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Seismicity parameters of Nepal by cumulative slope point change method

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Abstract

Nepal is one of the most seismically active countries with several seismic sources that are capable of generating moderate to high magnitude earthquakes. In this study, earthquake catalogue was developed by considering six major source zones. The completeness time period was determined by performing sensitivity analysis for various magnitude bin widths and time intervals. The seismicity parameters were computed by the least square method (LSM) and maximum likelihood method (MLM). LSM was based on Gutenberg Richter's scale relationship, whereas for the maximum likelihood method, it was performed by a new method called cumulative slope point change method (CSPCM). The CSPCM was introduced to account the drawbacks of maximum curvature method (MCM), especially for bulk number of data. Furthermore, paper compares the LSM and the MLM for the calculation of seismicity parameters. The comparison shows that the proposed CSPCM based on MLM is reliable in terms of theoretical and analytical way as compared to LSM and MCM.

Keywords: *Completeness magnitude, Seismic hazard, Seismicity parameters*

1. Introduction

An earthquake is a disastrous event that occurs around seismic regions of the Earth. It is complicated to predict earthquakes and their occurrence zones; however, the collection of past events of earthquake data help to know about the seismicity patterns. For the detailed study of earthquakes, it is essential to know about their seismicity parameters. For any scientific analysis, it is important to assess the quality and homogeneity of data (Woessner & Wiemer, 2005). Generally, Gutenberg's Richter method is used in seismicity analysis and its associated terms ‘a’ and ‘b’ are the main seismic parameters. In spatial analysis, the value of ‘b’ is directly related to the stress built up in the source (Chingtham et al., 2014). The low value of ‘b’ indicates there is a buildup in stress which will show the possibility of generating a big earthquake. In contrast, numerous smaller-magnitude earthquakes can be associated with the low values of ‘b’ where low stress is built up. The magnitude size distribution of a region and crustal stress level both are provided by the seismicity parameter ‘b’ (Nayak & Sitharam, 2019).

In probabilistic seismic hazard analysis, all possible earthquakes in a region are combined that have the potential to be damaging. The key elements for the studies of ground motion are the seismicity parameter and the location of the site. In the seismic hazard analysis of Nepal, each researcher’s result (Rajaure, 2021; Ram & Wang, 2013; Parajuli et al., 2021) differs and the difference in the results is possibly resulted from completeness magnitude, seismicity parameter value (especially ‘b’) and source characterization. It is difficult to predict exact value of seismicity parameters due to various reasons such as; variation in seismic source study, accuracy in instrumentally recorded data, and uncertainty of seismo-tectonic behavior (Rajaure & Paudel, 2018). A good study of seismic hazard analysis, therefore, requires the preparation of a comprehensive earthquake catalogue and estimation of good seismicity parameters. An earthquake catalogue is the collection of past historical earthquake data of certain regions, and it contains information about the location (latitude and longitude), depth, time, and magnitude of the earthquake.

Many researchers (Ram & Wang, 2013; Parajuli et al., 2021; Chamlagain & Niroula, 2020; Stevens et al., 2018) have computed the seismicity parameters on the basis of their own source characterization during the probabilistic seismic hazard analysis. However, detailed studies about seismicity parameter calculation is lacking. Rajaure & Paudel, (2018) calculated the seismicity parameter by considering two source segmentation methods but the Main Himalayan Thrust although well-defined source was not considered in the study. Moreover, the authors calculated the completeness period by Steep (1972) method. From the theoretical point of view, Stepp (1972) method is suitable for the range of up to 5 magnitudes in the case of the earthquake catalogue of Nepal. However, in case of the maximum likelihood method, authors do not mention the completeness magnitude which is a crucial part of seismic hazard analysis. This completeness magnitude is the part of the maximum likelihood method (Aki, 1965) for evaluating the ‘b’ value without considering the completeness time.

Recently Parajuli et al. (2021) computed the seismicity parameters by taking the cut off magnitude 5 for all sources by the least square approach which underestimates the earthquake magnitude of 4 to 5.

Prakash et al. (2016) calculated the seismicity parameters with the help of Zmap (Wiemer & Wyss, 2001) tool and used a bin width of 0.1 size. As a result, there was an error in the estimation of the seismicity parameters by nearly 0.2. A detailed study of the completeness magnitude of Bangladesh done by Rahman et al. (2018) showed the contours of 'a' and 'b' values. Later more reliable completeness period of Pakistan using the Stepp (1972) method was done by Waseem (2021) changing bin width of magnitude.

Structures are generally designed for ground motion, not for an earthquake's magnitude and distance (Abrahamson, 2006). The ground motion of an earthquake can be obtained by seismic hazard analysis. Better seismicity parameters are required while performing the probabilistic seismic hazard analysis. The maximum curvature method (MCM) is the most widely used method for finding the completeness magnitude but it does not give accurate results for the large number of data (cluster earthquakes). Likewise, the sensitivity character of the least square method (LSM) requires lots of time for computation of seismicity parameter, sometimes it is not possible to get actual value from it, especially in the case of highly scattered data. Therefore, in this paper, the seismicity parameters of six different seismic source zones of Nepal have been investigated by using an alternative method called cumulative slope point change method (CSPCM) and is further compared with the values obtained using LSM. The CSPCM gives a more accurate value of the seismicity parameter than the MCM as well as the LSM. This technique covers a wide range of seismic hazard analysis parameters, including recurrence parameters, earthquake frequency, and others. Since these parameters have a great deal of influence, it is necessary to compute them more accurately. CSPCM addresses many uncertainties that are linked on both at theoretical and analytical level for the calculation of seismicity parameters.

2. Methodology

2.1 Data collection and homogenization

Mainly two types of secondary earthquake data were collected: instrumental recorded data and past recorded data from various research articles. Global Centroid Moment Tensor (GCMT), United States Geological Survey (USGS) and International Seismological Centre (ISC) are the main sources for instrumentally recorded data. All the recorded data from these sites were merged into a single catalogue. The duplicate events were removed and finally, a homogenized catalogue was obtained. As the merged catalogue contains different units of magnitude (body wave magnitude, surface wave magnitude, local wave magnitude, and moment magnitude), all recorded magnitudes were converted into moment magnitude as per the relationship given by Nath et al. (2017).

2.2 Source characterization

All areal sources have been considered since an extensive study of the source geometry of the South Asian region has not been done yet. The 3-D source geometry of MHT has been more or less modeled accurately (Elliott et al., 2016; Hubbard et al., 2016). However, in the study done by (Chamlagain & Niroula, 2020), consideration of 3-D geometry didn't yield any significant difference in hazard level. Hence, for simplicity as well as to check variation in the results, all sources including MHT have been modelled as areal sources similar to the studies: (Chamlagain & Niroula, 2020) and (Stevens et al., 2018). The extent and boundary of the MHT subduction interface were based on its interseismic coupling. Interseismic coupling gives us a tentative idea about the portion of the fault: whether it is locked (coupling value of 1) and storing the stress in the form of strain energy or it is creeping (coupling value of 0) at long term plate velocity. Based on the study done by (Stevens & Avouac, 2015) on the coupling of MHT, the value of interseismic coupling >0.5 has been considered as the locked portion of MHT as this portion is expected to be capable of producing future large earthquakes.

The Northern Graben sources (SZ-3, SZ-4, SZ-5, and SZ-6), which lie in southern Tibet, are known for producing shallow earthquakes of high magnitude. Normal faulting mechanisms have been observed up to 50 km from the fault traces of the Northern Grabens, namely Thakkola graben, Gyirong graben, Kung Co graben, and Pum Cu graben (Stevens et al., 2018). In this study, the boundary of northern sources has been considered to accommodate seismic clusters as well as the fault mechanism based on the plate tectonics, fault geometry, and earthquake pattern of the area (size and depth of earthquake). For instance, SZ-3's eastern and western boundaries are 150 km apart from Pum Cu Graben to encompass other seismic clusters nearby. The southern source, which is considered a stable continental region, is very less seismically active as compared to the MHT (continental) source and the northern graben sources. However, earthquakes of moderate magnitude do occur on occasion, most likely due to the flexure of the converging Indian plate (Chamlagain & Niroula, 2020; D Chamlagain et al., 2020).

It has been apparent from numerous studies that MHT is the major source of seismic hazards in the Himalayan region. Therefore, in this study, major emphasis has been given to the source characterization of the MHT. The source characterization map of our study is shown in Figure 1.

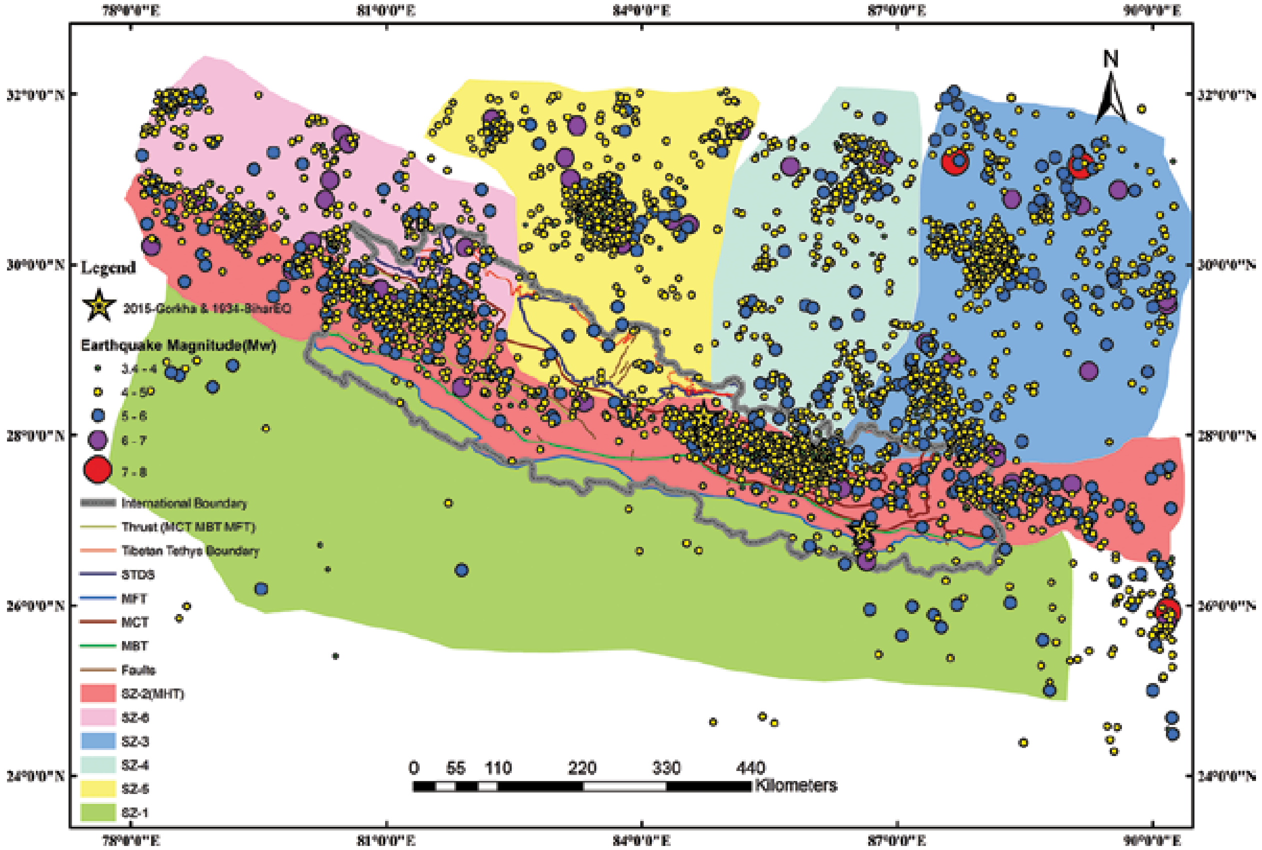

Figure 1: Homogenized earthquake data with source characterization

2.3 Declustering

Declustering is the removal of dependent earthquakes (aftershocks and foreshocks) from the earthquake catalogue and it can be done using various algorithms (e.g. Gardener and Knopoff ,1974). Technique (Gardner & Knopoff, 1974) for declustering is based on the procedure of identifying the aftershocks and foreshocks within the seismicity catalogue (Van Stiphout et al., 2012) have been used for this study. This method has been applied by many researchers (Chamlagain & Niroula, 2020; Goda et al., 2015; Rajaure, 2021) in the past. The earthquake data after declustering is shown in Figure 2.

2.4 Completeness test for time period

Generally, two methods are available for determining the completeness time period of earthquake magnitude class (Singh et al., 2015); Stepp (1972) method and Linear Cumulative Method. In this study, Stepp (1972) method has been used for evaluating the completeness period for different classes of earthquake magnitude. In this method, the declustered data is divided into different class of earthquake magnitude and time interval. The rate of occurrence of each earthquake magnitude class is evaluated. The mean rate of occurrence is correlated with the constant slope line ($1/\sqrt{T}$) for the evaluation of the completeness period for different classes of magnitude (Nasir et al., 2013). The completeness period for each classes of earthquake magnitude is the length of a time interval where there is no deviation of plotted points from the constant slope line

(1/√T).

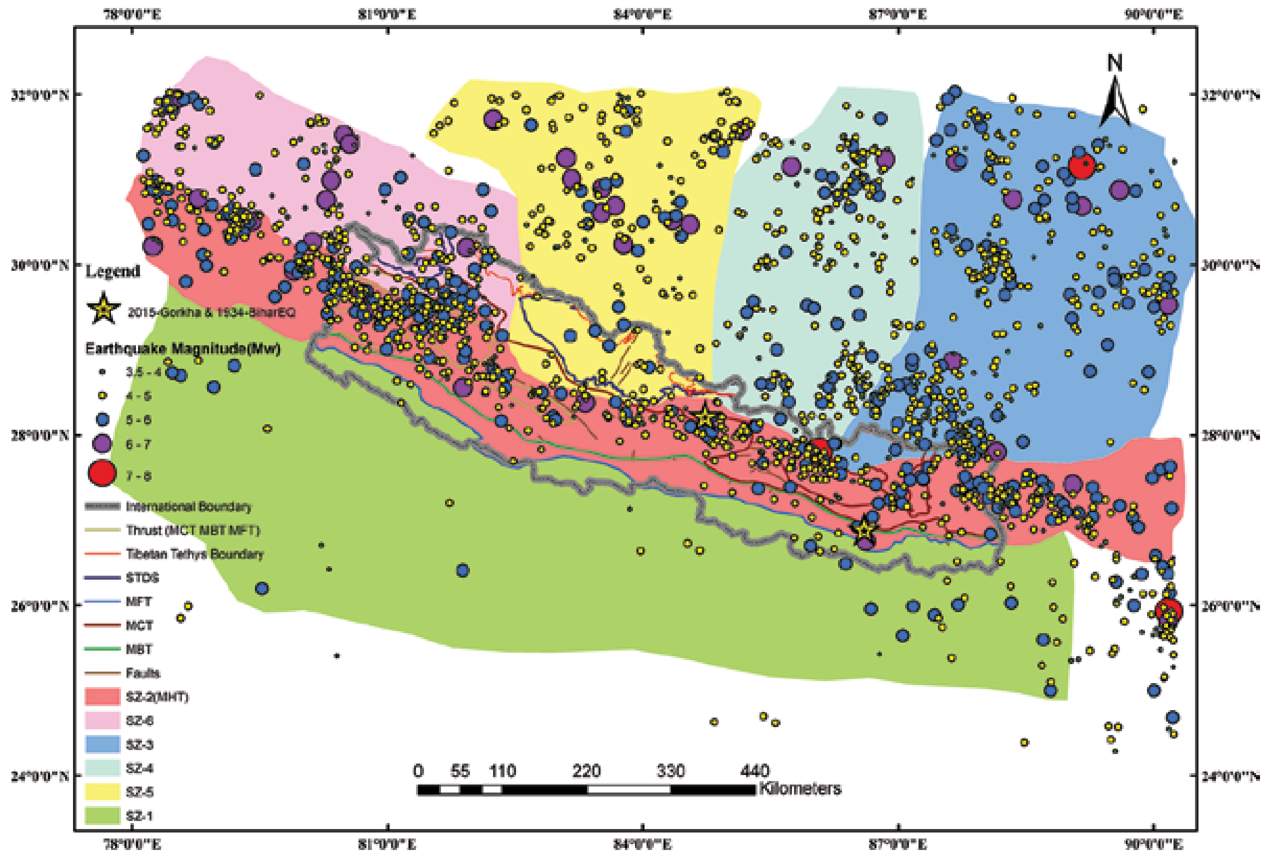

Figure 2: Declustering of earthquake data

2.5 Completeness magnitude

For the calculation of seismicity parameters from the maximum likelihood method (Aki, 1965), completeness magnitude is necessary. Among the various methods available for detecting the completeness of magnitude, a new method (CSPCM) has been used in this study. In CSPCM, the first point corresponding to a lower magnitude scale where the slope changes is termed as the magnitude of completeness. The result is also compared with the maximum curvature method where the highest peak of discrete events is termed as the magnitude of completeness.

2.6 Gutenberg recurrence law

It is the empirical relationship between the frequency of earthquakes in a region and their magnitudes (Beitr, 1945).

Mathematically, it is given by:

$$LogNm=a-bm \qquad (1)$$

where 'a' and 'b' are the seismicity parameter and N (m) is the number of earthquakes with magnitudes larger or equal to 'm'. Parameter 'a' describes the total activity of an earthquake in a particular region and 'b' describes the relative number of small earthquakes and large earthquakes (Rajaure & Paudel, 2018). For finding the 'b' value, mainly two approaches are available, the MLM and the LSM. The least square method is based on completeness time interval whereas maximum likelihood method is the function of completeness magnitude rather than time.

The relationship for calculating b value from maximum likelihood method is as per (Kijko & Smit, 2020) is given as:

$$b=1/2.303\ (M_{avg}-M_C) \qquad (2)$$

where, M_{avg} is the average of magnitude greater than the magnitude of completeness (M_c).

3. Results and Discussion

3.1 Completeness period analysis

As mentioned by Stepp (1972), the length of the interval up to which it does not deviate represents the completeness period for a particular range of earthquake magnitude. Accordingly, completeness period for magnitude above 5 is difficult to predict in the earthquake catalogue of Nepal. Above magnitude 5, there is an abrupt change in data pattern and most of the sources have a smaller number of events which creates difficulties for finding the completeness period. Therefore, sensitivity analysis was performed for the completeness period by changing the magnitude range and time interval. Completeness period for earthquake magnitude shows better visualization on five years' time interval. For magnitude above 6, the completeness period was estimated based on arbitrary assumption rather than theoretical approach and, consequently, there is biasness in the final result.

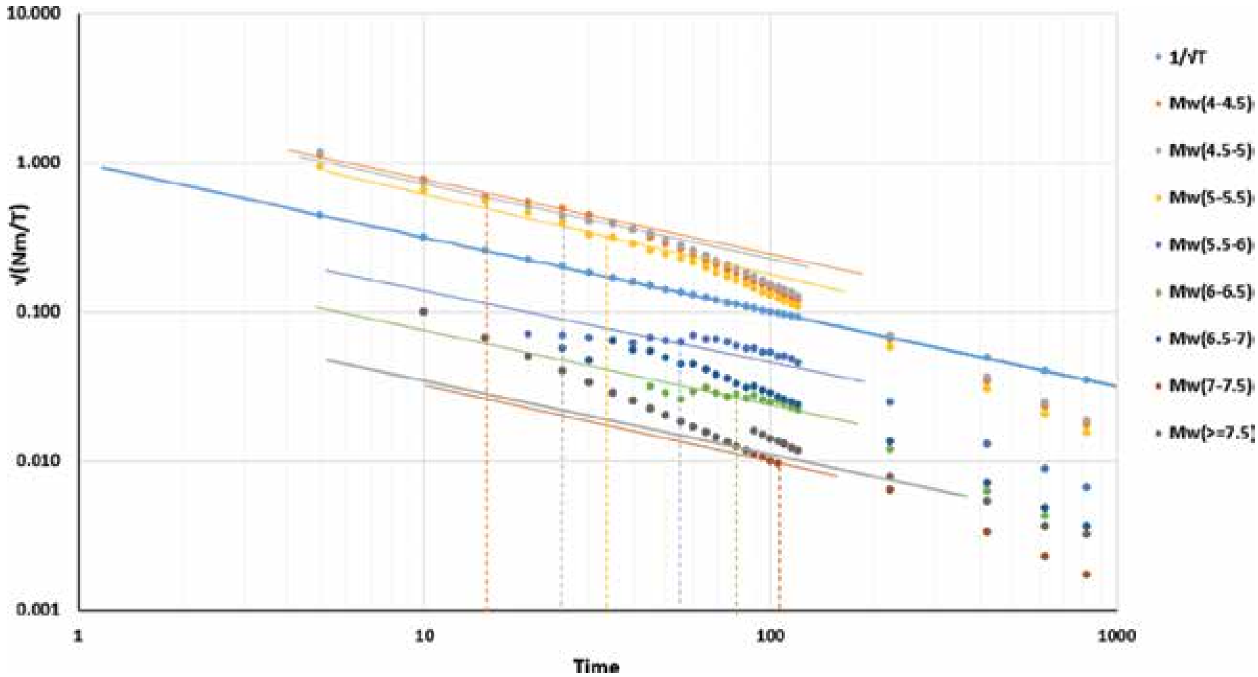

Figure 3: Completeness test of MHT using 0.5 magnitude bin width and five years' time interval

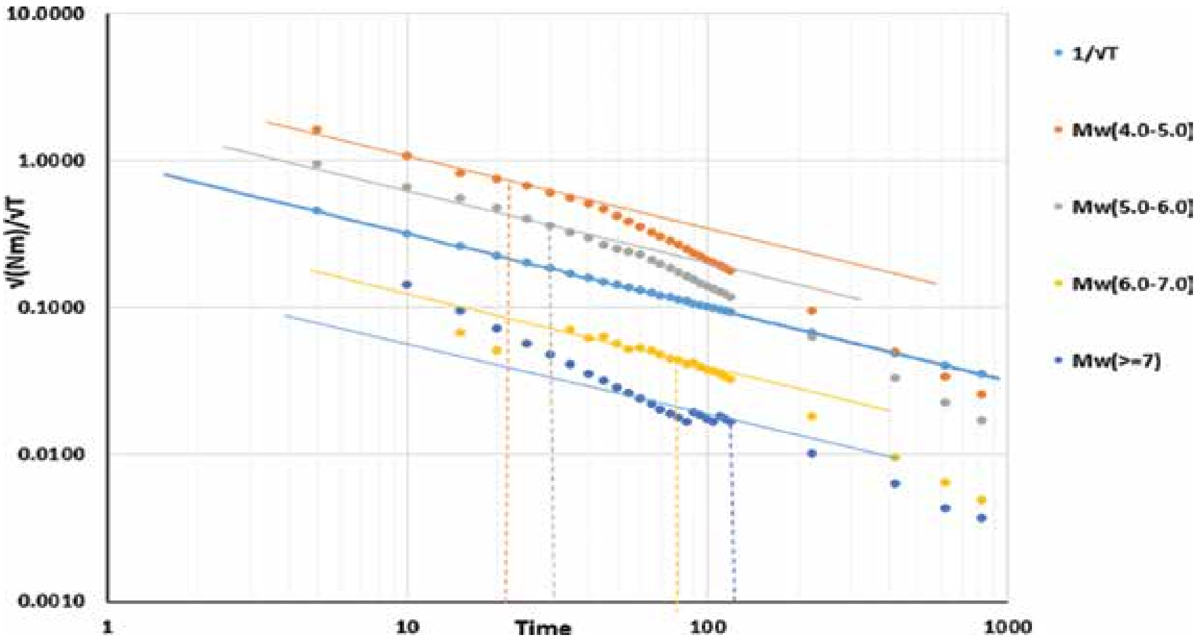

Figure 4: Completeness test of MHT using 1 magnitude bin width and 5 years' time interval

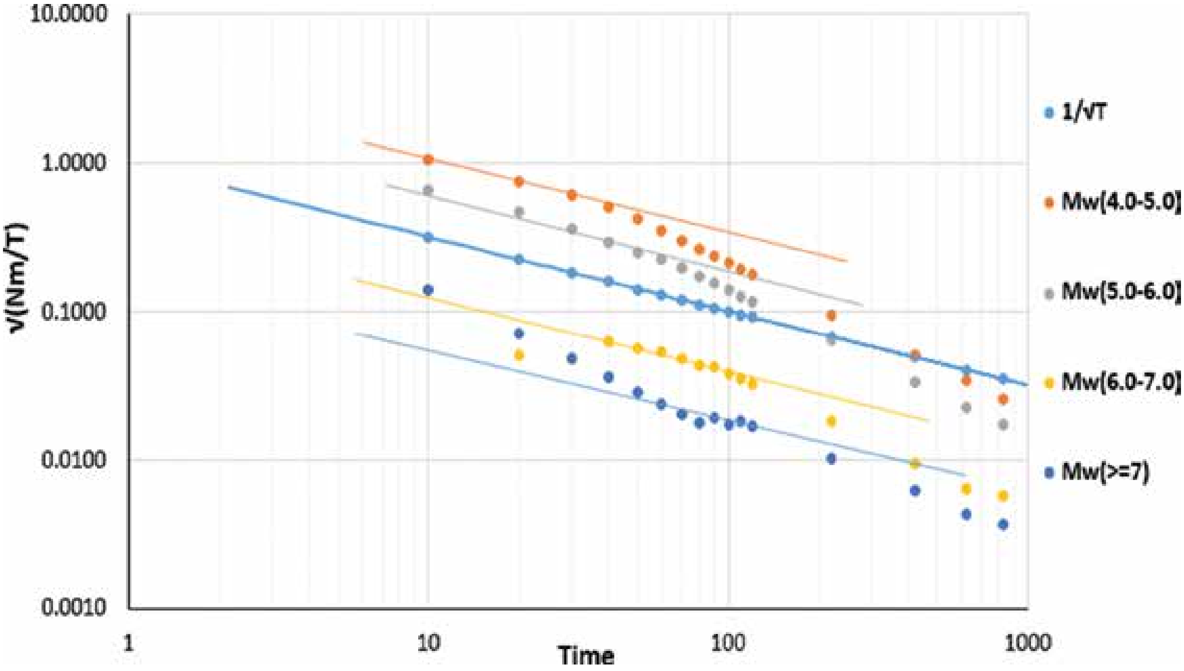

Figure 5: Completeness test of MHT using 1 magnitude bin width and 10 years' time interval

The above figures (3, 4, 5, and 6) indicate that 10 years completeness period is different in each case. For large number of data, Stepp (1972) gives more reliable value of completeness period. In the case of earthquake recorded data of Nepal, there is significant gap above magnitude 5.5. Therefore, Stepp (1972) may not give reliable completeness period above magnitude 5.5.

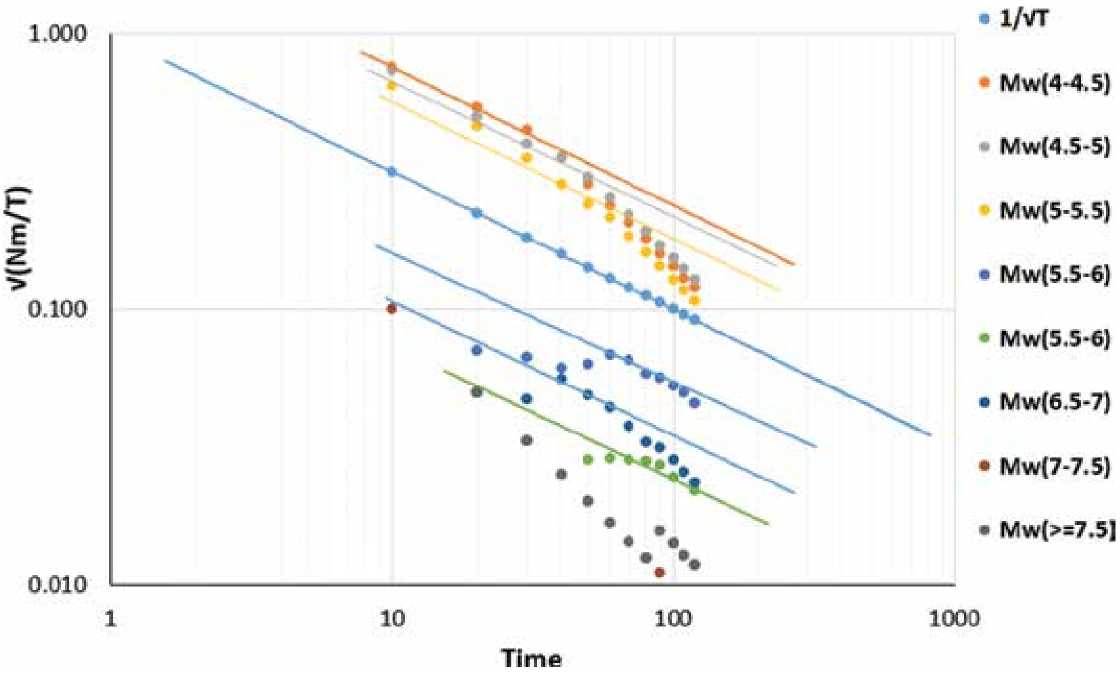

Figure 6: Completeness test of MHT using 0.5 magnitude bin width and 10 years' time interval

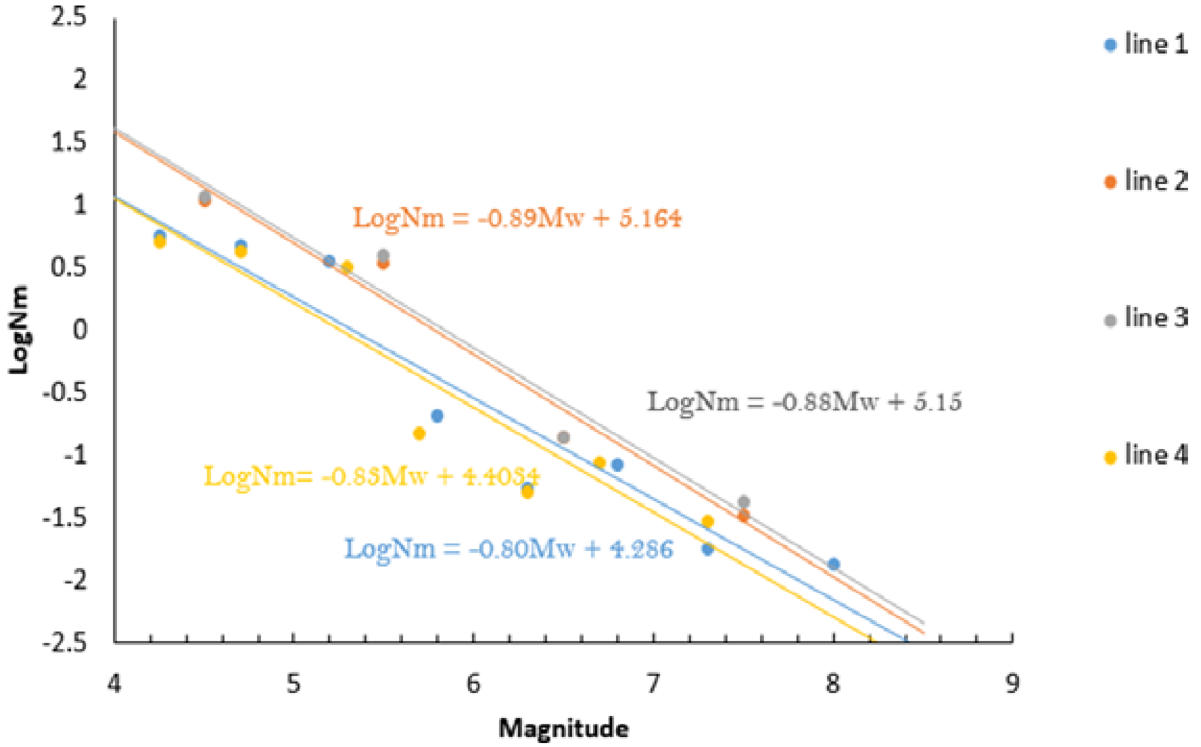

Figure 7: Seismicity parameters of MHT source by LSM using different completeness period analysis.

Note: Line 1 represents 0.5 magnitude bin width and 5 years interval, line 2 represents 1 magnitude bin width and 10 years interval, line 3 represents 1 magnitude bin width and 5 years interval, line 4 represents 0.5 magnitude bin width and 10 years' time interval.

3.2 Least square analysis and seismicity parameters

The seismicity parameter for MHT source by LSM using different completeness periods and sample data are shown in Figure 7.

The graph depicts that LSM is mainly dependent on three parameters: time interval, completeness period, and magnitude sample. This scenario is similar for all the seismic sources. If the completeness period is different, it is not possible to get the actual seismicity parameter because the number of events change for the computation of rate of occurrence of the earthquake and might give to bias output. For less number of data, LSM does not give the realistic value of 'a' and 'b'. For instance, in source zone 1, the scatterness of data is high.

3.3 Maximum curvature vs CSPCM for completeness magnitude

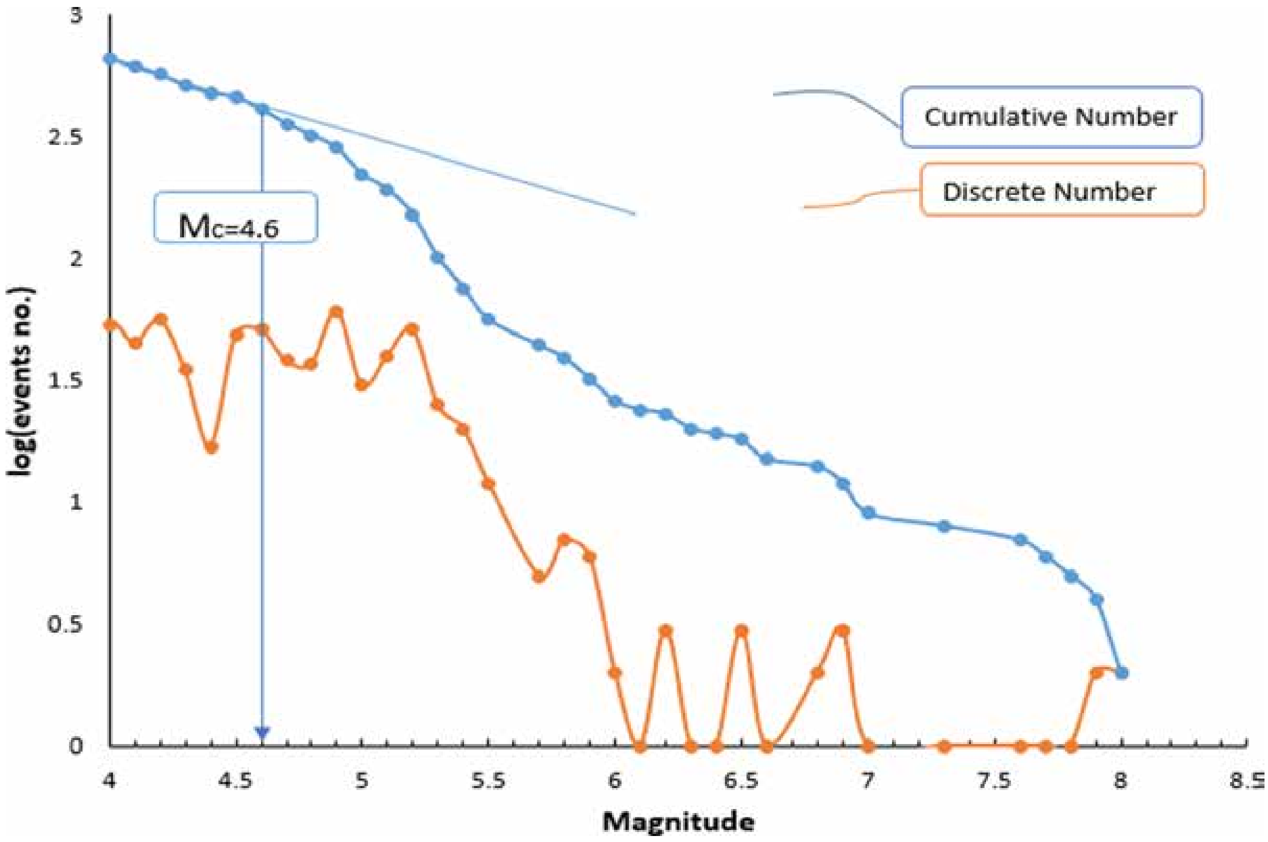

Figure 8: Completeness magnitude of SZ-2 (MHT)

Maximum curvature method is mostly used to calculate the completeness magnitude. However, according to Mignan & Woessner (2012), the maximum curvature method, sometimes underestimates the completeness magnitude in the case for bulk data. This drawback of the maximum likelihood method is also shown in this study, especially for cluster data. For MHT source, value of 'b' was about 0.66 which shows MHT is highly prone from the large scale magnitude. However, in reality there are significantly huge number of small scale magnitude which means the value of 'b' has to be nearer to 1. In the case of cluster catalogue data, maximum curvature method underestimates the magnitude of completeness for all sources. For the elimination of such type of error, alternative method Cumulative Slope Point Change Method has been introduced**.** Mathematically, it is based on the procedure of drawing the tangents to the cumulative curve corresponding to the magnitude point and finally finding the slope at each point. The point on the line with an abrupt change in slope is termed as the completeness magnitude. Alternatively, it can be obtained by drawing the best fit line on magnitudes points on the cumulative curve. The completeness magnitude for different seismic source zone calculated from CSCPM is shown in Table 1 and for the MHT, it is also shown in Figure 8.

Table 1: Completeness magnitude of each source zone

Seismic Source Zone	**Completeness Magnitude**
SZ-1	4.3
SZ-2 (MHT)	4.6
SZ-3 (NG-1)	4.6
SZ-4 (NG-2)	4.4
SZ-5 (NG-3)	4.5
SZ-6 (NW)	4.5

3.4 Seismicity parameters

Both LSM and CSPCM show higher seismicity parameters for the cluster data than for the decluster earthquake data. The seismicity parameters for all sources are shown in Table 2.

Table 2: Seismicity parameters of different seismic source zones

Seismic Source Zone	**Seismicity Parameters**							
	Maximum Likelihood Method						**Least Square Method**	
	Cluster Earthquake Data			**Decluster Earthquake Data**				
	a (cum.)	**a (annual)**	**b**	**a (cum.)**	**a (annual)**	**b**	**a**	**b**
SZ-1	6.73	4.91	1.14	4.67	3.16	0.72	1.84	0.556
SZ-2 (MHT)	7.73	5.071	1.03	6.42	4.35	0.83	4.28	0.8
SZ-3 (NG-1)	7.84	5.67	1.06	6.41	4.33	0.9	4.41	0.86
SZ-4 (NG-2)	6.7	4.65	0.986	5.88	3.96	0.86	4.31	0.9
SZ-5 (NG-3)	6.25	4.28	0.87	5.80	3.85	0.83	3.74	0.8
SZ-6 (NW)	7.03	4.99	1.08	5.53	3.52	0.77	4.64	0.85

The seismicity parameters thus obtained are compared with the results from other studies. The seismicity parameter of MHT is given special attention in this study because it is the most influential seismic source when performing the seismic hazard analysis of Nepal. Stevens et al. (2018) estimated the value of 'b' for the MHT source to be 1.025 by considering the aftershocks, foreshocks, and main shocks in the earthquake catalogue. The proposed cumulative slope change point method gives the value of 'b' 1.03 for MHT source, considering all earthquake magnitude which is very close to the value of Stevens et al. (2018). Likewise, the seismicity parameter of the declustered earthquake data were compared with Chamlagain et al. (2020)despite slight differences in source characterization. Authors predicted the value of 'b' to be 0.78, considering a small segment of source characterization of the eastern parts of Nepal. The proposed CSPCM estimated value of b for the MHT source to be 0.82 which is close to Chamlagain et al. (2020) and LSM was used for estimation of seismicity parameter. This shows that the proposed method (CSPCM) can be used for the estimation of seismicity parameters.

4. Conclusions

Seismic source characterization of Nepal was done by categorizing it into six seismic source zones. In case of insufficient data due to abrupt change or gap recorded earthquake data, Stepp (1972) method does not give accurate completeness period. For the calculation of the seismicity parameters, maximum likelihood method gives a more reliable value as compared to least square method. However, the accuracy of LSM can be increased by analysis of larger data sets. The alternative method (CSPCM) for calculation of 'b' value gives better completeness magnitude as compared to MCM, especially in the case of bulk number of data. This alternative method (CSPCM) for the calculation of seismicity parameters covers the uncertainties related to sensitivity nature and volume of data whereas other methods do not consider them together. Therefore, this method definitely helps in more precise calculation of seismicity parameters as well as study of seismic hazard.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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