Generation of Synthetic Ground Motion for a Hard Rock Site in Intra Plate Region

A RAVI KIRAN, S BANDOPADHYAY, M K AGRAWAL AND G R REDDY
Reactor Safety Division, Bhabha Atomic Research Centre, Mumbai, INDIA
Email: arkiran@barc.gov.in

Abstract: Synthetic ground motion simulation is used for developing attenuation relation for region in which earthquake record data is scarce. Peninsular India is an intra plate region where strong motion data is scarce and hence, synthetic ground motion is suitable for developing attenuation relation for Peninsular India. The present paper describes the details of generation of synthetic ground motion for a Peninsular Indian hard rock site. Stochastic finite fault method is used for the ground motion simulation. The seismological parameters such as spectral decay parameter, quality factor and stress drop derived from the data of Jabalpur, Koyna and Killari earthquakes are considered for the simulation.

Keywords: Synthetic ground motion simulation, Peninsular India, Intra plate region, Stochastic finite fault method

1. Introduction

Ground motion attenuation relation usually describes hazard parameter, i.e. ground acceleration, velocity and displacement in terms of magnitude and distance. There are two approaches available for developing attenuation relation. First one is regression from strong motion data base and the second one is from simulation. First method is suitable for inter plate regions such as Western North America (WNA) where seismicity rates are such that sufficient strong ground motion is available for regression analysis. Second method is suitable for intra plate regions such as Eastern North America (ENA) where seismicity rates are less. Peninsular India is an intra plate region where strong motion data is scarce and not representative of existing hazard. Hence, the second approach based on simulation is suitable for development of attenuation correlation for Peninsular India. Finite fault stochastic simulation method is used for this purpose. The simulation of ground motion requires careful selection of seismological parameters. The seismological parameters for simulation should be selected from the same region (Peninsular Indian shield region) or regions having similar characteristics such as Eastern North America (ENA). Very few strong motion records are available for Indian shield region. Parameters such as spectral decay parameter, quality factor and stress drop derived from the data of Jabalpur, Koyna and Killari earthquakes are considered for Peninsular India. The description and selection of various seismological parameters is provided in the paper. These parameters are used for synthetic ground motion simulation using stochastic finite fault method. The simulations have been carried out for hard rock Peninsular Indian site with average shear wave velocity at 30m depth (Vs30) of 2900m/s [1]. The present paper provides the details of synthetic ground motion.

2. Description of Various Parameters in Seismological Model

In the present study, ground motion simulation is carried out using Extended Finite-Fault Simulation (EXSIM) software [2]. The software is based on stochastic finite fault modeling in which, fault plane is divided into M x N sub faults. The acceleration spectrum of $i^m$ sub fault, $A_i(f)$ is described by,

$$A_i(f) = \left[\frac{M_0\gamma}{2\pi^2f^4}\left[1 + \left(\frac{f}{f_c}\right)^2\left[2 + \frac{\gamma}{\delta f}\right]\exp(-\pi f R_i/R_d)\exp(-\pi f R_i/R_c)\right]\right]^{1/2}$$

Where, $M_0$, $f_0$, and $R_i$ are the $i^m$ sub fault seismic moment, corner frequency, and distance from the site, respectively.

The term $\exp(-\pi f k)$ is a high-cut filter to model near surface/upper crustal attenuation and scattering processes. The parameter kappa ($k$) is known as spectral decay parameter, which represents the effect of intrinsic attenuation upon the wave field as it propagates through the crust from source to receiver.

The quality factor, $Q$, is inversely related to anelastic attenuation. The implied 1/R geometric attenuation term is applicable for body-wave spreading in a whole space.

Corner frequency, $f_{0ij}$ is given by

$$f_{0ij} = 4.9E6\beta \left(\frac{\Delta \sigma}{M_{0ij}}\right)^{1/2}$$

Where,

- $\Delta \sigma$ is stress drop in bars,
- $M_{0ij}$ is seismic moment (in dyne cm) which is related to Magnitude ($M$) by,
\[ \log M_0 = 1.5M + 16.1 \]  
and \( \beta \) is in shear wave velocity in km/s

3. Selection of Seismological parameters for generation of Synthetic Ground Motion

The simulation of ground motion requires careful selection of seismological parameters. Parameters such as spectral decay parameter, quality factor and stress drop derived from the data of Jabalpur, Koyna and Killari earthquakes are considered for the simulation. The details of these parameters are provided here.

3.1 Spectral Decay Parameter (kappa)

A key parameter for the description of high frequency ground motion is “kappa \((k)\)”, which is the decay slope of the Fourier spectrum of acceleration at near source distances \([3]\). It is normally associated with near-surface/ upper crustal attenuation and scattering processes. It is a site and distance dependent parameter that represents the effect of intrinsic attenuation upon the wave field as it propagates through the crust from source to receiver. In literature two different forms are available for near surface attenuation and scattering process.

First form is proposed by Anderson and Hough (1984) \([3]\) and is given by:

\[ P(f) = \exp (-\pi k f) \]  

Second form is proposed by Hanks (1982) \([4]\) and is given by:

\[ P(f) = [1 + (f/f_m)^\beta]^{-1/2} \]  

Where, \( f_m \) is cut-off frequency. The ground motion predictions using above two forms are similar if \([5]\).

3.1.1 The values of kappa for intra-plate region

As Peninsular India is similar to intra plate regions of the world, intra plate earthquake records on rock sites are considered for evaluation of kappa. The list of Intra-plate records used for evaluation of kappa is given in Table 1. Kappa is measured by finding a linear approximation to the Fourier amplitude spectrum plotted in log-linear space. The slope of the linear approximation is \(-\pi k\). The Fourier amplitude spectra along with linear approximations for various earthquakes are shown in Figures 1 to 11.

<table>
<thead>
<tr>
<th>Eq.Id</th>
<th>Name of earthquake</th>
<th>( M )</th>
<th>( R_{ep} ) (km)</th>
<th>( d ) (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Koyna earthquake (1967)</td>
<td>6.5</td>
<td>12.7</td>
<td>12</td>
</tr>
<tr>
<td>2.</td>
<td>Saguennay earthquake (1988)</td>
<td>6.0</td>
<td>45.1</td>
<td>29</td>
</tr>
<tr>
<td>3.</td>
<td>Saguennay earthquake (1988)</td>
<td>6.0</td>
<td>91.8</td>
<td>29</td>
</tr>
<tr>
<td>4.</td>
<td>Saguennay earthquake (1988)</td>
<td>6.0</td>
<td>112.9</td>
<td>29</td>
</tr>
<tr>
<td>5.</td>
<td>Saguennay earthquake (1988)</td>
<td>6.0</td>
<td>147.6</td>
<td>29</td>
</tr>
<tr>
<td>8.</td>
<td>Nahanni earthquake (1985)</td>
<td>6.1</td>
<td>45.3</td>
<td>7</td>
</tr>
<tr>
<td>9.</td>
<td>Mineral Virginia earthquake (2011)</td>
<td>5.8</td>
<td>53.5</td>
<td>6</td>
</tr>
<tr>
<td>10.</td>
<td>Mineral Virginia earthquake (2011)</td>
<td>5.8</td>
<td>124.1</td>
<td>6</td>
</tr>
<tr>
<td>11.</td>
<td>Mineral Virginia earthquake (2011)</td>
<td>5.8</td>
<td>256.4</td>
<td>6</td>
</tr>
<tr>
<td>12.</td>
<td>Miramichi earthquake (1982)</td>
<td>4.8</td>
<td>5.8</td>
<td>6</td>
</tr>
</tbody>
</table>

**Figure 1** Linear-log plot of Fourier amplitude spectrum for Koyna earthquake (Eq. Id. 1)

**Figure 2** Linear-log plot of Fourier amplitude spectrum for Saguennay earthquake (Eq. Id. 2)
Figure 3 Linear-log plot of Fourier amplitude spectrum for Saguenay earthquake (Eq. Id. 3)

Figure 4 Linear-log plot of Fourier amplitude spectrum for Saguenay earthquake (Eq. Id. 4)

Figure 5 Linear-log plot of Fourier amplitude spectrum for Saguenay earthquake (Eq. Id. 5)

Figure 6 Linear-log plot of Fourier amplitude spectrum for Nahanni earthquake (Eq. Id. 6)

Figure 7 Linear-log plot of Fourier amplitude spectrum for Nahanni earthquake (Eq. Id. 7)

Figure 8 Linear-log plot of Fourier amplitude spectrum for Nahanni earthquake (Eq. Id. 8)

Figure 9 Linear-log plot of Fourier amplitude spectrum for Nahanni earthquake (Eq. Id. 9)

Figure 10 Linear-log plot of Fourier amplitude spectrum for Mineral Virginia earthquake (Eq. Id. 10)
The values of the slopes were converted to the spectral decay parameter and subsequently given in the Table 2. It is observed that average value of kappa for various intra-plate earthquakes is 0.015.

Table 2: Values of spectral decay parameter (kappa) for various intra-plate earthquakes

<table>
<thead>
<tr>
<th>Earthquake name and Id.</th>
<th>kappa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Koyna earthquake (Eq. Id. 1)</td>
<td>0.06</td>
</tr>
<tr>
<td>Saguenay earthquake (Eq. Id. 2)</td>
<td>0.0036</td>
</tr>
<tr>
<td>Saguenay earthquake (Eq. Id. 3)</td>
<td>0.0019</td>
</tr>
<tr>
<td>Saguenay earthquake (Eq. Id. 4)</td>
<td>0.0014</td>
</tr>
<tr>
<td>Saguenay earthquake (Eq. Id. 5)</td>
<td>0.004</td>
</tr>
<tr>
<td>Nahanni earthquake (Eq. Id. 6)</td>
<td>0.0134</td>
</tr>
<tr>
<td>Nahanni earthquake (Eq. Id. 7)</td>
<td>0.07</td>
</tr>
<tr>
<td>Nahanni earthquake (Eq. Id. 8)</td>
<td>0.009</td>
</tr>
<tr>
<td>Mineral Virgina earthquake (Eq. Id. 9)</td>
<td>0.0018</td>
</tr>
<tr>
<td>Mineral Virgina earthquake (Eq. Id. 10)</td>
<td>0.0004</td>
</tr>
<tr>
<td>Mineral Virgina earthquake (Eq. Id. 11)</td>
<td>2.6E-5</td>
</tr>
<tr>
<td>Average value</td>
<td>0.015</td>
</tr>
</tbody>
</table>

3.1.2 The values of kappa for Peninsular India

An earthquake of magnitude, Mw 5.8 has struck the city of Jabalpur on 21 May 1997 [6]. From the records of this earthquake, it is observed that spectral acceleration begins to fall off beyond 32 Hz [6]. For estimation of ground motion, S. K. Singh et al have used $f_m$ as 35 Hz [6]. This corresponds to kappa value of about 0.01 using eqn. (5). Another earthquake of magnitude, Mw 4.7 has struck the city of Jabalpur on 16 October 2000 [6]. From the records of this earthquake, it is observed that spectral acceleration begins to fall off beyond 17 Hz [7]. This corresponds to kappa value of about 0.0187. Raghu Kant & Iyengar [8] have taken the range of $f_m$ as 20-25 Hz for attenuation simulations for Peninsular India based on limited strong ground motion records of Koyna and Killari earthquakes. This corresponds to kappa value of about 0.0127-0.016. For Design Basis Ground Motion assessment of Jaitapur site, kappa values of 0.01, 0.013 and 0.016 are considered [9]. Kappa values derived from the data of Jabalpur, Koyna and Killari earthquakes are considered for generation of Synthetic Ground Motion. Accordingly, kappa values of 0.01, 0.014 and 0.018 are used in the simulation.

3.2 Seismological Quality factor (Q)

The quality factor Q is inversely related to anelastic attenuation. The seismological quality factor Q is amongst the many parameters required for input into the seismological model. Q defines the wave transmission quality of the earth’s crust in the study region. Regional Q factors are obtained from the seismological monitoring and the entire anelastic attenuation is represented by the term: 

$$\exp \left( -\frac{\pi R_i}{\lambda Q} \right)$$

of Eqn. [1]), which represents the effects of whole path attenuation of seismic waves propagating from the source to just below the site.

3.2.1 The values of Q-factor for Indian peninsular shield region

For the Koyna region, Mandal and Rastogi [14] find the frequency dependent quality factor, $Q$ as $169f^{0.77}$. Low Q value for Koyna region suggests that it is a tectonically active area. From the spectral analysis of Jabalpur earthquake of year, 1997 [6], Singh et al have estimated Q value for Indian shield region as $508f^{0.48}$. The same Q value has been estimated from another Jabalpur earthquake of year, 2000 [7]. For the entire Indian shield region, Singh et al [15] have estimated Q value as $800f^{0.42}$. However, this value of Q was found to be inadequate for Jabalpur earthquakes [7]. Raghukant & Iyengar [8] have considered Q as $508f^{0.48}$ for Western-Central (GC) region, $169f^{0.77}$ for Koyna-Warna (KW) region and $460f^{0.83}$ for Southern India (SI) region. For Design Basis Ground Motion assessment of Jaitapur site, Q-values of $84f^{0.65}$, $118f^{0.65}$ and $152f^{0.65}$ are considered [9]. Indian shield region is similar to areas of moderate seismicity of the world and Q$_{\text{er}}$ values for Indian shield are in the range of 200-600 [10]. Due to proximity and geotechnical similarity, Q-factor of $508f^{0.48}$ derived from the records of Jabalpur earthquakes is considered for simulation.

3.3 Stress drop ($\Delta \sigma$)

The stress drop is the difference between the stress across a fault before and after an earthquake. Stress builds up on the fault over time, and then is released during an earthquake.

3.3.1 The values of Stress drop for Indian peninsular shield region

Singh et al have estimated stress drop as 420 bar, from the spectral analysis of Jabalpur earthquakes 1997 [6] and observed that the stress estimates are higher than average probably due to unusual depth of 36 km. They recommend to use 100 and 300 bar for such an earthquake. Same value of 420 bar is estimated from the spectral analysis of another
Jabalpur earthquake in year 2000 [7]. For the Koyna earthquake of 1967 (Mw 6.3), the recorded strong motion is in good agreement with the prediction curves of a stress drop of 100 bar [6]. Raghukan & Iyengar [8] have taken the range of stress drop as 100-300 bar for attenuation simulation of Peninsular India. For Design Basis Ground Motion assessment of Jaitapur site, stress drop values of 140, 170 and 200 bar are considered [9]. Based on the stress drop value of Koyna earthquake and studies of Jabalpur records, stress drop values of 100, 200 and 300 bar are considered for simulation.

3.4 Rupture Parameters

The rupture width and lengths are estimated using the empirical relations given by D. L. Wells et al, which are based on regression analysis of several historical earthquakes [16]. The regression equations used are as follows:

\[ \log(RA) = a + b \cdot M \]
\[ \log(RW) = c + d \cdot M \]

Where,

- \( RA \) – rupture area (km²)
- \( RW \) – rupture width (km)
- \( M \) – Magnitude

\( a, b, c \) and \( d \) are coefficients and are given below:

- \( a = -3.49 \) and \( b = 0.91 \) obtained from 148 seismic events and \( c = -1.01 \) and \( d = 0.32 \) obtained from 153 seismic events [16].

4. Validation of Synthetic Ground Motion Procedure

Validation of the synthetic ground motion procedure has been done for Koyna earthquake (Eq. Id. 1, \( M=6.5, \) Repi = 12.7 km). Simulation has been carried out using median values of seismological parameters and six random time histories are generated. Comparison of response spectral shape of simulations and record for Koyna earthquake is shown in Figure 12. Tripartite plot for synthetic ground motion with Magnitude of 6.0 and various distances is shown in Figure 13. In this plot, constant displacement, velocity and acceleration regions are checked for the synthetic ground motion.

5. Generation of Synthetic Ground Motion

Parameters for simulation of synthetic ground motion are provided in Table 3. The simulations are performed with the computer code EXSIM (Extended Finite-Fault Simulation) [18] to generate synthetic ground motion. EXSIM is an open source stochastic finite fault algorithm that generates time series of ground motion for earthquakes [19]. A total of 12, 852 horizontal component ground motion records were simulated. These records have been used to obtain Response spectra with 5% damping and are shown in Figure 14.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range / Different values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kappa</td>
<td>0.01, 0.014, 0.018</td>
</tr>
<tr>
<td>Q-factor</td>
<td>508±48</td>
</tr>
<tr>
<td>Stress drop</td>
<td>100, 200, 300</td>
</tr>
<tr>
<td>( \beta ), Shear wave velocity (km/s)</td>
<td>2.9</td>
</tr>
<tr>
<td>Magnitude</td>
<td>4.5, 5.0, 5.5, 6.0, 6.5, 7.0 and 7.5</td>
</tr>
<tr>
<td>Hypocentral distance (km)</td>
<td>10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 125, 150, 175, 200, 250 and 300</td>
</tr>
<tr>
<td>for ( M \leq 5.5, d=5 ) km</td>
<td>5.5&lt;( M \leq 6.5, d=10 ) km</td>
</tr>
<tr>
<td>Depth of focus (km)</td>
<td>6.5&lt;( M \leq 7.0, d=15 ) km</td>
</tr>
<tr>
<td>( M &gt; 7.0, d=20 ) km</td>
<td></td>
</tr>
</tbody>
</table>

Figure 12: Comparison of response spectral shape of simulation and record for Koyna earthquake (Eq. Id. 1, \( M=6.5, \) Repi = 12.7 km)

Figure 13: Tripartite plot for synthetic ground motion with \( M = 6.0 \) and various distances

Figure 14: All response spectra obtained from simulation (\( \xi = 5\% \))
6. Conclusion

Synthetic ground motion simulation has been carried out for a hard rock Peninsular Indian site. Stochastic finite fault method is used for the ground motion simulation. The seismological parameters such as spectral decay parameter, quality factor and stress drop derived from the data of Peninsular Indian earthquakes. Validation of the synthetic ground motion procedure has been done using Koyna earthquake record. A strong motion data base has been generated for a wide range of earthquake magnitudes and distances.

References


