Synthesis of Strong Ground Motion Using Modified Semi-Empirical Technique

A. Joshi, Pushpa Kumari, and M. L. Sharma

***Abstract*—This paper presents use of the semi-empirical technique given by Midorikawa (1993) for simulation of strong ground motion due to great earthquake. Modification in this technique has been made in the present work to incorporate the effect of radiation pattern and seismic moment. The rupture model of Sumatra earthquake of magnitude 9.0 (Mw) which occurred on 26th Dec, 2004, is used as a test model for simulations due to great earthquake. The comparison of the simulated and observed record has been made in terms of ground motion record. Comparison establishes the efficacy of the modified technique for effectively simulating strong ground motions due to a great earthquake. The developed technique is applied to simulate strong motion record due to great earthquake from several probable ruptures in the vicinity of Andaman Island. Several simulations show that the Andaman region can experience peak ground acceleration of the order of 1.6 g due to any probable great earthquake.**

***Index Terms*—Semi-empirical, earthquake, strong motion, andaman**

I. Introduction

The semi-empirical method given by Midorikawa (1993) is used for simulation of strong ground motion in a wide frequency range for major to large earthquakes (Joshi and Midorikawa, 2004, Joshi et al., 2010). Very few examples are there which illustrate application of this method for simulations due to great earthquake. This is due to dependency of this method on limited and constrained attenuation relations. In the present work, modifications in the semi-empirical approach have been made to remove its dependency on attenuation relations. In the modified technique scaling of envelope function has been done by including the seismic moment and the radiation pattern terms. Sumatra earthquake of 26th Dec, 2004 has been modeled using modified semi-empirical technique.

Sumatra earthquake that occurred in the coast of northern Sumatra was the largest seismic event on earth in last 40 years. Parameters of this earthquake are given in Table I. It ruptured along the boundary between the Indo-Australian plate and the Eurasian plate along the northwestern Sumatra, the Nicobar Island and the Andaman Island. This mega-thrust earthquake has released about 20×1017 J of energy and has triggered a devastating tsunami in the entire south Asia (Lay et al., 2005). The epicenter of this earthquake was about 155 km west of the Sumatra and about 255 km south-east of Banda Aceh, Indonesia. The focal point was at a depth of 30 km and the rupture length was estimated to be 750 km (Sorensen et al., 2007).

Manuscript received May 20, 2012; revised June 29, 2012.

A. Joshi and Pushpa Kumari are with the Department of Earth Sciences, IIT Roorkee, India (e-mail: pushpa19chary@gmail.com).

M. L. Sharma is with the Department of Earthquake Engineering, IIT Roorkee, India.

TABLE I: Parameters of the Sumatra, Indonesia earthquake of 26th Dec, 2004

Hypocenter	Size	Fault plane solution	Reference
00:58:50 s UTC	M_0 = 4.0×10^{22} Nm	NP1 φ = 329°, δ = 8°, λ = 110°	CMT Harvard
3.09 °N 94.26 °E Depth 29 Km	Mw = 9.0	NP2 φ = 129º, δ = 83º, λ = 87º	

This earthquake was recorded by several networks operated by different worldwide agencies. The nearest broadband station which has recorded this earthquake is PSI station at an epicentral distance of 355 km. Data recorded on PSI station has been obtained from http://ohpdmc.eri.u-tokyo.ac.jp site. The sensor at PSI station has sensitivity 0.75×108 count/m/sec with sampling frequencies 20 samples/sec. The record at PSI station was provided in seed format, which have been processed after proper conversion into ASCII format using SEISAN software. The algorithm used for processing of data is based on that given by Boore and Bommer (2005) which includes linear correction, instrumental scaling, padding and acausal band-pass filtering. The velocity record at PSI station has been band-passed in a frequency range 0.3–4.0 Hz for correctly representing particle ground motion. This record is required for comparison of observed and simulated record obtained from semi-empirical approach.

II. Methodology

The modified semi-empirical method proposed by Joshi and Midorikawa (2004) uses the concept of stochastic simulation technique together with the semi empirical technique for simulation of strong motion time series. This technique uses the time series obtained from stochastic simulation technique and the envelope function obtained from the semi empirical technique. In this technique the amplitude spectrum of white noise is replace by the acceleration spectra of target earthquake. Following shape of acceleration spectra is used (Boore, 1983) for simulation of acceleration record:

$$A(f) = CS(f)D_S(f)F_R(f,R) \qquad (1)$$

where, C is a constant scaling factor which includes seismic moment (M_0) radiation pattern coefficient ($R_{\theta\varphi}$), amplification due to free surface (FS), reduction factor ($PRTITN$), density (ρ) and shear wave velocity (β) and defined as follows:

$$C = M_0.R_{\theta\varphi}.FS.PRTITN / 4\pi\rho\beta^3 \qquad (2)$$

Filters $S(f)$, $D_S(f)$, and $F_R(f, R)$ in eq. (1) represents the source acceleration spectrum, near-site attenuation of high frequencies and effect of anelastic attenuation, respectively. The convolution of correction function with obtained acceleration record $a_{ij}(t)$ gives acceleration record $A_{ij}(t)$ for ij^{th} subfault. The subscript i and j define the position of the subfault along length and the width of the rupture plane, respectively. The accelerogram $A_{ij}(t)$ from different subfaults reaches the observation point differently. This is further windowed by the envelope function $e_{ij}(t)$ defined in eq. (4) as follows:

$$ac_{ij}(t) = e_{ij}(t) \cdot A_{ij}(t) \qquad (3)$$

The acceleration envelope waveform $e_{ij}(t)$ is computed from the following functional form modified after Joshi and Midorikawa (2004):

$$e_{ij}(t) = T_{ss}(t / T_d)\exp(1 - t / T_d) \qquad (4)$$

where, T_d is duration parameter and T_{ss} is transmission coefficient of the incident shear waves (Lay and Wallace, 1995) used for modeling the effect of transmission of energy which contributes significantly in shaping the attenuation rate of the peak ground acceleration. The T_d used in eq. (4) has been calculated for the Sumatra earthquake using following equation which was initially given by Midorikawa (1989):

$$T_d = 0.0015 \times 10^{0.5M} + 0.2R^{0.81} \qquad (5)$$

where, M and R are the magnitude of the target earthquake and the hypocentral distance, respectively. The rectangular rupture plane of the target earthquake of seismic moment M_o is divided into $N \times N$ subfaults of seismic moment M_o' following the self similarity law given by Kanamori and Anderson (1975). The rupture starts from the nucleation point which coincides with the hypocenter of the earthquake and propagates radialy within the rupture plane. The record $ac_{ij}(t)$ released from different subfaults reaches the observation point at different times. The summation of all records reaching the observation point at different time lag t_{ij} gives the resultant record $Ac(t)$ at the observation point which is expressed as:

$$Ac(t) = \sum_{i=1}^{N}\sum_{j=1}^{N} ac_{ij}(t - t_{ij}) \qquad (6)$$

A. Sumatra Earthquake: Generation of Synthetic Ground Motion

Semi-empirical approach is dependent on simple modeling parameters which can be easily calculated and predicted. This approach require various parameters like length, width, nucleation point, velocity structure, rupture velocity, location and geometry of rupture plane and its subfaults. The geometrical parameters of subfaults are calculated using the self similarity laws given by Kanamori and Anderson (1975). The geometry and location of the rupture responsible for the Sumatra earthquake is kept similar to that used by Sorensen et al. (2007) and are given in Table II. The entire rupture plane of area 750×150 sq km is divided into 100 subfaults. Each subfault represents an earthquake of magnitude (M_w) 7.0.

TABLE II: PARAMETERS OF THE RUPTURE MODEL OF THE SUMATRA EARTHQUAKE

Modeling Parameter	References
Dip = 10 °	Sorensen et al. (2007)
Strike = 329 °	CMT Harvard
V_r = 3.0 km/sec	Lay et al. (2005)
Q(f) = $100f^{0.8}$	Sorensen et al. (2007)

A FORTRAN code named MSEMP (Modified Semi Empirical Modeling Program) has been developed to simulate records at any observation point which requires coordinates of recording station in a Cartesian system in which the X and the Y axes are parallel to the strike and the dip direction of the rupture plane, respectively. Using starting parameters given by different workers, each parameter has been checked for ±5% of its initial value and simulated records have been compared at PSI station with observed ones. It is seen that nucleation point (5, 3) subfault at depth of 38 km gives minimum root mean square error. The final modeling parameter after several simulations and comparison is shown in Fig. 1.

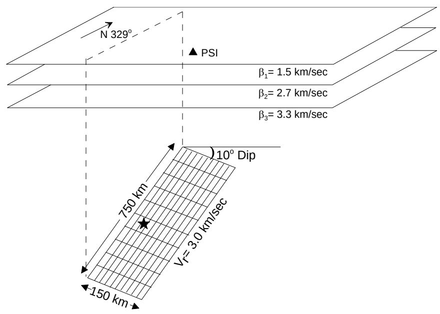

Fig. 1. Rupture model of the Sumatra earthquake consisting 10×10 subfaults placed in a layered medium at strike 329 °N. Solid triangle shows the location of PSI station and star shows the starting position of rupture.

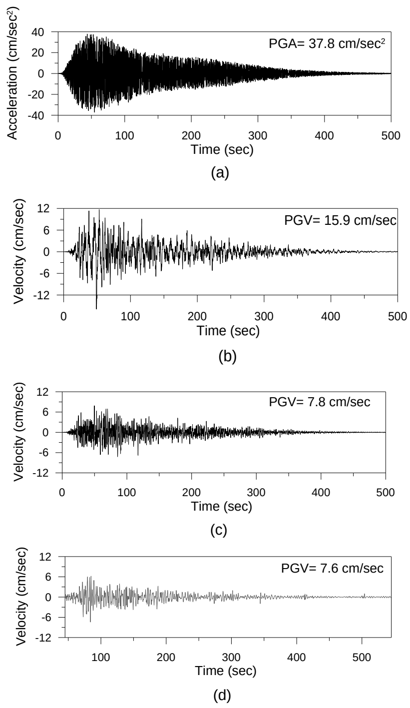

Fig. 2. (a) Simulated accelerogram, (b) Velocity record obtained from integration of simulated acceleration record, (c) Filtered velocity record and (d) Observed velocity record at PSI station filtered in a range of 0.3–4.0 Hz.

The records at PSI station has been simulated from the final rupture model. The simulated acceleration record at PSI station is shown in Fig. 2(a). Comparison of observed and simulated velocity record at PSI station shown in Fig. 2 indicates that the simulated record bears realistic shape as that of observed record and the peak ground velocity of observed and simulated record is also comparable. Predominant frequencies of observed and simulated velocity record are observed 0.44 Hz and 0.42 Hz, respectively which also indicate a close similarity. A comparison of parameters of simulated and observed records confirms the efficacy of modified semi-empirical approach to model a great earthquake.

B. Hypothetical Earthquake: Generation of Synthetic Ground Motion

In this work the modified semi-empirical method has been used to simulate strong ground motion due to a hypothetical great earthquake in the Indian subcontinent having similar parameters as that of the Sumatra earthquake. The hypothetical earthquake has been modeled in the Andaman region which lies north of the source region of the Sumatra earthquake. This region lies in the zone V of the Seismic Zoning Map of India which is the highest seismically hazardous zone. The identified source zone has potential of generating an earthquake of magnitude 8.5 (Bhatia et al., 1999).

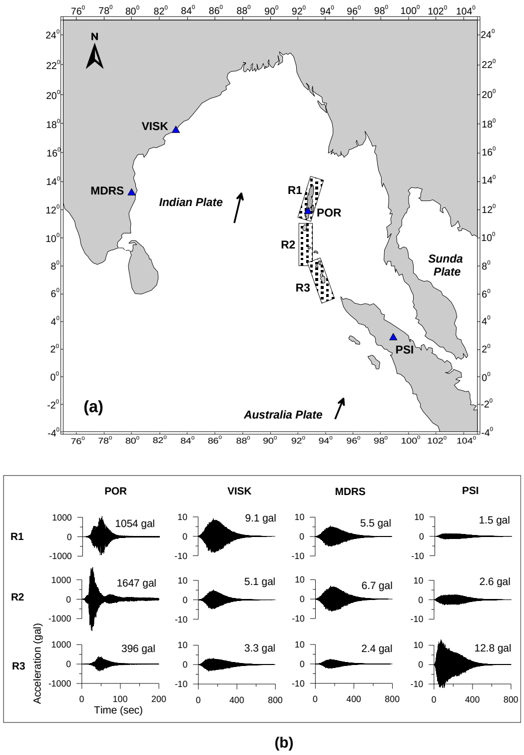

Fig. 3. (a) Location of ruptures for hypothetical earthquake in Andaman region shown by rectangles. Station location for simulation has been indicated by solid triangles. (b) Synthetic acceleration records at POR, VISK, MDRS and PSI stations for hypothetical earthquake in Andaman region for three possibilities of ruptures.

The rupture plane for this hypothetical earthquake is placed in this source zone at strike 17 ºN, 360 °N and 340 °N which follows the trend of source zone defined by Bilham et al. (2005) and shown in Fig. 3(a). The velocity structure given by Parvez et al. (2003) for the Andaman region has been used in this simulation. The acceleration records have been simulated at POR, PSI, MDRS and VISK stations and shown in Fig. 3(b) for different possibility of rupture position in Andaman and Nicobar Island. Simulated record shows that any great earthquake can give peak ground acceleration of the order of 1.6 g in the Andaman region. The order of peak ground acceleration obtained for this hypothetical earthquake in the near source region indicates that the seismic hazard potential of any probable great earthquake is very high in this region.

III. Conclusion and Discussion

The modified semi-empirical method can be applied to region having limited regional and global information about the nature of the buried fault. The modified semi-empirical method defined in present paper uses seismic moment and radiation pattern in place of attenuation relation in the conventional semi-empirical approach given by Midorikawa (1993). Modified method has been used to simulate strong motion record due to the Sumatra earthquake. The comparison of observed and simulated record from final model at PSI station confirms the efficacy of the approach. The modified semi-empirical technique is used to generate earthquake scenario due to probable earthquake in Andaman Nicobar Island, India. The simulations for several possibilities of rupture model indicates that Andaman region can experience peak ground acceleration of the order of 1.6 g due to any probable great earthquake in this region.

References

[1] S. Midorikawa, “Semi empirical estimation of peak ground acceleration from large earthquakes,” *Tectonophysics* 1993, vol. 218, pp. 287–295.

[2] A. Joshi and S. Midorikawa, “A simplified method for simulation of strong ground motion using rupture model of the earthquake source,” *J. Seism.* 2004, vol. 8, pp. 467–484.

[3] A. Joshi, M. Mohanty, A. R. Bansal, V. P. Dimri, and R. K. Chadha, “Use of spectral acceleration data for determination of three-dimensional attenuation structure in the Pithoragarh region of Kumaon Himalaya,” *J. Seism.* 2010, vol. 14, pp. 247–272.

[4] T. Lay, H. Kanamori, J. A. Charles, C. A. Richard, N. M. Steven, L. B. Susan, R. B. Michael, R. Butler, R. D. Heather, G. Ekstrom, K. Satake, and S. Sipkin, “The Great Sumatra-Andaman Earthquake of 26 December 2004,” *Science* 2005, vol. 308, pp. 1127–1133.

[5] M. B. Sorensen, A. Atakan, and N. Pulido, “Simulated Strong Ground Motions for the Great M 9.3 Sumatra-Andaman Earthquake of 26 December 2004,” *Bull. Seism. Soc. Am.* 2007, vol. 97, pp. S139–S151.

[6] D. M. Boore and J. Bommer, “Processing of strong motion accelerograms: needs, options and consequences,” *Soil Dynamics and Earthquake Engineering* 2005, vol. 25, pp. 93–115.

[7] D. M. Boore, “Stochastic Simulation of High Frequency Ground Motion Based on Seismological Models of Radiated Spectra,” *Bull. Seism. Soc. Am.* 1983, vol. 73, pp. 1865–1894.

[8] T. Lay and T. C. Wallace. *Modern Global Seismology*. Academic Press, California, 1995, vol. 521.

[9] S. Midorikawa, “Synthesis of ground acceleration of large earthquakes using acceleration envelope waveform of small earthquake,” *J. Struct. Construct. Eng.* 1989, vol. 398, pp. 23–30.

[10] H. Kanamori and D. L. Anderson, “Theoretical basis of some empirical relations in seismology,” *Bull. Seism. Soc. Am.* 1975, vol. 65, pp. 1073–1095.

[11] S. C. Bhatia, M. R. Kumar, and H. K. Gupta, “A probabilistic seismic hazard map of India and adjoining regions,” *Annali Di Geofisica* 1999, vol. 42, pp. 1153–1164.

[12] R. Bilham, E. R. Engdahl, N. Feldl, and S. P. Satyabala, “Partial and complete rupture of the Indo-Andaman plate boundary 1847-2004,” *Seism. Res. Lett.* 2005, vol. 308, pp. 1–21.

[13] I. A. Parvez, F. Vaccari, and G. F. Panza, “A deterministic seismic hazard map of India and adjacent areas,” *Geophys. J. Int.* 2003, vol. 155, pp. 489–508.