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Simulation of the 1934 earthquake in Kathmandu, Nepal

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ABSTRACT

In this study, utilizing appropriate target spectra and a special envelope function, an artificial time history is generated for the major earthquakes of 1934 and 2015 A.D. The peak ground acceleration (PGA), mean time period, predominant period, significant duration, response spectra, and Fourier spectra of the 2015 earthquake are obtained from the simulated time history. These ground motion parameters of simulated earthquake are compared to those of the recorded earthquake of 2015. For the earthquake of 1934 A.D., the maximum PGA derived from the simulation and the PGA derived from the damage-based MMI scale are compared. These earthquakes' significant duration is also compared with other subduction zone earthquakes. Compared to other subduction zone earthquakes, Nepal's earthquakes have a longer significant duration.

KEYWORDS Historical earthquakes, Peak Ground Acceleration, Simulated Earthquake, Significant Duration

1. Introduction

Nepal is a mountainous country, the majority of which is located in the subduction zone of the Tibetan and Indian Plateaus, through which the Main Himalayan Thrust (MHT), the interface of the plane of detachment between these plates, travels. According to (BECA 1993), Nepal is traversed by 92 more minor faults in addition to the South Tibetan Detachment System (STDS), Main Boundary Fault (MBT), Main Central Fault (MCT) and Main Frontal Thrust (MFT) or Himalayan Thrust Frontal (HFT). Nepal experienced major earthquakes in 1255, 1344, 1408, 1505, 1681, 1767, 1810, 1833, 1934, 1968, 1980, 1988, 2011, and 2015 A.D. (Panta 2002). The majority of these events are either undocumented or only briefly mentioned in the literatures. This study focuses on the Nepal-Bihar earthquake, the biggest earthquake of the 20th century that struck Nepal on January 15, 1934 around 2:24 PM (NST). This earthquake left the traces of surface rupture in a 150 km-long section of the MFT between 85° 50' and 87° 20' E and caused a co-seismic slip of 5.3 to 8.5 m (Sapkota et al. 2013; Rizza et al. 2019). The eastern and central regions of Nepal as well as the northern section of Bihar in India experienced heavy shaking as a result of this earthquake, 8519 people died, including 3850 men and 4668 women in Nepal and 7188 people in India. In Nepal, 207740 buildings and constructions were damaged (Rana 1935). According to (Sapkota et al. 2016), there were 1% fatalities close to the epicenter, 0.5% in Kathmandu, and 5% in Bhakatpur's urban areas. Beyond the Kathmandu valley, Bhojpur, Udayapur, Birgunj, and Jaleshwar were more severely damaged than other places. In Kathmandu Valley, the places like Tundikhel, Balaju, and Jamal, settlements were
visible, and there were cracks in the earth's surface in Shankhamul. On the other hand, a trail road in Godawari was damaged. The majority of the ancient buildings and temples were damaged elsewhere. Table 1 gives a more detailed explanation on damage to the various cities in Kathmandu Valley.

### Table 1: Affected cities of Kathmandu Valley (Source: Modified after Rana 1935)

<table>
<thead>
<tr>
<th>Degree of damage</th>
<th>Cities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Severely affected</td>
<td>Panga, Balaju, Sundhara, Sankhamul, Lubhu, Sanagaun, Harisiddi, Khokana, Bungmati, Bhadgaun, Chapagaun, Sipadol, Thimi</td>
</tr>
<tr>
<td>Highly affected</td>
<td>Thannkot, Sankhi, Manohara, bhotahity, Hadigaun, Patan, Godawari, Changunarayan</td>
</tr>
<tr>
<td>Moderately affected</td>
<td>Swoyambhu, Gokarna, Sundarijal, Kirtipur, Nagarjum, Jamal, Chandragiri, Dahachowk, Machhegaun, Maharajgunj, Budhanilkantha, Gokarna, Dharmasthali, Shangla, Jitpur, Thali, Chobhar, Nagarkot, Bode</td>
</tr>
</tbody>
</table>

It is necessary to convert statistical information and descriptions into intensity or PGA to quantify the earthquake. Based on available damage and casualty data, the intensity of one of the significant earthquakes that struck Nepal in 1833 A.D. was determined (Bilham 2019). By using an analytical approach that considered the fault, the path's damping, and the amplification factor, the seismic intensity of the Nepal earthquake that occurred in 1988 A.D. was determined (Sato and Kiyono 1989). Using the 1934 earthquake as a point source, a probabilistic seismic hazard assessment was performed (Bhattarai et al. 2011). It found PGAs of 0.1 g (in the southeast region) to 0.35 g (near the epicenter) for a return period of 475 years and 5% damping. The damage level was also assigned for different regions of Nepal due to the 1934 earthquake.

In this study, the damage data and casualties mentioned (Rana 1935) are compared to the description of the modified Mercalli intensity (MMI) scale. A suitable MMI is then provided for all impacted locations, which is shown in a contour illustrated in Figure 1.
Figure 1: Earthquake intensity (MMI) due to the 1934 earthquake

The epicenter of the largest earthquake that hit the central region since 1934 was discovered in the MCT of Gorkha district. This earthquake was occurred on April 25, 2015, at 11:57 a.m. (N.S.T.). In the 31 affected districts of Nepal, there were 8790 fatalities and 22300 injuries, according to the report (Government of Nepal 2015). Thirty-one districts were divided into 14 highly affected and 17 partly affected districts. Figure 2 displays the earthquake's damage by 2015 earthquake, with grade 1 suggesting low damage and grade 5 denoting severe damage. According to USGS data gathered at the Kantipath Station, this earthquake's maximum PGA was 0.16 g (USGS 2023); however, the highest PGA ever recorded at Kirtipur is 0.242 g. There was another big earthquake with a magnitude of 7.8 Mw occurred in Turkey in 2023. The 2015 earthquake in Nepal had a similar magnitude as this earthquake. However, the highest PGA in Turkey earthquake was 2.212 g (USGS 2023). A total of 59259 persons were killed as a result of this earthquake. When comparing these two earthquakes of equal magnitude but vastly different PGA ratings, the 2015 earthquake's damage is enormous despite its low PGA. Every major earthquake in Nepal, including the one in 2015, has left behind significant devastation.
Let us use the damage to the Patan Durbar Square region as an example to contrast the 1934 and 2015 earthquakes. Figures 3 and 4 show the damage caused by the corresponding earthquakes in this region. In these photos, the Patan Durbar Square 'Dewals' and Temples in the background had more serious damage from the 1934 earthquake than from the 2015 earthquake. The average number of fatalities due to earthquakes in 1934 and 2015 was 1.4% and 0.5%, respectively (Sapkota et al. 2016). Larger shaking and nonengineered masonry construction may have contributed to the 1934 earthquake's high death toll and destruction.

The abovementioned description of damage and casualties is contrasted with the explanation of the Modified Mercalli Intensity (MMI) scale, and a suitable MMI is provided. Here, MMI-IX and MMI-VIII are given for the 1934 and 2015 earthquakes in the Kathmandu Valley.
respectively. The intensity-PGA relation shown in equation 1 can therefore be used to calculate PGAs (Gutenberg and Richter 1942).

\[ \log a = -0.5 + 0.33I \]

where, \( a \) - PGA (in gal), \( I \) - Modified Mercalli Intensity

Substituting the intensities of the 1934 and 2015 earthquakes, the PGAs for these earthquakes are found to be 0.295 g and 0.138 g, respectively.

2. **Generation of artificial ground motion**

Although Nepal has had numerous significant earthquakes since 1255 A.D., there are no instrumental recordings of strong ground motion prior to 1978 A.D. In addition to property damage and mortality, Nepal's earthquakes also cause landslides, floods, settlements, land fractures, fire, epidemics, and other problems. Seismic risk analysis and dynamic analysis are crucial in a location such as this where earthquakes are the main threat. However, because Nepal lacks a recorded time history of past earthquakes, artificial time histories must be generated.

Artificial ground motion generation primarily uses three techniques (Yang et al. 2022).

1. Linear scaling of real ground motion records.
2. Spectrum-compatible pure artificial or synthetic time history.
3. Spectrum-compatible time histories based on real records.

In the first-ever spectrum-compatible time history, a stationary random process was multiplied by a user-specific envelope function to produce a nonstationary random process. Iterative frequency domain adjustments were made to this nonstationary random process until the desired target spectrum was obtained (Jennings et al. 1968). In a different study, the nonstationary properties of actual ground motion were simulated (Levy and Wilkinson 1975) utilizing the external envelope function of real ground motion. In another study, the time history was simulated using a stochastic method while taking into account the source, site, and path effects as a function of magnitude and epicenter (Boore 2003). Based on a filtered white noise process with time-varying parameters that are related to the ground motion parameters, another stochastic technique was created (Razaeian and Kiureghian 2008). Recently, the response spectrum compatible ground motion was simulated using wavelet-based multiresolution analysis (Chen et al. 2021).

In Nepal, the spectrum-compatible time history for Pokhara was acquired for three return periods. The disaggregation method utilized in this study took into account how each type of earthquake contributes to the total hazard. When there are few records available for hazard
investigations, this technique can be helpful (Parajuli et al. 2008). In another study, the uniform hazard spectra derived using PSHA findings were used to create a spectra-compatible artificial time history, which was then compared to the time history and Fourier spectrum of the 2015 earthquake (Chaulagain et al. 2017). In a different study, the target spectrum from three attenuation laws was used to generate synthetic ground motion in Kathmandu, which was then compared to the recorded time history from 2015 and showed the applicability of those attenuation laws for Nepal (Parajuli and Shrestha 2018). Additionally, to fix the ground motion parameters for Nepal, the 2015 earthquake was simulated by the stochastic method, and the simulated earthquake was found to be similar to the recorded earthquake (Parajuli and Ghimire 2018).

The method that requires real ground motion history is not feasible in Nepal because there are not enough ground motion recordings. As a result, a synthetic time history that is consistent with the spectrum is generated in this study. Two significant earthquakes that hit Nepal in 1934 and 2015 are considered. In the beginning, 2015 earthquake is simulated at Kathmandu. The time history of the 2015’s simulated earthquake is compared to that recorded earthquake. This comparison established the validity on the result of simulation. Then, the same approach is used to simulate the 1934 earthquake. The input variables for earthquakes that are taken into consideration are shown in Table 2.

Table 2: Parameters used for the 1934 and 2015 earthquakes

<table>
<thead>
<tr>
<th>Earthquake parameters</th>
<th>1934</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment magnitude (Mw)</td>
<td>8.1</td>
<td>7.8</td>
</tr>
<tr>
<td>Epicentral distance, R (km)</td>
<td>176</td>
<td>81</td>
</tr>
<tr>
<td>Focal depth, H (km)</td>
<td>15</td>
<td>8.2</td>
</tr>
<tr>
<td>Source</td>
<td>(Ambraseys and Douglas 2004; Chamlagain et al. 2011; Sharma et al. 2016; Rizza et al. 2019)</td>
<td>(Kobayashi et al. 2015; Basu et al. 2022; USGS 2023)</td>
</tr>
</tbody>
</table>

The suitable target spectrum must be chosen to simulate earthquakes. In this study, the target spectrum is derived from spectrum obtained using attenuation rules. Since Nepal has yet to develop its own attenuation law, attenuations developed for the subduction zone are chosen. In a study, it is advised to utilize Young’s attenuation to estimate the seismic input in Nepal (Maskey and Mishra 2005). Additionally, Kanno’s attenuation was developed using many strong motion data for a subduction zone in Japan. These two sets of target spectra from Young’s and Kanno’s attenuation laws (Youngs et al. 1997; Kanno et al. 2006) and another set from their average are used in this study. After the simulation, it was found that using the target spectrum from an average of Young’s and Kanno’s attenuation law, the recorded and simulated
earthquakes of 2015 matched. Therefore, for both earthquakes of 1934 and 2015, the target spectrum is defined using the average of Young’s and Kanno’s attenuation law. After defining target spectrum for each of the earthquakes, the total duration (T_D) is determined using equation 2 (Kempton and Stewart 2006). Equations 3 and 4 are used to compute the T_B and T_C portions of total duration (T_D) (Ohsaki 1994).

\[ \ln T_D = \ln \left( \frac{\exp(b_1 + b_2(M-6))/10^{1.5M+16.05}}{4.9 \times 10^6 \beta} \right)^{-\frac{1}{3}} + C_2 r + C_1 s \]

\[ T_B = [0.12 - 0.04(M - 7)]T_D \]

\[ T_C = [0.05 - 0.04(M - 7)]T_D \]

where the values of coefficients \( b_1, b_2, c_1 \) and \( c_2 \) are 2.79, 0.82, 1.91, and 0.15, respectively, \( \beta \) is the shear wave velocity equal to 3.2 km/sec, \( s \) is the soil type and is equal to 1 for soil and zero for rock, \( M \) is the magnitude of the earthquake and \( r \) is the epicentral distance. Then, the envelope function \( E(t) \) is obtained by using the relation as in equations 5 to 7 (Ohsaki 1994).

\[ 0 \leq t \leq T_B: E(t) = (t/T_B)^2 \]

\[ T_B \leq t < T_C: E(t) = 1 \]

\[ T_B \leq t < T_C: E(t) = \exp \left( \frac{\ln 0.1}{T_D - T_C}(t - T_C) \right) \]

In the envelope function, \( T_D \) is split into \( N \) segments, as shown in equation 8. The ratio of simulated spectra (\( S_{DS} \)) to target spectra (\( S_{DT} \)) is used to determine the ordinates for each segment. Next, the cumulative value is normalized to the final sum to derive the probability density function. Additionally, the probability density function spanning the range of 0 to \( 2\pi \) is used to generate the phase angle at random. The acceleration of random motion is assumed in terms of the Fourier series when the envelope function is defined, as indicated in equation 10.

\[ \Delta t = \frac{T_D}{N} \]

\[ R_D = \frac{S_{DS}}{S_{DT}} \]

\[ C_K = \sum_{K=0}^{N} F_K \cdot (\cos \phi_K + i \sin \phi_K) \]

where \( C_K \) is the amplitude of acceleration, \( F_K \) is the \( k \)th Fourier amplitude, \( \phi_K \) is the \( k \)th Fourier phase angle and \( N \) is the number of cycles.

In the initial iteration, the Fourier amplitude \( F_K \) is taken to be unity, and the acceleration is calculated using an inverse Fourier transformation. To make the simulated time history
resemble the recorded time history, the accelerations are multiplied by the envelope function. The acceleration time history is used to derive the response spectra, and equation 9 is used to calculate the ratio \( R_D \) for each time step. The original Fourier amplitude is then multiplied by the estimated ratio \( R_D \) to create a new Fourier amplitude. Until the simulated and target spectra match, this loop is repeated. The MATLAB code is used to carry out the iteration procedure.

3. Results

The plot of simulated and recorded earthquake of 2015 A.D. in Kirtipur, Kathmandu is shown in Figure 5. Similarly, Figure 6 displays the plot of simulated time history of the 1934 earthquake in Kathmandu.

Figure 5: Simulated and recorded 2015 earthquake at Kathmandu

Figure 6: Simulated 1934 earthquake at Kathmandu

Table 3 lists the ground motion parameters, including the maximum PGA, time period, predominant period, and significant duration. According to (Bolt 1973; Trifunac and Brady 1975), the relevant duration is the period of time between 5% and 95% of the Arias intensity.

Table 3: Ground motion parameters for recorded and simulated earthquakes

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>2015 recorded</th>
<th>2015 simulated</th>
<th>1934 simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N‒S component</td>
<td>E‒W component</td>
<td></td>
</tr>
<tr>
<td>Maximum PGA (g)</td>
<td>0.242</td>
<td>0.168</td>
<td>0.230</td>
</tr>
<tr>
<td>Time period (Sec)</td>
<td>0.41</td>
<td>0.43</td>
<td>0.48</td>
</tr>
<tr>
<td>Predominant period (Sec)</td>
<td>0.26</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>Significant duration (Sec)</td>
<td>39.8</td>
<td>38.7</td>
<td>17.2</td>
</tr>
</tbody>
</table>
The response spectra, Fourier spectra, and other ground motion parameters are generated from these time histories using 'Seimosignal-2021'. Figure 7 shows the response spectra for the simulated time histories of 1934 and 2015 and the actual time history of the 2015 earthquake. Figures 8 to 10 show the Fourier spectra of the aforementioned earthquakes.

Figure 7: Response spectra for recorded and simulated time histories of 2015 and 1934 earthquakes for soil at 5% damping

Figure 8: Fourier spectrum for the 2015 recorded earthquake N‒S component

Figure 9: Fourier spectrum for a simulated earthquake of 2015

Figure 10: Fourier spectrum for the 1934 simulated earthquake

To compare the significant duration of Nepal’s earthquake, some shallow subduction zone earthquakes were taken and processed in ‘Seismo-Signal 2021’. The signification durations of the considered earthquakes are presented in Table 4.

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Date</th>
<th>Fault Zone</th>
<th>Magnitude</th>
<th>Focal depth(km)</th>
<th>Significant duration (Sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kobe earthquake</td>
<td>17/01/1995</td>
<td>Philippine sea - Pacific plate</td>
<td>6.9Mw</td>
<td>25</td>
<td>12.86</td>
</tr>
<tr>
<td>Chichi earthquake</td>
<td>20/09/1999</td>
<td>Philippines - Eurasian Plate</td>
<td>7.7M$_{S}$</td>
<td>8</td>
<td>11.78</td>
</tr>
</tbody>
</table>
4. Discussion

We discovered a match between the ground motion parameters of observed and simulated earthquakes in 2015 in the data shown in Table 3. While the greatest PGA in Kirtipur determined from the simulation is 0.23 g, the maximum PGA of the 2015 earthquake recorded at the Kirtipur station is 0.168 g for the E‒W component and 0.242 g for the N‒S component. Additionally, the mean time period and predominant period for actual and simulated earthquakes in 2015 are similar. Although there is a sizable disparity in time between the recorded and simulated earthquakes, it is undeniable that the 2015 earthquake had a longer duration. Similarly, the peak PGA of 1934 earthquake obtained from simulation is 0.273 g. This number is close to the PGA value obtained from intensity-PGA conversion relation of (Gutenberg and Richter 1942), which yielded a value of 0.295 g. The value of PGA of 1934 earthquake obtained from simulation is also comparable to the value, 0.1 g to 0.35 g obtained from seismic hazard assessment using 1934 earthquake as a scenario earthquake (Bhattarai et al. 2011). So, the peak PGA of the simulated time history of 1934 earthquake match to the PGA values from previous researches.

The simulated earthquake of 1934 had mean and predominant periods of 0.84Sec and 0.74Sec, respectively. Meanwhile, the same earthquake has a significant duration of 25.8 Sec. According to (Rana 1935), the shaking of the 1934 earthquake lasted from 2 to 8 minutes at various locations and 2 to 3 minutes in the Kathmandu Valley. The significant duration of 25.8 Sec, which was derived from a simulated time history, is reasonable in relation to this shaking period since it depicts the longer duration of the earthquake.

Table 4 reveals that all the considered earthquakes in other subduction zones have a significant duration less than 20 Sec. But it is evident that the significant duration of the earthquakes that occurred in Nepal is more than 20 Sec. Hence, the earthquakes that occurred in Nepal are longer duration earthquake. Therefore, it is clear that even at low PGAs, the Nepalese earthquakes caused significant damage since they started at a shallow depth and lasted for a longer time.

5. Conclusion

The following conclusions can be made on the basis of the data and findings from this investigation.

1. To simulate the earthquakes of 1934 and 2015, a suitable target spectrum is derived from the average of Young's and Kanno's attenuation laws.
2. The maximum PGA of the 2015 earthquake measured in Kirtipur is 0.242 g, while the maximum PGA of the 1934 earthquake in Kathmandu, as determined by synthetic ground motion, is 0.273 g. Therefore, the PGA of the Kathmandu earthquake in 1934 is greater than that of the earthquake in 2015.

3. Nepal has shallow crustal earthquakes that tremble for longer than equivalent events in other subduction zones. Therefore, one of the causes of greater damage is longer-lasting shaking.

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**Author Contributions**
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**Data Availability**
“If authors receive a request for access to data utilized in research, they will make the data available.”