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PROBABILISTIC SEISMIC HAZARD ANALYSIS OF POKHARA METROPOLITAN CITY

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Abstract

Earthquakes occur randomly in space and time, making accurate predictions challenging. However, estimating earthquake occurrences to a certain extent is possible. This study employs Probabilistic Seismic Hazard Analysis (PSHA) for the Pokhara Metropolitan City. The process involves preparing an earthquake catalog through data collection, homogenization, merging, declustering, and completeness analysis. Subsequently, source characterization identifies seven areal seismic sources: MHT, NG-1, NG-2, NG-3, NE, NW, and South. G-R parameters 'a' and 'b' are then calculated. Finally, ground motion predicting equations are chosen, and site effects in the form of Vs30 values are incorporated. Using R-crisis software, the hazard, expressed as Peak Ground Acceleration (PGA) and spectral acceleration (SA) for 2% and 10% probability of exceedance over 50 years, is computed throughout the Pokhara Metropolitan City.

Keywords: *PSHA, R-CRISIS, PGA, SA, Pokhara Valley, KTP station, 2015 Gorkha Earthquake*

1. INTRODUCTION

Nepal lies in a seismically active region[1]. A large part of the reason why Nepal is considered to be seismically active is due to the presence of a main Himalayan thrust that spans throughout the country. The main Himalayan thrust present in the subduction zone is the main source of seismic hazards in the country [2]. The Himalayas in the North were created as a result of the continuous collision of the Eurasian plate with the Indian plate. These plates and the collision are all situated in the subduction zone. History shows that there has been the appearance of large earthquakes in Nepal. The earthquakes of 1897, 1905,1934, 1950, and the latest 2015 Gorkha earthquake are some of the destructive earthquakes that have occurred in Nepal.

Earthquakes occur when the elastic energy is released through the rupture of the fault and the earthquake is felt in the form of ground motion on the surface. Pokhara is one of the most popular cities of Nepal, particularly admired for its natural scenery. However, the presence of this city is associated with the disastrous earthquakes of the past; in particular, the earthquakes that occurred about 750+/-50BP according to the detailed ^{14}C datings [3] Historical records show that there have been three significant earthquakes that have shaped the Pokhara Valley. Those are the earthquakes (moment magnitude>8) of 1100,1255 and 1344 A.D[3]. Each time the earthquake occurred, there was an avalanche in the Sabche, which is surrounded by the peaks of Annapurna IV, Annapurna III, and Macchapuchuare from east to west and because of that, there was a huge flow of debris from the mountains into the valley[4]. The debris mostly contained the gravel discharge[4][5]. The Pokhara gravels form the primary component of the basin fill, with their upper-layer serving as the foundation beneath the geomorphological surface on which the town of Pokhara has been constructed [6] [7].

As the history and the origin of the Pokhara metropolitan city are associated with high-magnitude earthquakes, this research is necessary to better understand how the earthquakes will affect the city in the future.

2. LITERATURE REVIEW

Khanal et al.,2023[8] compared G-Rparameters using LSM and MLM methods, analyzing seismic events from 1900 to 2021 in Nepal. Results showed G-R parameters of 3.59 and 0.72 (LSM) and 5.51 and 0.61 (MLM) for the complete catalog. When considering only the MHT as a source, the parameters were 3.06 and 0.71 (LSM) and 6.72 and 0.98 (MLM). The MHT is a subduction interface, with a suggested b value of around 1. The results showed that MLM better represented seismicity for well-characterized source zones compared to LSM.

The declustering algorithm used in probabilistic seismic hazard analysis (PSHA) can have a significant impact on the results. In a study by Chhetri et al. (2022)[9], the authors investigated the effect of different declustering algorithms; Reasenberg,1985[10] and Gardner and Knopoff(1974)[11] on PSHA for Kathmandu Valley. They found that the Gardner-Knopoff (1974) declustering algorithm produced results that were closest to the PGA value obtained at the KTP station. This suggests that the Gardner-Knopoff (1974) declustering algorithm is more effective than the other two models for declustering purposes in this region.

Chamlagain & Niroula, 2020[2] conducted a probabilistic seismic hazard analysis by considering the three-dimensional geometry of the main Himalayan thrust. In the paper, two different geometric ramp models; single and double were considered. PSHA was determined separately using these ramp models and the results were compared. The results showed that the PGA value for the 760-year return period for the single ramp model was 0.25g and for the double ramp, the model was 0.27g. Furthermore, these values were validated by the PGA value of 0.26g of the 2015 Gorkha Earthquake. This paper showed that the use of the models whether it be single or double ramp did not play any significant difference in estimating the PGA values. This research further mentioned the inadequacy of GMPEs due to the lack of significant differences in PGA values.

Baruwal et al., 2020[12] conducted a seismic hazard assessment for Pokhara Valley using earthquake data from 1900-2020. They homogenized the catalog with Scordilis (2006)[13] and Ambraseeys (2000)[14], declustered with Gardner & Knopoff (1974)[11], and assessed completeness with Stepp (1972)[14]. Source characterization involved dividing the area into seven sources, using Wells and Coppersmith (1994) [16] models. Seismicity parameters and ground motion attenuation were considered, resulting in seismic hazard curves. For a 10% probability, Peak Ground Acceleration (PGA) at soil and rock sites were 0.525g and 0.387g; for a 2% probability, they were 0.915g and 0.694g, respectively.

Pradhan et al., 2020[17] conducted the PSHA of Nepal.PGA for a 500-year return period was estimated at the bedrock level. A hazard map to show the results of probabilistic seismic hazard analysis was prepared in this paper. R-CRISIS software was used for preparing the hazard map. The results of this research showed the PGA values in the range of 0.09g to 0.5g with maximum hazard in the Western and Eastern parts of Nepal.

3. Methodology

3.1 Study Area

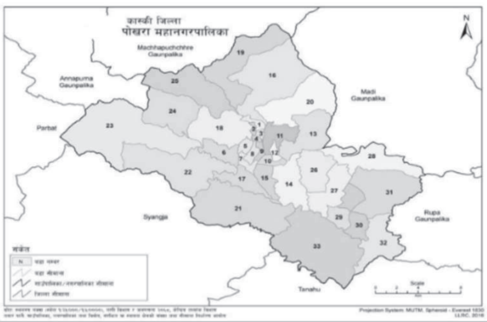

Figure 1 Map of Pokhara Metropolitan City (Source: Pokhara Metropolitan)

Pokhara lies in the lap of the lesser Himalayan and is located on the west side of MHT [18] Geographically, Pokhara Valley is located between 28˚10'00" N to 28˚16'00" N latitude and 83˚58'30" to 84˚02'03" E longitude. The valley consists of 33 wards with a total area of 462.2 km^2. Pokhara is one of the largest growing cities of Nepal. The urbanization of the city has been going on rapidly. Though the urbanization of the city has been going on rapidly it is not going in a planned way [1]. The seismic building design in the Pokhara Metropolitan City before the introduction of NBC:105 in 1994 was conducted using the IS code. This NBC: 105 code for seismic design of buildings in Nepal has undergone many revisions the latest being in 2020 A.D. This means that many of the older buildings in Pokhara were designed using the IS code; without taking into account the actual seismicity of the region. The NBC was implemented more after the 2015 A.D. to improve the seismic performance of the buildings. However, the code failed to give the site-specific seismic zone factors which are extremely important for the seismic design of the buildings. Considering how the land is shaped in Pokhara, how the city has grown chaotically, and the way buildings have been designed over the years, it makes the area more vulnerable or more likely to experience damage during earthquakes. unplanned urbanization, and the building design throughout the years; Thus, it is necessary to have proper site-specific seismic zone factor values for the seismic design and construction of the buildings in Pokhara Metropolitan city**.**

3.2 Catalog of Earthquake Events

The earthquake data was collected for Nepal and its surrounding region within 26° N to 32° N latitude and 79° E to 89°E longitude. This was done by downloading and compiling the seismic data from global seismic activity monitoring platforms like United States Geological Survey, GCMT, and ISC. The final compiled catalog contains the record of the past earthquake events starting from the year 1900 A.D. to 2023 A.D. The data is collected from these earthquake recording sites because Nepal has only a few seismic stations and as a result, we only get a little data on earthquake events, which may not be enough to make an earthquake catalog.

3.3 Homogenization and Merging

Homogenization is the process of converting all of the different types of magnitude into a single type, in this case, moment magnitude M_w. Before the homogenization and merging of the catalog is done the duplicate events are to be removed because the catalog is derived from the different recording sites and thus, there is a high chance of duplication of the events in the catalog. Thus, the merging of the catalog allows to keep only one such event. Homogenization is done using the equations developed by Nath et al.,2017[20], and all of the magnitude is converted to moment magnitude as it does not undergo saturation like over any magnitude range, whereas other types of magnitude do. For example, the surface wave magnitude of an earthquake gets saturated in the magnitude range of 7-8. Similarly, the body and local wave magnitude get saturated even earlier i.e., in the magnitude range of 6-7. Therefore, moment magnitude is more preferred.

3.4 Declustering

Declustering is the process of removing the dependent events of the earthquake such as foreshocks and aftershocks. Gardner and Knopoff, 1974[11] algorithms will be used for declustering. This algorithm was chosen by studying the research conducted by Chhetri et al., 2022[9] where the researcher compared the effect of declustering algorithms and found Gardner & Knopoff, 1974[11] to be the best declustering model for a well-characterized source. Thus, declustering was done using the Gardner & Knopoff, 1974 algorithms with the help of the Z map tool in MATLAB.

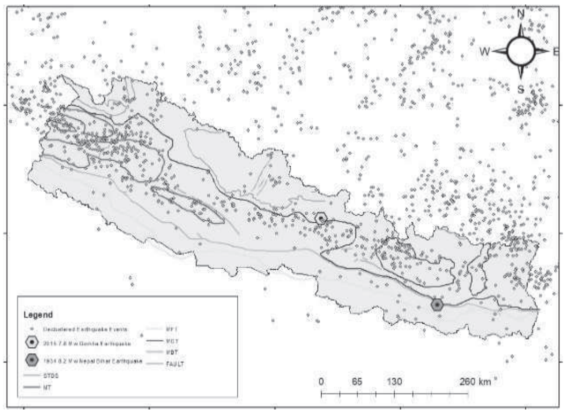

Figure 2 Earthquake events after declustering

3.4 Completeness Analysis

Completeness analysis is done to check the completeness of the earthquake catalog. Completeness analysis gives the minimum threshold of magnitude beyond which the earthquake catalog is complete. Stepp, 1972[15] is used for completeness analysis. Stepp, 1972 algorithms based on MLM on MATLAB will be used for completeness analysis and also for the computation of the G-R parameters based on Kijko,1988[21]. MLM is chosen for the completeness analysis because it takes into consideration uncertainties associated with the earthquake magnitudes and also considers the earthquake magnitudes larger than the observed highest magnitude [21][22]. LSM on the other hand is favourable for the estimation of the probabilities of the highest magnitude of earthquakes[23]. Similarly, the results of the research conducted by Chhetri et al., 2022[9] indicated that for well-characterized source zones, the MLM better represents the seismicity of the source than the LSM. Therefore, MLM is chosen in this study.

3.5 Source Characterization

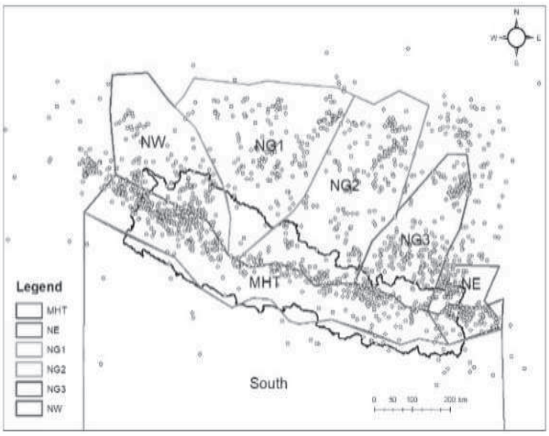

Figure 3 Source Zones

Source characterization is necessary to recognize the seismic sources and quantify the various uncertainties that are connected with source parameters. There are two main uncertainties; spatial uncertainty and size uncertainty associated with earthquakes. Spatial uncertainty refers to the lack of knowledge of the geographical position of the future earthquake. Size uncertainty refers to the knowledge gap in knowing the magnitude with which the earthquake will occur in the future. These uncertainties are taken into consideration by source characterization. To consider spatial uncertainty in earthquake occurrence, seven seismic source zones are chosen based on literature references, specifically Stevens et al., 2018[24], and Chamlagain and Niroula, 2020[2]. These identified source zones help account for spatial uncertainty by assuming that earthquakes can originate from any of these.

Only the areal sources are considered in this study and the zones are selected based on the location, occurrence time, and past earthquake pattern. These seven sources are named Main Himalayan Thrust (MHT), North East (NE), Northern Graben-1 (NG1), Northern Graben-2 (NG2), Northern Graben-3 (NG3), Northwest (NW) and South. The reasons for the selection of these source zones are mentioned below.

Main Himalayan Thrust

Main Himalayan Thrust is a geological structure responsible for the convergence of the Indian Plate beneath the Eurasian Plate, resulting in the dynamic landscape of the Himalayan region and giving rise to seismic activity in the area. MHT has the capacity of producing very large earthquakes and based on historical data, MHT contributes to the highest seismic hazard in Nepal[24].

Northern Grabens

In the southern Tibetan plateau, there lies the north-south striking grabens. These grabens were formed to accommodate the stretching of the earth's crust. The cause of the stretching were the forces acting perpendicular to the Himalayan arc[24][25][26][27]. In this plateau, there are many grabens one of which is the Thakkhola graben, which stands 30km wide in the north and decreases to merely 2km in the south[24]. Along the western margin of the Thakkhola graben, there is the Dangardzong normal fault. Similarly, Gyirong, Kung Co, and Pum Qu are other grabens in the southern Tibetan plateau. Historical records show the presence of earthquakes with moment magnitude greater than six in the Thakkhola and Pum Qu grabens[24]. Therefore, based on the presence of Grabens, the northern grabens are divided as northern graben-1, 2, and 3 (NG-1, NG-2, and NG-3) in this research.

Northeast and Northwest

In the Northeast and Northwest parts of Nepal, a noticeable concentration or cluster of seismic activities can be observed (Figure 4). These events are tied to inferred strike-slip faults associated with the Shillong Plateau in the east and the Northwest fault in the west [2]. In the northwest, there is the Karakoram fault and this fault is known to be active since the last known glacial advance [24][28].

South

In comparison to the Himalayan mountains, the Indo-Gangetic plain doesn't experience earthquakes as often. However, now and then, there are moderate earthquakes in this flat region. These earthquakes might happen because the Indian plate is bending as it moves.

To take into account the shaking of the earthquakes in the model, the Indo-Gangetic plain is taken as a separate area in this research. We consider it on its own in the models because it's different from the Himalayas [2]. This helps to understand how earthquakes work in this region better. But first, this is done by considering the south as a separate source zone.

3.6 G-R parameters

Gutenberg-Ritcher law states that the magnitudes of the earthquakes are distributed exponentially as $\text{Log10N}(m) = a - bm$, where N(m) is the number of earthquakes that have a magnitude greater than or equal to m. 'a' is constant and indicates the total seismic or earthquake activity in the particular area and 'b' value gives the ratio between the small and large earthquakes[29].

After the data filtration is completed, G-R parameters are computed using the maximum likelihood method by Kijko, 1988 [21] using the Z map tool in MATLAB.

The values of G-R parameters are calculated in MATLAB following the maximum likelihood method for the six sources MHT, NE, NG1, NG2, NG3, and NW. The seismic events recorded in the south seismic source zone are quite low in number and the maximum likelihood method in MATLAB cannot be carried out with the available amount of data. Therefore, the least square method is followed to compute the a and b values of south seismic source zones.

As per Stevens et al., 2018[24], the b value of MHT must fall within the range of 1+/-0.05 while for the all-other source zones NG-1, NG-2, NG-3, South, NE, and NW; it must fall within 1+/-0.025. All of the computed b value in this paper is within those limits as seen in Table 1.

Table 1 Shows the seismicity parameters and reference for the maximum magnitude needed for the hazard computation

Source Zones	a	b	Min. M_w	Max. M_w	References for Max. M_w
MHT	7.868	1	5.2	9	Stevens & Avouac(2016)
NE	7.235	0.98	4.9	6.9	Earthquake Catalog
NG1	5.663	1.02	5.2	7.1	Elliot et al.,2010
NG2	6.276	1.02	4.9	7.396	Earthquake Catalog
NG3	7.307	0.98	4.9	7.16	
NW	7.579	1.05	4.9	7.1	Murphy et al.,2014
South	5.44	0.97	4	7	Chamlagain & Niroula, 2020

Also, to calculate the annual rate of exceedance (λ), the bounded Gutenberg-Ritcher law is followed. The formula for the annual rate of exceedance is

Annual rate of exceedance (λ) = $\exp(\alpha-\beta m_o)*[\exp(-\beta(mu-m_o))-\exp(-\beta*(mu-m_o))]/(1-\exp((-\beta*(Mu-m0))))$ for $m_o \leq m \leq m_{max}$

where, $\alpha= 2.303*a$ and $\beta=2.303*b$

The bounded Gutenberg Ritcher law is also helpful to decrease the seismic risk of any region as under the normal G-R law, the seismic source can produce any magnitude of earthquake. Thus, in PSHA, the Bounded Gutenberg-Ritcher law is used to represent the hazard.

3.7 Ground Motion Predicting Equations and the Estimation of Hazard

The Ground Motion Prediction Equation (GMPE) is a fundamental tool used in seismology and earthquake engineering to estimate the level of ground motion, such as ground shaking, velocity, or acceleration, that can be expected at a specific location due to an earthquake occurring at a particular source location. GMPEs specifically tailored to Nepal or the Himalayan region have not been established due to the scarcity of strong-motion data resulting from inadequate instrumentation [24]. The creation of reliable Ground Motion Prediction Equations for a particular area heavily relies on the availability of comprehensive strong-motion data collected from earthquakes within that region.

R-CRISIS is a Windows-based software designed for conducting Probabilistic Seismic Hazard Analysis (PSHA) through a fully probabilistic approach. It generates output in the form of hazard curves and hazard values. The software includes various built-in Ground Motion Prediction Equations (GMPEs) tailored for different source zone categories. To integrate these GMPEs, a weightage approach was employed, selecting the most appropriate equations based on the weighted approach outlined by Niroula & Chamlagain, 2020[2]. The figure below illustrates the combination of models with suitable weightage.

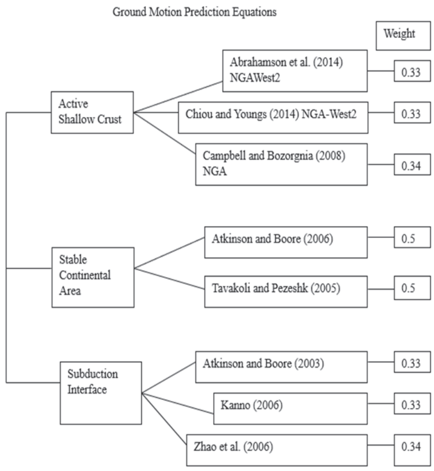

Figure 4 Hybrid models of GMPE

Tectonically, the MHT source is classified as a subduction interface where plates converge. The South and North grabens (NG-1, NG-2, and NG-3) are identified as active shallow crust regions, while the North-East and North-West sources are designated as stable continental areas. Accordingly, relevant Ground Motion Prediction Equations (GMPEs) are used from the hybrid models seen in the figure above.

3.8 Site Effects

The average shear wave velocity at 30m depth or Vs_{30} is included to incorporate the site effect in this study. The inclusion of the Vs_{30} value has become a common practice or standard to represent the seismic site conditions. The condition at the site plays a huge role in the potential damage from the seismic waves coming from the earthquakes, especially of large magnitude [30].

The Vs_{30} values in m/s for the Pokhara metropolitan city are downloaded from the USGS Vs_{30} database map. These values are included in the R-crisis software to show the local site effects. The map of Pokhara showing Vs_{30} values is shown in the figure below.

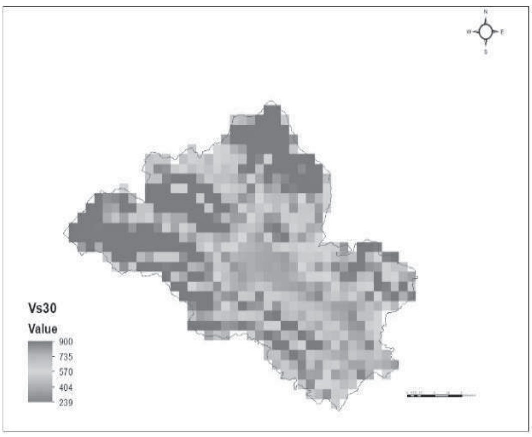

Figure 5 Map showing the Vs_{30} value in Pokhara metropolitan city.

Finally, the seismic hazard is computed at the bedrock level and ground level using the R-CRISIS software.

3.9 Validation

The Peak Ground Acceleration (PGA) value calculated at the KTP station on a rock site was 0.246g for a 10% probability of exceedance in 50 years. This closely aligns with the recorded PGA of 0.2599g during the 2015 Gorkha earthquake, resulting in a difference in error of 5.34%. This level of error indicates a successful validation of the model, signifying that the model's outcomes are in strong agreement with observed data. It's worth noting that this error could be attributed to the oversight of seismic source geometry in this study.

4. RESULTS AND DISCUSSION

The PGA values for the Pokhara metropolitan city at the ground level range from 0.425-0.402g for a 2% probability of exceedance in 50 years and 0.329-0.313g for a 10% probability of exceedance in 50 years. The estimated PGA value for Pokhara metropolitan city at the bedrock level for 2% and 10% probability of exceedance in 50 years are in the range of 0.358g-0.353g, and 0.229-0.226g respectively.

PGA	2% probability of exceedance in 50 years	10% probability of exceedance in 50 years
Bedrock	0.358g-0.353g	0.229-0.226g
Ground level	0.425g-0.402g	0.329g-0.313g

In the range shown above, high PGA values indicate higher hazard whereas low PGA values indicate low potential hazard in the city.

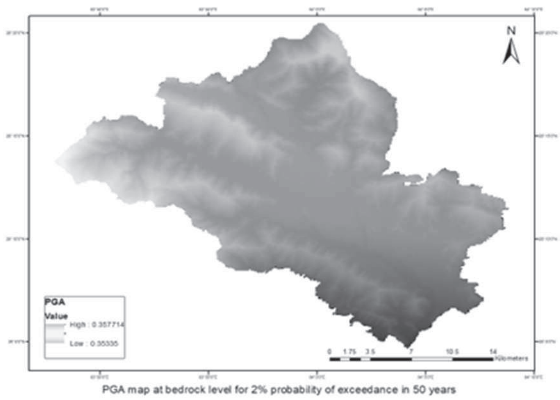

Figure 6 PGA map of Pokhara metropolitan city for 2% probability of exceedance in 50 years at bedrock level

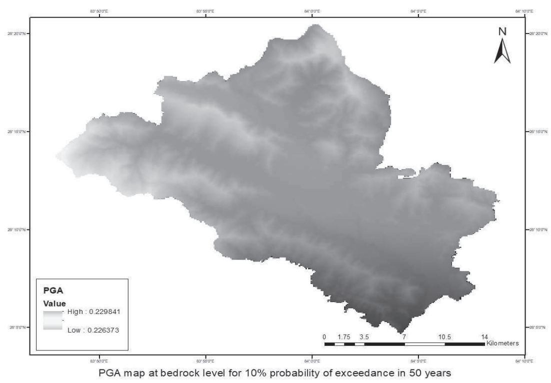

Figure 7 PGA map of Pokhara metropolitan city for 10% probability of exceedance in 50 years at bedrock level

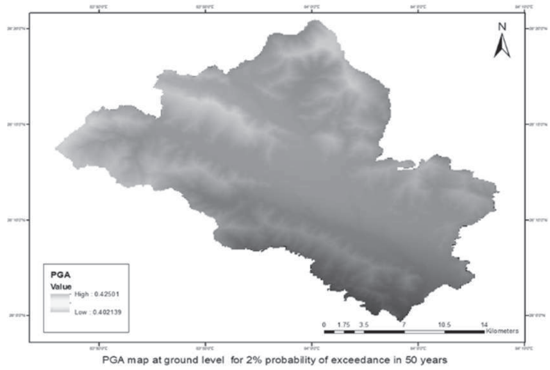

Figure 8 PGA map of Pokhara metropolitan city for 2% probability of exceedance in 50 years at the ground level

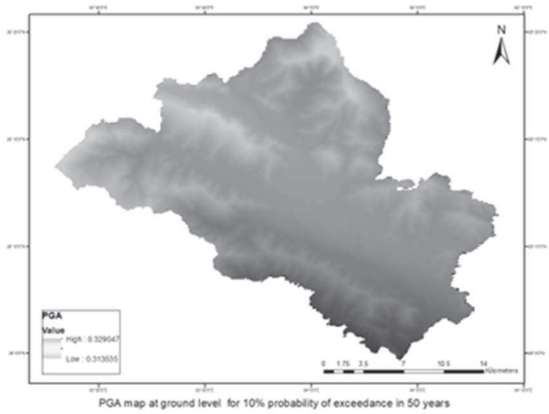

Figure 9 PGA map of Pokhara metropolitan city for 10% probability of exceedance in 50 years at ground level

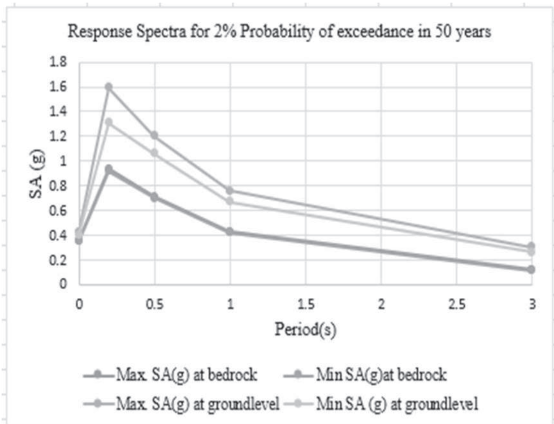

Figure 10 Response spectra period of 0-3seconds for 2% probability of exceedance in 50 years

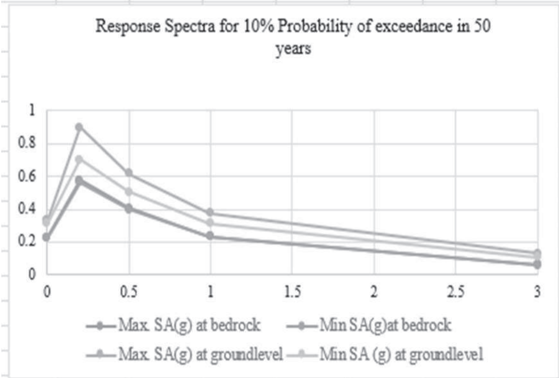

Figure 11 Response spectra period of 0-3 seconds for 10% probability of exceedance in 50 years.

The research findings reveal that PGA (Peak Ground Acceleration) values across different areas within the Pokhara metropolitan city display variability rather than uniformity, falling within a range. Notably, disparities in hazard values between rock and ground can be observed. At the bedrock level, the hazard values exhibit a descending order from North to South. This discrepancy is primarily attributed to the seismic coupling of the Main Himalayan Thrust (MHT) as it progresses from North to South.

Similarly, at the ground level, observations indicate variations in both PGA and SA (spectral acceleration) values within the city, with the highest hazard identified in the Southern part. The contrasting hazard values at the ground level arise from differences in shear wave velocity. Regions with higher shear wave velocity correspond to elevated hazard levels, while areas with lower shear wave velocity exhibit lower levels of hazard.

Overall, the highest hazard can be seen in the South Eastern and South Western parts of the city. Notably, hazard values are more pronounced in the hillside areas compared to the flat terrain within the city. This is because shear wave velocity based on slope data is used to indicate the site effect. Areas with higher slopes have higher shear wave velocity and, thus, higher levels of hazard. Ward number 33, followed by 32 and 21, shows the highest seismic hazard, while the lowest hazard is observed in wards number 19, 16, and 2.

The Nepal National Building Code (NBC: 105:2020) specifies a peak ground acceleration (PGA) value of 0.3g for Pokhara Metropolitan City, for a 10% probability of exceedance in 50 years. In this research, PGA values are computed ranging from 0.313g to 0.329g for the same probability and time frame at ground level. While the results are similar, they are not identical, possibly due to the NBC:105:2020 considering soil non-linearity in hazard computation, a factor not addressed in this study. The NBC code classifies soil into types A, B, C, and D, incorporating site effects data for hazard computation. The soil type A is recognized as the hard or stiff soil types, B is recognized as medium soil types, C as the soft soil sites and D as very soft soil types. In contrast, this study uses site effect data from USGS based on topographical slope rather than actual soil data, potentially contributing to the differences in PGA values. It's important to assess and address these variations by reviewing methodologies, comparing soil classifications, and consulting experts in seismic hazard analysis. From this research, it can be said that the hazard estimated for Pokhara Metropolitan City, especially for the design of earthquake resistance structures is quite low, and proper revision of the code for hazard purposes in the context of Pokhara Metropolitan City is necessary.

The obtained results were compared with findings from previous research relevant to this study. Baruwal et al., 2020[12], reported a PGA of 0.525g for a 10% probability of exceedance in 50 years and 0.915g for a 2% probability of exceedance in 50 years at a soil site. Discrepancies between these values and the current study may arise from differences in source characterization, attenuation models utilized, and computation methods. Specifically, Baruwal et al., 2020[12], manually computed hazard values, while this research employs software assistance for the analysis. Additionally, the attenuation model in the previous study was based on Youngs et al., 1997[31], whereas the present study employs various hybrid models for attenuation relationships.

Similarly, Ram & Wang, 2013[31], computed PGA values at the bedrock level for Pokhara within the range of 0.425-0.475g for a 10% probability of exceedance in 50 years and 0.85-0.925g for a 2% probability of exceedance in 50 years. These figures differ significantly from the values calculated in this study, primarily due to variations in homogenization techniques, attenuation models, and the range of recorded values from the earthquake catalog. Ram & Wang, 2013[33], utilized earthquake records from 1964-2011, while this study's catalog is based on earthquake records spanning from 1900-2023. Furthermore, all earthquake magnitudes were homogenized into surface wave magnitude, and Nepal was divided into 23 seismic source zones, with a different attenuation model utilized in Ram & Wang's research, sourced from CEA, 2005, China[32], as opposed to the model employed in this study.

5 SUGGESTION AND RECOMMENDATIONS

The findings of this research; the PGA and SA values can be used to identify the vulnerable and risky areas within the city. This will help in land use planning, and prepare for any kind of emergencies that may occur in the future due to seismic hazards. Similarly, the PGA and SA values can be used to estimate the seismic loads, and based on that the design of structures can be done.

From this research, it can be recommended that an earthquake catalog be prepared by collecting more and the latest earthquake data from different recording sources. This will help in representing the seismicity rate of the study area more accurately and help in the better computation of ground motion parameters. Moreover, the region-specific ground motion predicting equations must be applied for the better computation of the hazard values. Similarly, other different kinds of source zones such as fault sources, line sources, etc could be considered. Also, the 3D geometry of the fault and source zones can be considered to represent the hazard values more accurately. Moreover, the site effect data based on the local soil data obtained rather than the slope-based data can be used to represent the site effect in future studies. This is because if the slope-based shear wave velocity data is used, the areas with higher slopes will have higher hazards whereas the areas will lower slopes will contain lower hazards. This will not justify the non-linear property of the soil, therefore site effect data based on actual local soil data must be used.

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