eISSN: 2976-1190

Journal of Engineering and Sciences

Vol. 3 Issue 2 Nov 30, 2024

DOI: https://doi.org/10.3126/jes2.v3i2.72198

Journal homepage: Journal of Engineering and Sciences (nepjol.info)

Publisher: Research Management Cell, Pashchimanchal Campus, Lamachour, Pokhara

A review on probabilistic seismic hazard analysis of Nepal

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(Manuscript Received: 07/07/2024; Revised: 07/09/2024; Accepted: 20/09/2024)

Abstract

Different research papers on Nepal's probabilistic seismic hazard analysis (PSHA) have been reviewed to compare the methodology used and the results obtained. Multiple types of research related to PSHA have been performed so far in Nepal, each using different source models. All research was collected and analyzed to obtain the research gap for future studies. This review attempts to present the risk of seismic hazards in Nepal and the gaps that need to be addressed for a proper seismic hazard analysis in the near future. The results from the review have found a lack of understanding regarding the most valid source model in the context of Nepal. No Ground Motion Prediction Equations (GMPEs) are tailored specifically for Nepal. There is also a lack of detailed earthquake source characterization based on actual tectonic settings and fault composition. These reasons might contribute to inaccuracy while performing a proper hazard analysis.

Keywords: Peak Ground Acceleration; PSHA; Seismic Source Zone; Source Model

1. Introduction

Seismic hazard analysis is of utmost importance for Nepal due to its location in a seismically active region (Upreti, 1999). Nepal is situated along the boundary of the Indian and Eurasian tectonic plates, making it highly susceptible to earthquakes (Aaa Amos, 2015). Seismic hazard analysis is crucial to mitigate earthquake-related risks, protect public safety, enhance infrastructure resilience, and ensure sustainable development of the country. It plays a significant role in disaster risk reduction and overall societal well-being in this seismically active region.

1.1. Seismic Hazard and Risk in Nepal

Nepal experiences high seismic activity due to the collision of the Indian and Eurasian plates (Upreti, 1999). Being in the heart of the Himalayas, Nepal experiences many more powerful earthquakes than magnitude 4. Even though most of these earthquakes have magnitudes between 4 and 6, they often do not cause much harm. It is important to note that Nepal has historically experienced damage from earthquakes with a magnitude of 6.5 or greater. It is crucial to realize that the magnitude of an earthquake alone cannot accurately describe the breadth of its destruction. Other aspects, like energy release, shaking duration, focal depth, building susceptibility, and several others, are critical in determining the earthquake's damage level.

Nepal's complex tectonic setting includes the Main Frontal Thrust (MFT) and other fault systems (Hubbard et al.,2016). It is thus important to understand the formation of the Himalayas and the

plate tectonics of Nepal in order to perform proper hazard analysis. Research done so far has stated that the
stratigraphy of Nepal comprises five major tectonic zones extending from east to west. They are the Terai Zone, Churia Zone, Lesser Himalaya, Higher Himalaya, and the Tibetan Tethys Zone. The plate tectonics is dominated by three master thrusts, The Main Frontal Thrust, the Main Boundary Thrust, and the Main Central Thrust. All of these thrusts come together at the same depth in a low angle decollement known as The Main Himalayan Thrust (Upreti, 1999). These geological features contribute to the region's high seismic hazard. Nepal has a history of devastating earthquakes, including the 1934 Bihar-Nepal earthquake and the more recent 2015 Gorkha earthquake (Ambraseys & Douglas, 2004). These events have caused significant loss of life and damage to infrastructure.
Table 1 shows that there is a need for seismic hazard analysis in Nepal to reduce its impact and save loss of life and property.

Table 1. History of Earthquake in Nepal (Ambraseys & Douglas, 2004)

Date	Epicenter	Mag.	Death
1408-08	Nepal-Tibet Border	8.2	2,500
1505-06-06	Karnali Zone	8.9	6,000
1681-01	Northern Koshi zone	8.0	4,500
1833-08-26	Kathmandu, Bihar	8.0	6,500
1934-01-15	Nepal,India	8.0	10,700-12,000
2015-04-25	Gorkha	7.8	8,857
2015-05-12	Dolakha	7.3	213

1.2. Probabilistic Seismic Hazard Analysis

Probabilistic Seismic Hazard Analysis (PSHA) is a scientific approach used to assess earthquake risk by estimating the likelihood of various levels of ground shaking at a given location over a specified time period (Cornell, 1968). PSHA considers uncertainties in earthquake occurrence, seismic source characteristics, and ground motion prediction. It provides valuable information for engineering, urban planning, and disaster preparedness efforts. PSHA involves several fundamental concepts and methodologies (Reiter, 1990).

Seismic Sources: PSHA begins by identifying and characterizing seismic sources, such as fault lines and seismic zones. These sources are defined based on geological and seismological data.

Magnitude-Frequency Relationships: PSHA uses historical earthquake data to estimate seismic events' frequency and magnitude distribution in each source zone. This information is critical for understanding earthquake occurrence.

Ground Motion Prediction Equations (GMPEs): GMPEs relate earthquake source characteristics to ground motion parameters (e.g., peak ground acceleration, spectral acceleration). They provide estimates of ground shaking at specific locations for different seismic events.

Hazard Curves: PSHA calculates hazard curves, representing the probability of ground shaking exceeding specified levels at a given site over a specified time frame. These curves are generated for various ground-shaking intensity levels.

1.3. Review of Literature

Stevens et.al (2018) performed PSHA for Nepal, using a mix of the fault and area source models to describe six seismic sources. They used OpenQuake to analyze and estimate peak ground acceleration (PGA) at 2% and 10% probability of exceedance in 50 years, along with hazard curves at various locations. They found that PGA reaches 0.6g at a 10% probability of exceedance in 50 years and is high over most of Nepal. They predicted that the hazard is high in southern Nepal and fairly evenly distributed across the west-northwest–east-northeast direction. After comparing the outcomes of a simulated Gorkha earthquake scenario using various ground-motion prediction equations (GMPEs) against actual observations, they discovered that none of the GMPEs considered adequately explained all the observed characteristics. As a result, they recommended the development of GMPEs tailored specifically to the region's unique seismic attributes and behavior (Stevens et al., 2018).

P.M. Pradhan (2020) carried out PSHA and prepared a hazard map regarding peak Horizontal Acceleration (PHA) for a 500-year return period. The areal source models were used for analysis since no fault information was available. After the devastating occurrence of the Nepal - Gorkha earthquake, determining all the earthquake motion parameters before further designing the structures was necessary. The methods involved in this paper were studying earthquake catalog, seismic source zones, minimum and Maximum magnitudes, seismicity parameters, attenuation relationship, and modeling all the data in the software CRISIS2007. The analysis concluded that the PHA value varies from 0.09 g to 0.5g for Nepal, which clearly proves that the Eastern and Western parts of Nepal are more hazardous to earthquakes. These results were then compared with other values obtained from the different researchers, and it found that the values differed from those of Pandey et al., 2002 only because of the limited earthquake data at that time (Pradhan et al., 2020).

Champlain (2020) adopted a fault source (MHT) and areal sources, i.e., northern grabens in Tibet, strike-slip event dominant sources in eastern and western Nepal, and a source south of MHT for performing PSHA. After the devastating earthquake of 2015 AD, revision of NBC-105 was felt necessary for the safe design of buildings, for which the reassessment of the seismic hazard by adopting a probabilistic approach was a great step to be taken. For PSHA, the earthquake catalog was studied, sources were characterized, and recurrence parameters were estimated. Since the Himalayan region does not have specific GMPEs, three types of GMPEs, namely subduction zone, active shallow crust, and stable continental area, were selected, and their equations were implemented. The limitation was that even these GMPEs could not predict the ground motion for the Himalaya-Tibet region; a logical tree approach was adopted to minimize the uncertainty. The result concluded that there is a high value of PGA in the locked portion of MHT due to the presence of a hanging wall and a lower value of PGA in the northern part of Nepal. These results differed from the previous studies because the locked portion of MHT was considered a separate fault source, and those studies used different GMPES without considering the subduction zone, i.e., MHT. The results were consistent with the seismic hazards in Pakistan and India. The PGA obtained for a 10% probability of exceedance in 5o years was finally adopted to revise NBC-105 (Acharya et al., 2020).

Ghimire and Parajuli (2016) performed a probabilistic seismic hazard assessment in Nepal using the Uniform Density Model. All the earthquake catalogs from 1255 to 2015 A.D. were used to prepare the seismic hazard map. Spatial uncertainty, magnitude uncertainty, and temporal uncertainty were tried to minimize. The attenuation laws developed for subduction zones were used to determine PGA and SA. Matlab was used to obtain the result. It was concluded that a curve with the highest slope indicates the absence of a major earthquake and that a flat slope indicates the presence of a major earthquake. Even though the findings were extremely useful in understanding the seismic hazard of Nepal, it does have some limitations, too, it assumed that all the sources were equally capable of producing earthquakes and that occurrence would be in the center of each cell, which could be different in practicality. Similarly, it is mentioned that the probability of exceedance of earthquake of each source was at the same average rate, which too cannot be true in practice. Another weak point that one should highlight is that it uses a model that says the earthquake densities were equally distributed in all areas, whether there was an earthquake or not (Ghimire & Parajuli, 2016).

Subedi and Parajuli (2016) performed a probabilistic seismic hazard analysis of Nepal, which was divided into four area sources based on the density of historical earthquakes up to 2016-9-18. Dependent and repeated events were removed, and a delineation of seismic sources and models was performed, along with a completeness analysis. Evaluating various seismic parameters attenuation relationship and seismic hazard cure was obtained. Earthquake densities were obtained using Kernel Estimation. PGA and SA for different periods have been calculated for a 475-year return period. The maximum PGA for hard, medium, and soft soil were 300 gal, 400 gals, and 500 gals, respectively. The research concluded that a higher hazard exists in the central and far western regions of Nepal, where the concentration of historical earthquakes was higher (Subedi & Parajuli, 2016).

Thapa and Wang (2013) compiled an earthquake catalog for the surrounding region (latitude 26° N and 31.7° N and longitude 79° E and 90° E) from 1255 to 2011 used to delineate 23 seismic source zones in Nepal and the surrounding region. Using the seismic source information and probabilistic earthquake hazard parameters in conjunction with a selected ground motion prediction relationship, peak ground accelerations (PGAs) have been calculated at bedrock level with 63%, 10%, and 2% probability of exceedance in 50 years. The estimated PGA values in this study at 2% probability of exceedance in 50 years were about 1.7–2.0 times higher than at 10% probability of exceedance in 50 years and about 6.0–7.0 times higher than at 63% probability of exceedance in 50 years. The PGA distribution maps indicated that the highest hazard is in the far-western with the highest estimated PGA 0.57–0.62 g at 10% probability of exceedance in 50 years, and 1.0–1.1 g at 2% probability of exceedance in 50 years and eastern parts of Nepal with estimated PGA values 0.57–0.62 g at 10% probability of exceedance in 50 years, and 1.0–1.1 g at 2% probability of exceedance in 50 years. Southern Nepal has the lowest hazard compared to other parts of the country (Thapa & Wang, 2013).

Hubbard et al. (2016) developed a structural cross-section and a three-dimensional model of the MHT based on seismic observations from the 2015 Gorkha earthquake and suggested a double ramp model. The moderate ramp is inferred at a depth of 10 km, and the deep ramp is at a 15 km depth with a dip angle of 260. The dip of the southern flat is between 20 and 50, and the middle flat and the northern flat is 70 (Hubbard et al.,2016).

Rahman and Bai (2018) used PSHA to estimate the seismic hazard levels in Nepal. Three seismogenic source models are used (smoothed gridded, linear, and areal sources). 23 seismic source zones are utilized for the areal source, delineated by Acharya et al.,2020 and Ram and Wang (2013). For linear sources, active faults were considered (14 active faults are assigned). A smoothed, Grided source zone-free approach for the spatial smoothing of seismicity was used to avoid subjectivity in delineating areal seismic sources (Rahman & Bai, 2018).

Bhusal & Parajuli (2019) presented the results of PSHA for Nepal, taking areal and longitudinal fault sources using the Open Quake engine. Areal sources considered by Pandey et al. (2002) and Thapa & Guoxin, (2013) have been used to give equal weightage while forming the Logical tree. Major faults are collected from Pandey et al. 2002, Parajuli 2015, Steves et al., Rahaman et al., for the linear source without repetition, and MFT is taken as the major active fault (Bhusal & Parajuli, 2020).

Ghimire, S. (2019) performed a probabilistic seismic hazard analysis of Nepal considering five hundred and twenty-eight areal source models. All sources were divided into areal elements of 0.5° along longitude and 0.25° along latitude and assumed to be equally capable of producing earthquakes. The occurrence of earthquakes was taken in the center of each areal cell (Ghimire, 2019).

2. Methodology

Table 2. Past research, along with their source geometries used to perform PSHA

Researchers	Year	Source geometry
Parajuli	2015	Areal source
Hubbard et.al	2016	3D geologically informed model
Stevens, V. L., Shrestha, S. N., and Maharjan, D. K.	2018	Fault and area source models
Ghimire, S.	2019	Areal source
Bhusal & Parajuli	2019	Areal and longitudinal fault source
Acharya et al.	2020	Areal source
Poudyal, D. et al.	(2023).	Areal source

The criteria for selecting and reviewing literature are based on various source models. Past researchers have used different source models to depict their results. There is a need for a comparative analysis among the various source models used so far.

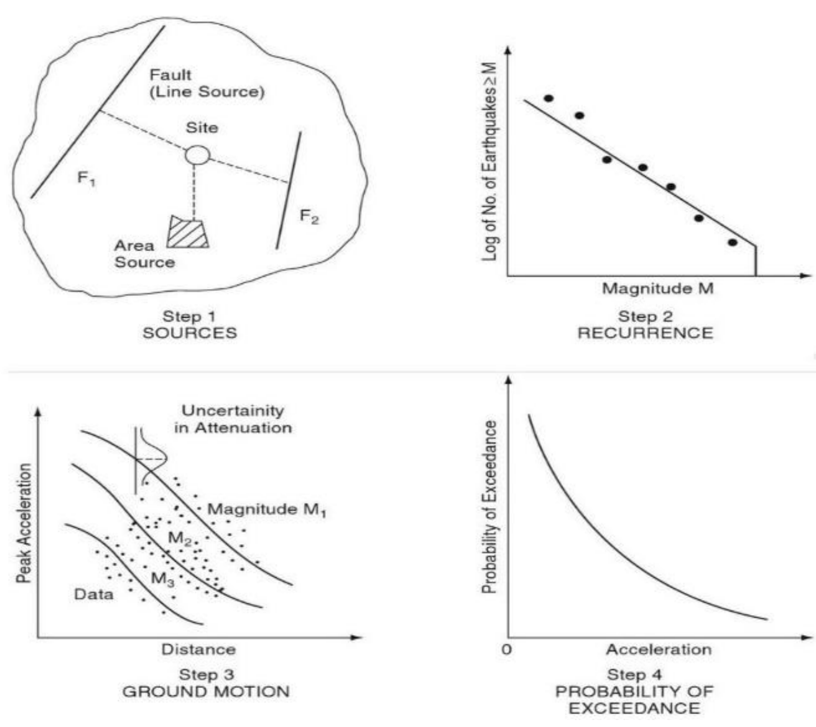

Figure 1: Four steps of a probabilistic seismic hazard analysis (Reiter, 1990)

2.1. Data Source and Data Quality

Past studies obtained the seismic data catalogs from different sources such as the International Seismological Centre (ISC), the United States Geological Survey (USGS), Global Centroid Moment Tensor (GCMT), the National Oceanic and Atmospheric Administration (NOAA), GEM Global Historical Earthquake Archive (GEM-GHEA), and Department of Mines and Geology (DMG). All these stations record data in different magnitude scales. For uniformity, all these data are converted to a common magnitude, i.e., moment magnitude. The primary foundation for PSHA relies on earthquake catalogs, encompassing instrumental data and historical records. However, there is a significant limitation regarding the instrumental earthquake catalog. The available data only covers a relatively short time span, typically around 55 to 60 years, which is considerably shorter than the time required for tectonic processes to generate earthquakes, as pointed out by Bilham in 2013. The instrumental earthquake catalog has been considered complete since 1964.

2.2 Seismic Hazard Models for Nepal

PSHA is a widely used approach that estimates seismic hazards by considering earthquake source characteristics, recurrence intervals, and ground motion prediction equations (GMPEs) (Cornell, 1968). PSHA provides a probabilistic assessment of seismic hazard by accounting for uncertainties. PSHA requires robust data on earthquake sources, fault characteristics, and GMPEs, which can be limited in Nepal. DSHA assesses the hazard associated with specific scenario earthquakes, typically characterized by worst-case scenarios. DSHA assumes the occurrence of a specific earthquake event and calculates the effects of ground shaking. DSHA does not consider the full spectrum of possible earthquakes and their probabilities. Hybrid models combine probabilistic and deterministic approaches to seismic hazard assessment. These models may incorporate deterministic scenarios for major fault ruptures or large earthquakes while considering the broader range of seismic sources and uncertainties through probabilistic methods.

3. Results

So far, PSHA has been performed mainly using areal, linear, fault, and 3D sources. The outcome obtained from each of these sources is different. Stevens et al. (2018) compared the results from a modeled Gorkha earthquake scenario using different GMPEs with observations. They found that none of the trialed GMPEs fully account for all the features observed. Developing a region-specific GMPE would be the next step for future seismic hazard analysis in Nepal. Stevens et al., (2018) also computed seismic hazards for Nepal considering both aerial and fault sources; however, variation in the geometry of the MHT has not been considered to estimate its relative contribution to hazard estimation. Rahman et al. (2018) performed a hazard analysis considering the seismicity of Nepal using three different seismogenic source models (smoothed gridded, linear, and areal sources) based on the complicated tectonics of the study area. Many seismic regions have complex fault systems with interconnected faults, fault branches, and fault interactions, and these models cannot capture the complexities of these fault systems. After the 2015 Gorkha earthquake, several studies have been carried out on the geometry of the MHT (e.g., Elliot et al., 2016; Hubbard et al., 2016; Wang et al., 2017). These studies and the earlier ones have come up with two contrasting models; the single and double ramp along the MHT. Each research team has performed PSHA defining their own seismic source model. No study has compared the results of considering different seismic source models and validated the best model specific to Nepal. There is a lack of detailed earthquake source characterization based on actual tectonic settings and fault composition.

4. Discussion

This study shows that Nepal lacks specific GMPEs. Developing the GMPEs specific to Nepal leads to more accuracy in PSHA. Source characterization should be based on the geometry of the MHT. This research also shows a lack of a validated seismic source model in the context

of Nepal.
The contribution of the fault geometry also needs to be addressed in the near future.

5. Conclusion

The main contribution of this literature review is to present the ideas of different researchers in a single platform and to perform a comparative analysis of various source models. Overall, the literature review lacks detailed source characterization and validation of strong ground motion with past earthquakes. There is a lack of validation of the best seismic source model for Nepal. Developing a region-specific GMPE would be the correct step for a reliable seismic hazard analysis.

6. Recommendations

a. Region-specific GMPEs need to be developed in order to perform a proper seismic hazard analysis
b. A valid seismic source model needs to be determined out of the multiple source models used so far by comparing the results obtained by each source model
c. Contribution of variation of fault geometry of the MHT needs to be considered whenever PSHA is carried out

Acknowledgment

We sincerely thank Assistant Professor Pawan Chhetri, Geotechnical Engineer, Pashchimanchal Campus, for his invaluable suggestions, which greatly contributed to the quality and depth of this manuscript.

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