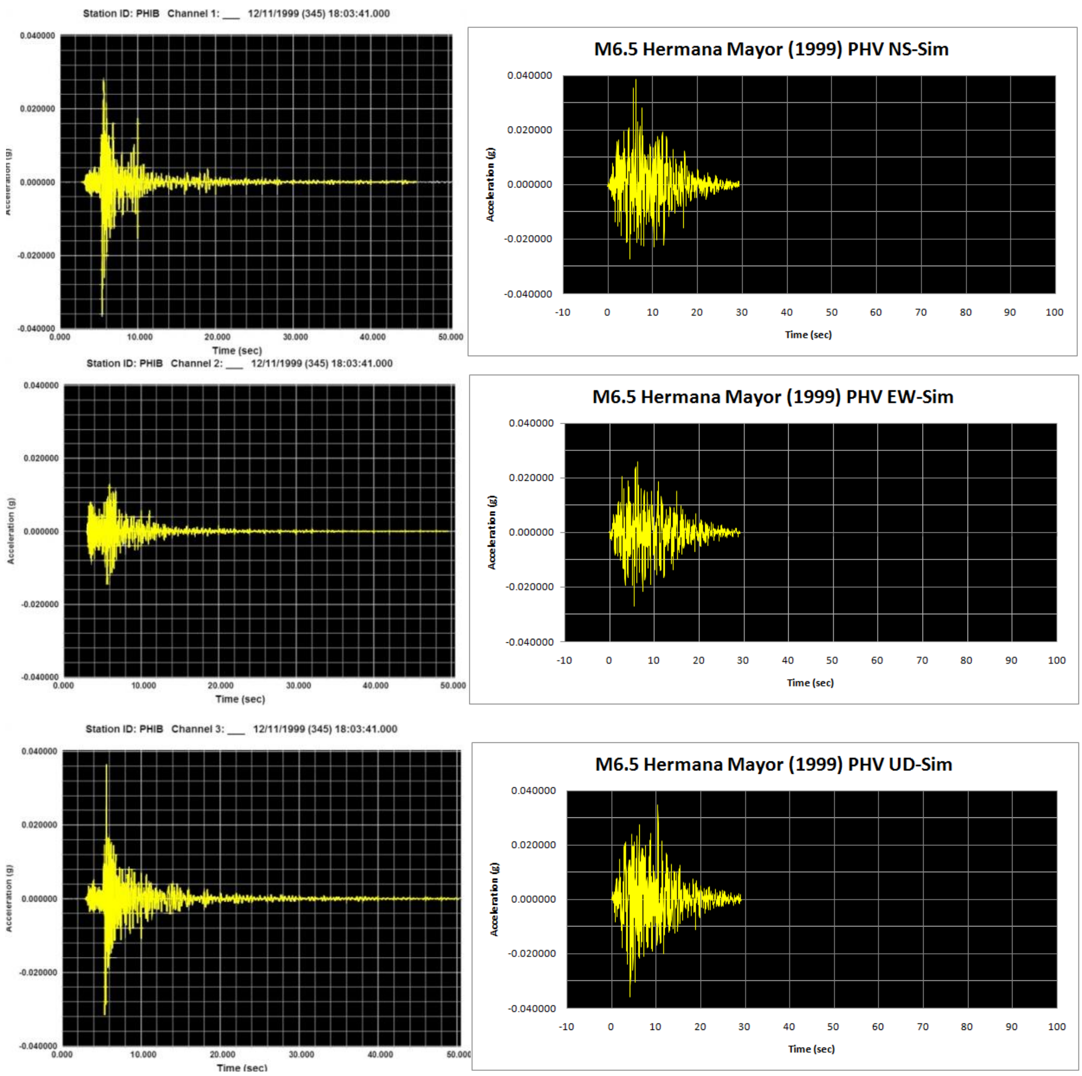

Figure 6. Acceleration time-histories of the 1999 Hermana Mayor Earthquake in the Philippines recorded in MRK (left) and simulated data using the 2^{nd} calibrated model parameters (right).

Since only the figure of the earthquake record is available (no digital data), comparison of the seismogram envelope and corresponding peak acceleration value was used to calibrate the model parameters. This is still acceptable since we only need a rough estimate of the parameters for local site conditions and there is only one available digital record of a strong ground motion in present time.

Table 1. SBM Parameters (Default and Calibrated Values)

Parameters	Inter-plate	Intra-plate	1st Calibration (MRK)	2nd Calibration (PHV)
Global stress drop	30	60	60	25
Local stress drop	161	180	200	200
Radiation factor	0.55	0.55	0.9	0.9
Quality factor	153	680	680	200
Quality power	0.88	0.36	0.36	0.88

The model parameters for the 1st calibration for local site condition already matched the parameters for intra-plate regime of earthquake without even reaching the maximum peak of the actual record. Since SBM is a physical model, not empirical, the extrapolation error should not be a concern. In addition to that, interplate and intraplate earthquakes are comparable when self-similar scaling is assumed (Halldorsson, 2005).

The parameters of the 2nd calibration are valid estimates since they are close to the values used by Halldorsson et al. (2004). The only major difference is the value calibrated for the radiation factor (in both calibrations). According to Boore and Boatwright (1984), the radiation coefficients are within a factor of 1.6 of the commonly used values of 0.52 and 0.63 for the rms of P- and S-wave radiation. Thus, the value of 0.9 is within the acceptable value.

Since there is no available digital format of the recorded Hermana Mayor earthquake at PHIVOLCS main building station, at present time, it is not possible to compare the amplitude spectra of the actual and simulated data.

3.3 Synthetic West Valley Fault Earthquake

Assuming the epicenter of the earthquake located at the middle of the fault system, three scenario magnitudes were simulated after the calibration of SBM parameters.

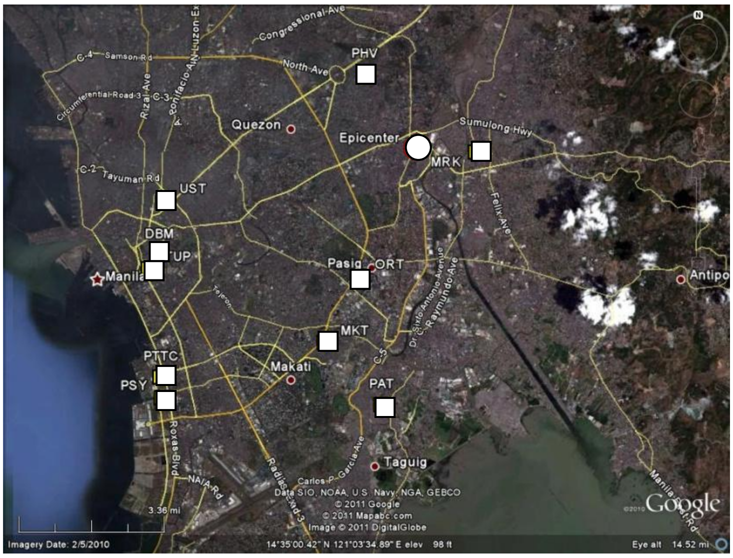

Figure 7. Epicenter (circle) and station locations (squares) of MMSTAR used in the simulation of scenario earthquake in West Valley Fault System.

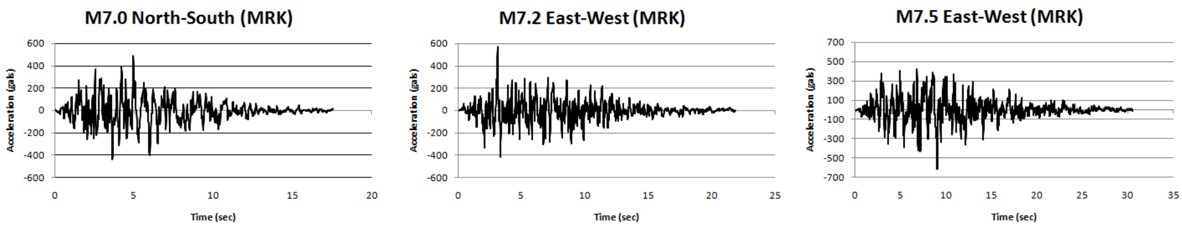

Figure 6. Time-histories of the component with the highest peak acceleration of three scenario magnitudes based from the study of Rimando and Knuepfer (2005) and estimation of PHIVOLCS.

According to the Philippine Seismic Hazard Map, Metro Manila has a peak ground acceleration (PGA) of 4.0 to 4.8 m/s (0.4 g to 0.5 g) with a 10% probability of exceedance in 50 years. The peak acceleration of the M7.0 is 4.89 m/s^2 (0.5 g) which is close to the maximum boundary of the PGA in Metro Manila; this provides the agreement with the deterministic simulation and the probabilistic description of hazard. On the other hand, magnitudes 7.2 and 7.5 have peak accelerations of 0.57 g and 0.63 g respectively.

4 CONCLUDING REMARKS

Based on the superimposed time-histories of the earthquake, we can say that the Specific Barrier Model can closely predict an actual earthquake record assuming an "average" seismic event and using only "average" model parameters. On the other hand, the corresponding spectral acceleration plots of each time-history illustrates similar trend with the actual PSA's indicating that the SBM can simulate actual records without prior adjustments of the default parameters.

The accuracy of the artificial earthquake records to be developed for the Philippines greatly depends on the seismological and geological parameters. At present time, the Specific Barrier Model can be the most preferred method of ground motion prediction that can be used in the Philippines since empirical method is impossible because of scarcity of recorded ground motion data.

Additional digital local earthquake records are important to improve the calibrated values of the model parameters of SBM. This will provide closely accurate representation of the ground motion generation and propagation for seismic hazard analyses of the country. Moreover, further studies for the model parameters should be taken to provide basis for the calibrated values. Analytical or statistical modeling can be used to estimate these parameters that rely on few data that is possibly available.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the following, Dr. Benedikt Halldorsson for the open-source SGMSv5 program, Kiban-Kyoshi Network (KiK-NET), Geologic Surveyed Database of Central Weather Bureau (CWB) Stations, PHIVOLCS and the financial support from the Department of Science and Technology of the Philippines through its Engineering Research and Development for Technology (ERDT) program.

REFERENCES

Aki, K. and P. G. Richards (1980). **Quantitative Seismology. Theory and Methods**, Volume I, II, W. H. Freeman and Company, San Francisco, USA, 948 pp.

Boore, D., and Boatwright, J. (1984). Average Body-Wave Radiation Coefficients, **Bull. Seism. Soc. Am.**

Halldorsson, B., Papageorgiou, A. (2004). Synthesis of Strong Ground Motions for Engineering Applications using the Specific Barrier Model, **Multidisciplinary Center of Earthquake Engineering Research**.

Halldorsson, B., Papageorgiou, A. (2004). Region Specific Ground Motion Simulations Using the Specific Barrier Model, **Engineering Seismology Laboratory**.

Halldorsson, B., Papageorgiou, A. (2005). Calibration of the Specific Barrier Model to Earthquakes of Different Tectonic Regions, **Bull. Seism. Soc. Am.**

Halldorsson, B., Ólafsson, S., Sigbjörnsson, R. (2007). A Fast and Efficient Simulation of the Far-Fault and Near-Fault Earthquake Ground Motions Associated with the June 17 and 21, 2000, Earthquakes in South Iceland. **Journal of Earthquake Engineering, 11**:343–370.

Halldorsson B., Mavroeidis, G., Papageorgiou, A. (2011). Near-Fault and Far-Field Strong Ground Motion Simulation for Earthquake Engineering Applications Using the Specific Barrier Model **Journal of Structural Engineering – ASCE Vol. 137**, No. 3. 433-444.

Joyner, W. B. and D. M. Boore (1986). On simulating large earthquakes by Green's function addition of smaller earthquakes, in S. Das et al. (Editor) **Earthquake Source Mechanics, Maurice Ewing Series, Vol 6**, Am. Geophys. Union.

Koo, R., *et al* (2009). Probabilistic Seismic Hazard Assessment for Central Manila in Philippines, **Australian Earthquake Engineering Society Conference**.

Nath, S.K. et al. (2009). Ground Motion Synthesis and Seismic Scenario in Guwahati City—a Stochastic Approach. ***Seismological Research Letters***. **80**. 223-242.

Nelson, A., Personius, S. (2000). Multiple large earthquakes in the past 1500 years on a fault in Metropolitan Manila, The Philippines, **Bull. Seism. Soc. Am.**

Papageorgiou, A. S. and K. Aki (1982). Aspects of the mechanics of earthquake rupture related to the generation of high-frequency waves and the prediction of strong ground motion., **Soil Dyn. Eq. Eng. 1**, 67–74.

Papageorgiou, A. and Aki K. (1983a). A specific barrier model for the quantitative description of inhomogeneous faulting and the prediction of strong ground motion. I. Description of the model, **Bull. Seism. Soc. Am. 73**, 693–722.

Papageorgiou, A. and Aki K. (1983b). A specific barrier model for the quantitative description of inhomogeneous faulting and the prediction of strong ground motion. Part II. Applications of the model, **Bull. Seism. Soc. Am. 73**, 953–978.

Papageorgiou, A. (2003). The barrier model and strong ground motion, **Pure Appl. Geophys. 160**, 603–634.

Rimando, R. and Knuepfer, P (2005). Neotectonics of the Marikina Valley Fault System and Tectonic Framework Structures in Northern and Central Luzon, Philippines. **Tectonophysics**. **415**. 17-38.

Zafarani, H., *et al* (2008). Calibration of the specific barrier model to Iranian plateau earthquakes and development of physically based attenuation relationships for Iran. **Soil Dyn. Eq. Eng.**