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ASSESSING IF FORESHOCKS AND AFTERSHOCKS ARE DEPENDENT EVENTS OF THE MAINSHOCK FOR NORTH-EAST INDIA

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Abstract

Seismic hazard assessment requires seismic activity parameters to be determined from declustered-complete earthquake (EQ) catalogue. While declustering, event with larger magnitude is considered as main event while other events, which fall within specific time and space windows, are treated as dependent events of the main event (either foreshocks or aftershocks), and are removed from the catalogue. In the present work, dependent events are identified in the catalogue by using widely followed dynamic windows for NE India. Two catalogues, one before declustering and another one after declustering, are analysed for the duration of completeness in order to check the effect of declustering on the completeness of each catalogue. Further, cumulative number of EQs per year in the complete part of catalogues are analysed for both the catalogues. It is observed that even though the EQ catalogue is complete since 1950, a significant reduction in cumulative number of EQs are observed in the declustered catalogue. Supporting such reduction, two observations, based on the analysis, are given in this work. While first observation relates occurrence of a larger event as a triggering phenomena for EQs in the nearby sources, second observation suggests that in case seismic sources are closer to each other, declustering defined dependent events may or may not be dependent in actual. As a result, there will be reduction in assessing maximum potential of each seismic source as well as underestimating the seismic activity of the region. Above observations are validated for 8 seismic sources as well as two EQ events (1950 and 1988). Present work suggests that the relative location of seismic sources should be given due importance while declustering the catalogue. Similarly, true potential of seismic source should be dealt before declustering.

Keywords: NE India, Earthquake catalogue, Declustering, Foreshock, Aftershock.

1 Introduction

Finding the seismic hazard of an area is very important as on the basis of potential hazard, construction and maintenance of different structures are carried out. Further, this will ensure that the structures shall not fail during future unseen seismic events. True seismic potential of an area is found out by performing seismic hazard analysis. For carrying out seismic hazard analysis, the most important input is the information about past earthquakes (EQs). Such information can be obtained from different sources like ISC [1], USGS [2] etc. and in addition to the existing literature on past EQs. Based on collected information, an EQ catalogue can be prepared containing information about already happened EQs within the seismotectonic region.

For seismic hazard analysis, it is considered that the EQs occur randomly and the phenomenon of occurrence follows Poisson's distribution. Major to great EQs are followed by a large number of dependent events (foreshocks and/or aftershocks). Thus, before proceeding for seismic hazard analysis, these dependent events must be removed from the catalogue. This process of removing dependent events from an EQ catalogue is called EQ declustering [3]. There are different methods followed all around the globe for separating dependent events from main events. Knopoff [4] was the first one to find that after removing aftershocks from the EQ catalogue, the resultant EQ catalogue was following Poissonian distribution [3]. After this, Gardner and Knopoff [5] introduced a space-time-distance criterion to remove aftershocks from the EQ catalogue collected for Southern California region. This method of removing aftershocks from an EQ catalogue was later known as window method of declustering. The length of space and time windows for declustering is depended on the magnitude of the main events. Further, Uhrhammer [6] modified these window lengths. Later, many researchers used Uhrhammer [6] version of windows for different parts of the world including various regions of India such as North East (NE) India [7–10]. In this presents study, the effect of declustering on EQ catalogue is examined. Further, the effect of declustering in understanding the true potential of seismic source is also assessed.

2 Seismicity of the study area

For the present study, NE India, which is situated from 20.5° E to 31.35° E latitude and 87° N to 98° N longitude, is taken as the study area. The seismicity of this area is very high and as per IS-1893 2016 [11], almost every places in the region belongs to seismic zone V defining highest seismic hazard zone. Looking at the past EQs occurred in the area, one can see a long history of major to great EQs in this area. The two great EQ; 1897 Shillong EQ and 1950 Assam EQ occurred in the region caused a large extent of damage. Besides these two great EQs, NE India had also experienced some of the major damage causing EQs. These include the 1869 Cachar EQ (Mw = 7.5), 1923 Meghalaya EQ (Ms = 7.1), 1930 Dhubri EQ (Ms = 7.1), 1943 Assam EQ (Ms = 7.2), 1947 Arunachal Pradesh EQ (Ms = 7.7), 1988 Manipur EQ (Ms = 7.3), 2009 Assam EQ (Mw = 5.1), 2011 Sikkim EQ (Mw = 6.9) and the very recent 2016 Imphal EQ (Mw = 6.7). Each of these EQs damaged a large number of roads, buildings, bridges etc. and triggered many landslides [12–15]. In addition to very high seismic hazard, NE India also witnesses EQs occurrence at a frequent rate and hence is among most seismically active regions of the world. It must be highlighted here that the region is bounded by Indian-Eurasian subduction zone in the north and by India-Burmese subduction zone in the east. Further, the rate and the direction of convergence at both of the above boundaries are different making regional tectonic setting complex. This can be understood from the fact that the regional seismicity is not only governed by seismic sources in the plate boundaries but active regional seismic sources as well. Besides this, seismologists believe that Assam seismic gaps are exists for the region, capable of generating major to great EQs in the near future [16,17].

3 EQ Catalogue

Nowadays, EQ data is available for almost all the regions of the world in different sources such as ISC [1] and USGS [2]. Besides these two sources, for the present study, EQ data from NDMA (2010) [18] and IMD [19] are also used while preparing EQ catalogue for the region. It is found that occurrence of EQ events ranges from 825 AD to December 2018 AD for the present study area. It is observed that the collected EQ events are in different magnitude scales such as; Richter magnitude (ML), body wave magnitude (Mb), surface wave magnitude (Ms) and Moment magnitude (Mw). Before going for further analysis, all of these EQ magnitudes need to be converted to one single magnitude. There are different correlations between different magnitude scales proposed by different researchers. For this study, collected EQ catalogue is converted to Mw scale by using the following correlation developed by Sitharam and Sil [8] specially for NE India.

$$Mw = 0.862Mb + 1.034 \tag{1}$$

$$Mw = 0.673ML + 1.730 \tag{2}$$

$$Mw = 0.625Ms + 2.350 \tag{3}$$

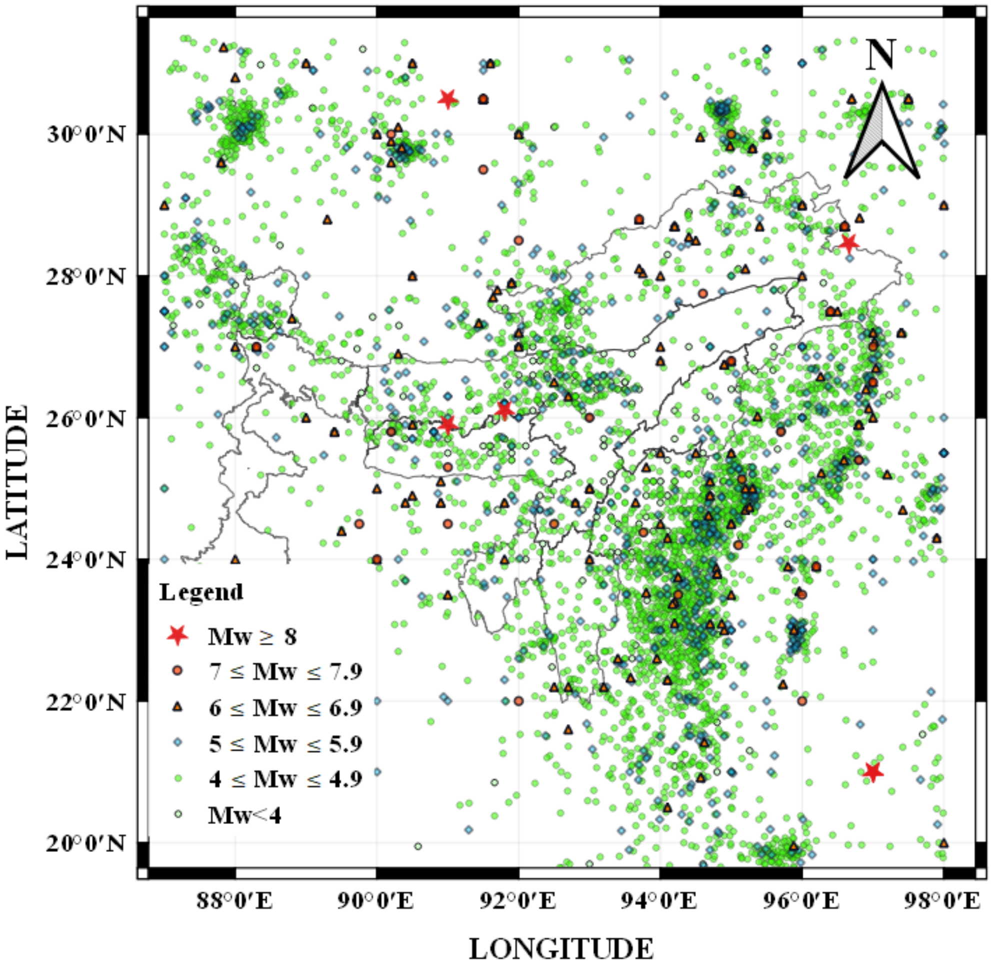

Fig. 1 – Past EQ events in and around of NE India

Further, as EQ data is collected from different sources, there are events which are reported by more than one source and thus such repeated events need to be removed. These repeated events are identified and removed from the catalogue by looking at their same time of occurrence, same locations of occurrence and EQs having close magnitude values. After removal of these repeated events, the total numbers of events remain in the catalogue are 5472 out of which, 209 numbers of total EQ events are having Mw < 4.0. The total numbers of events having Mw ranging from 4.0 to 4.9, 5.0 to 5.9, 6.0 to 6.9 and 7.0 to 7.9 are 4177, 839, 210 and 31 respectively. In addition, there are 6 EQ events in the catalogue having Mw ≥ 8.0 with highest event being 1950 Assam EQ (Mw = 8.5).

Fig.1 shows the past seismic events within the study area, after the removal of repeated EQs. Based on Fig.1, a larger cluster of EQs can be seen in the south-east parts of NE India region which is the Indo-Burma region. Similarly, south-west and extreme south-east parts of the whole area in Fig.1 are showing less number of EQ events. Further, places where great EQs had occurred (extreme south-east part, north-east part, northern part of the whole area), not any big cluster of EQ events can be observed around the epicentre.

4 Declustering of the EQ Catalogue

As mentioned earlier, window method modified by Uhrhammer [6] has been used by various researchers for NE and thus has been selected for the present work. In Urhammer method, dependent events are identified in space and time windows [5]. Approximate spatial (d in km) and temporal (t in days) windows sizes as per Uhrhammer [6] are given in Eq. (4) [3].

$$d=e^{-1.024+0.804M} \text{ and } t=e^{-2.87+1.235M} \tag{4}$$

Here, M is the magnitude of the EQ. For each EQ, d and t are calculated on the basis of its Mw and the aftershocks are identified by checking whether the subsequent EQs fall within above windows or not [3]. If a later EQ has larger magnitude, then previous EQ is considered as foreshock and time-space windows are recalculated on the basis of the Mw of larger event [3]. This way, the largest event is considered as the main event and all other events are removed from the catalogue. The Uhrhammer [6] method is applied on earlier developed EQ catalogue by using Matlab codes received from Dr. Jiancang Zhuang, co-author of van-Stiphout et al. [3] (based on personal communication). After declustering, 4444 numbers of EQ events remain in the catalogue. In the declustered catalogue, the numbers of EQ events having Mw < 4 Mw are 190. Similarly, the numbers of events remain in the Mw range of 4.0 to 4.9, 5.0 to 5.9, 6.0 to 6.9, 7.0 to 7.9 and Mw ≥ 8.0 are 3487, 624, 113, 25 and 5 respectively. Thus, approximately 19% of EQ events are removed from the catalogue after declustering. Table 1 shows the percentage of EQ events removed after declustering for different Mw ranges.

Table 1 – Percentage of EQ events removed for each Mw range after the declustering

Range of Mw	Percentage of events removed (%)
Mw < 4	9.09
4 ≤ Mw ≤ 4.9	16.52
5 ≤ Mw ≤ 5.9	25.63
6 ≤ Mw ≤ 6.9	46.19
7 ≤ Mw ≤ 7.9	19.35
8 ≤ Mw	16.67

5 Completeness analyses of two EQ catalogues

Once a declustered catalogue is available, it must be checked for completeness, before determining the seismic activity based on EQ catalogue. This is done because the catalogue may not contain complete events for all the years and for the various ranges of magnitudes. In this study, the completeness with respect to magnitude and time are checked for both the catalogues (catalogues before and after declustering). The minimum magnitude above which a catalogue is complete with respect to magnitude is called the magnitude of completeness (Mc) [20]. In this study, Mc is determined based on maximum curvature (MAXC) method introduced by Wiemer and Wyss [21]. In this method, firstly cumulative number of EQ events which are greater than or equal to a magnitude are plotted against that magnitude, generating a curve between the two variables. Then, the magnitude corresponds to the maximum curvature point is considered as the Mc. Fig.2

shows the cumulative number of EQ vs Mw plots for the catalogue before declustering (Fig.2 a) and for the catalogue after declustering (Fig.2 b). In both the cases, Mc = 4.0 is obtained.

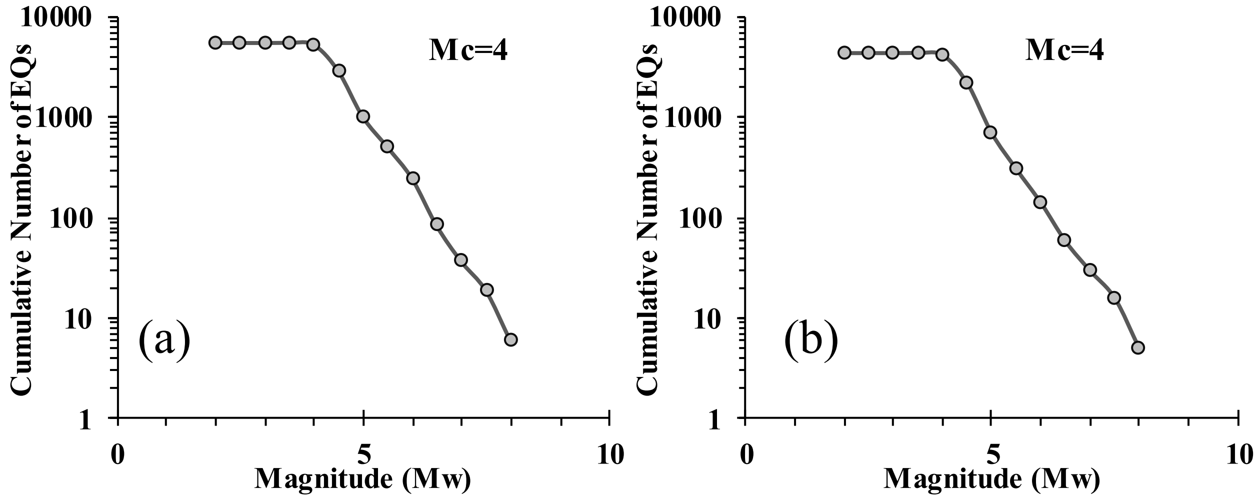

Fig. 2 – Cumulative frequency distribution plots and Mc values for (a) the catalogue before declustering and (b) for the catalogue after declustering

For finding the completeness with respect to time, both Stepp [22] and Visual cumulative (CUVI) [23] methods are used. Firstly, Stepp [22] method is used; where the EQs are needed to group into certain magnitude classes and the test is performed on each class separately. The EQ catalogue is divided into time bins starting from last year till which EQ information is available in the catalogue and going back in history with number of EQs in each time bin. The main assumption of Stepp [22] method is that the EQ events follow the Poisson distribution model. If for a definite unit time interval, x_1, x_2, x_3, ….. x_n are the numbers of EQ events, an unbiased mean rate (λ) can be calculated as;

$$\lambda = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{5}$$

and for such dataset, the variance will be;

$$\sigma_\lambda^2 = \frac{\lambda}{n} \tag{6}$$

Where *n* is the number of time bins. If the time interval is considered as one year, then *n* will be equal to T, where T is the sample length. Then the standard deviation (σ_λ) will become:

$$\sigma_\lambda = \sqrt{\frac{\lambda}{T}} \tag{7}$$

Stepp [22] found that for constant λ in each magnitude class, σ_λ behaves as $1/\sqrt{T}$. For the completeness test, the standard deviation (σ_λ) is plotted against time interval (T), for all classes of magnitudes and $1/\sqrt{T}$ line is also plotted against T in the same graphs. Stepp [22] concluded that the time up to which the plotted points are following a straight line, parallel to the 1/√T line, the data is considered complete for that T.

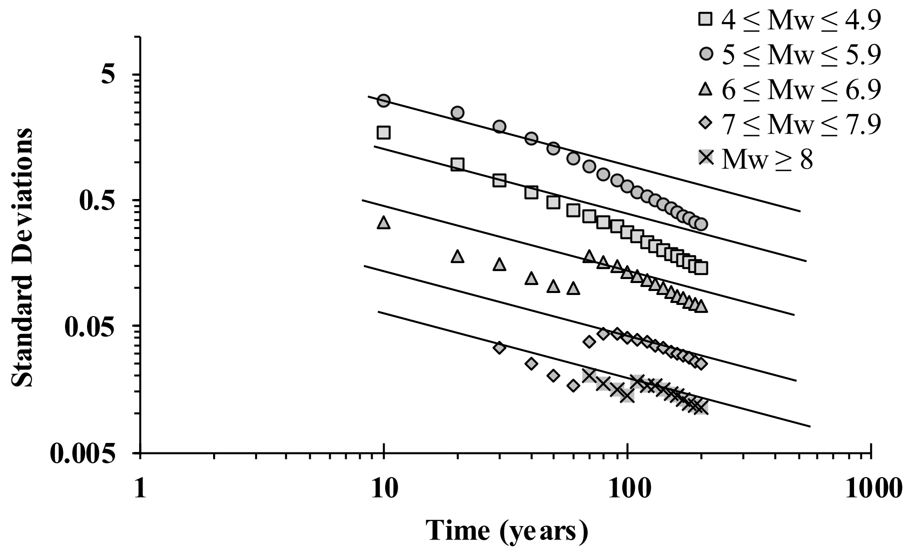

Fig. 3 – Standard deviation versus time interval plots for different magnitude classes for the EQ catalogue before declustering

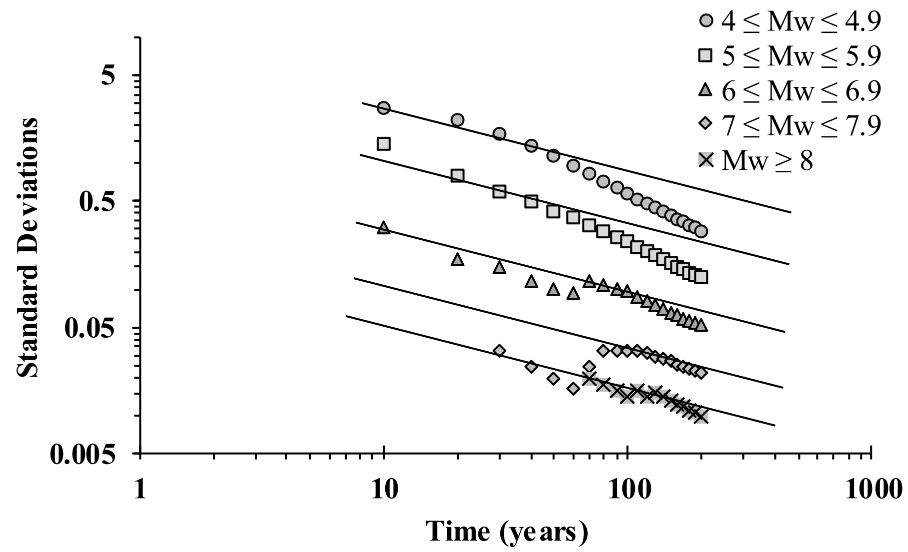

Fig. 4 – Standard deviation versus time interval plots for different magnitude classes catalogue after declustering

In the present study, the EQ events are grouped into five magnitude classes; (1) 4 ≤ Mw ≤ 4.9, (2) 5 ≤ Mw ≤ 5.9, (3) 6 ≤ Mw ≤ 6.9 and (4) 7 ≤ Mw ≤ 7.9 and (5) 8 ≤ Mw. Then, Stepp [22] method is used for all the five magnitude classes EQ events. In Fig.3, σ_λ versus T for different magnitude classes of the catalogue before declustering are plotted. In Fig.4, σ_λ versus T for different magnitude classes of the catalogue after declustering are plotted. For each catalogue, year of completeness for different magnitude classes are shown in Table 2. It is seen that the completeness periods for the two catalogue are same for each of the magnitude classes. For magnitude classes, 4.0 ≤ Mw ≤ 4.9, 5.0 ≤ Mw ≤ 5.9, 6.0 ≤ Mw ≤ 6.9, 7.0 ≤ Mw ≤7.9 and 8.0 ≤ Mw, the years of completeness are 60, 70, 130, 190 and 190 years respectively for both the catalogues.

Table 2 – Years of completeness for different magnitude classes

Magnitude Classes	Years of completeness	
	Catalogue before declustering	**Catalogue after declustering**
$4 \leq Mw \leq 4.9$	60	60
$5 \leq Mw \leq 5.9$	70	70
$6 \leq Mw \leq 6.9$	130	130
$7 \leq Mw \leq 7.9$	190	190
$8 \leq Mw$	190	190

In another attempt for completeness analysis with respect to time, Visual cumulative method (CUVI) [23] is used on the catalogue before and after declustering. In CUVI method, for different magnitude classes, cumulative number of events per year are plotted against years of occurrence. The catalogue is considered as complete from the year after which magnitudes are assumed to follow stationary occurrence process. In addition to completeness analysis, CUVI method is also used to check cumulative number of EQs occur per year for both the catalogues. Fig.5 shows the comparison between CUVI plots of the both catalogues for all the magnitude classes separately. From Fig.5, it can be seen that the years of completeness for all the magnitude classes are same for both the catalogues. For $4.0 \leq Mw \leq 4.9$ class, the completeness period found is between 1958 – 2018 (60 years), which is similar to the duration of completeness obtained based on Stepp [2] method. For other magnitude classes however, the duration of completeness obtained from CUVI method are significantly different from those obtained from Stepp [22] method. For $5.0 \leq Mw \leq 5.9$, $6.0 \leq Mw \leq 6.9$, $7.0 \leq Mw \leq 7.9$ and $8.0 \leq Mw$ magnitude classes, the completeness duration obtained from CUVI methods are 1922 – 2018 (96 years), 1915 – 2018 (103 years), 1905 – 2018 (113 years) and 1897 – 2018 (121 years) respectively.

Besides finding the periods of completeness, difference in terms of cumulative number of EQs per year, obtained from both the catalogues, are also observed from Fig.5. It can be seen from the Fig.5 that for magnitude classes $4 \leq Mw \leq 4.9$ and $8.0 \leq Mw$, the plots of cumulative number of events per year vs year are same for both the catalogues. It must be mentioned here that both these magnitude classes contain very less percentages of dependent events (see Table 1) and thus events for above two classes remain more or less same as can be observed in Fig.5. However, for other three magnitude classes ($5.0 \leq Mw \leq 5.9$, $6.0 \leq Mw \leq 6.9$ and $7.0 \leq Mw \leq 7.9$), differences in terms of cumulative number of EQs per year for the two catalogues can be observed from Fig.5. Further, it can be observed from Fig.5 that for these magnitude classes, 1950 Assam EQ which generated larger number of aftershocks, difference in terms of cumulative number of EQs per year between the two catalogues can be observed. In other words, reduction in cumulative number of EQs after 1950 Assam EQ can be found.

Additionally, the slope of the plot in Fig.5 gives the occurrence rate for particular magnitude classes. It can be seen from Fig.5 that for the above three magnitude classes, after 1950 Assam EQ, which triggered a large number of aftershocks, the slope is significantly changing for the EQ catalogue obtained after declustering (as shown by red circle in Fig.5). After 1950 Assam EQ, the slope is suddenly reducing indicating a sudden reduction in the occurrence rate of EQs in above three magnitude classes. Such reduction in the slope can be attributed to a possibility that many EQs, which in actual were supposed to occur as independent EQs later, had occurred before time due to the loading caused by 1950 EQ. Another possibility for reduction in the slope after 1950 is that during declustering process, many of the events which were actually independent were removed considering as dependent event of 1950 EQ since fallen within specific space and time windows. In both the cases mentioned above, collectively a change in cumulative number of EQs per year because independent events became dependent events is observed. In later section, more discussion on whether it is just an attribute or actual ground truth to consider such events as independent events, will be discussed.

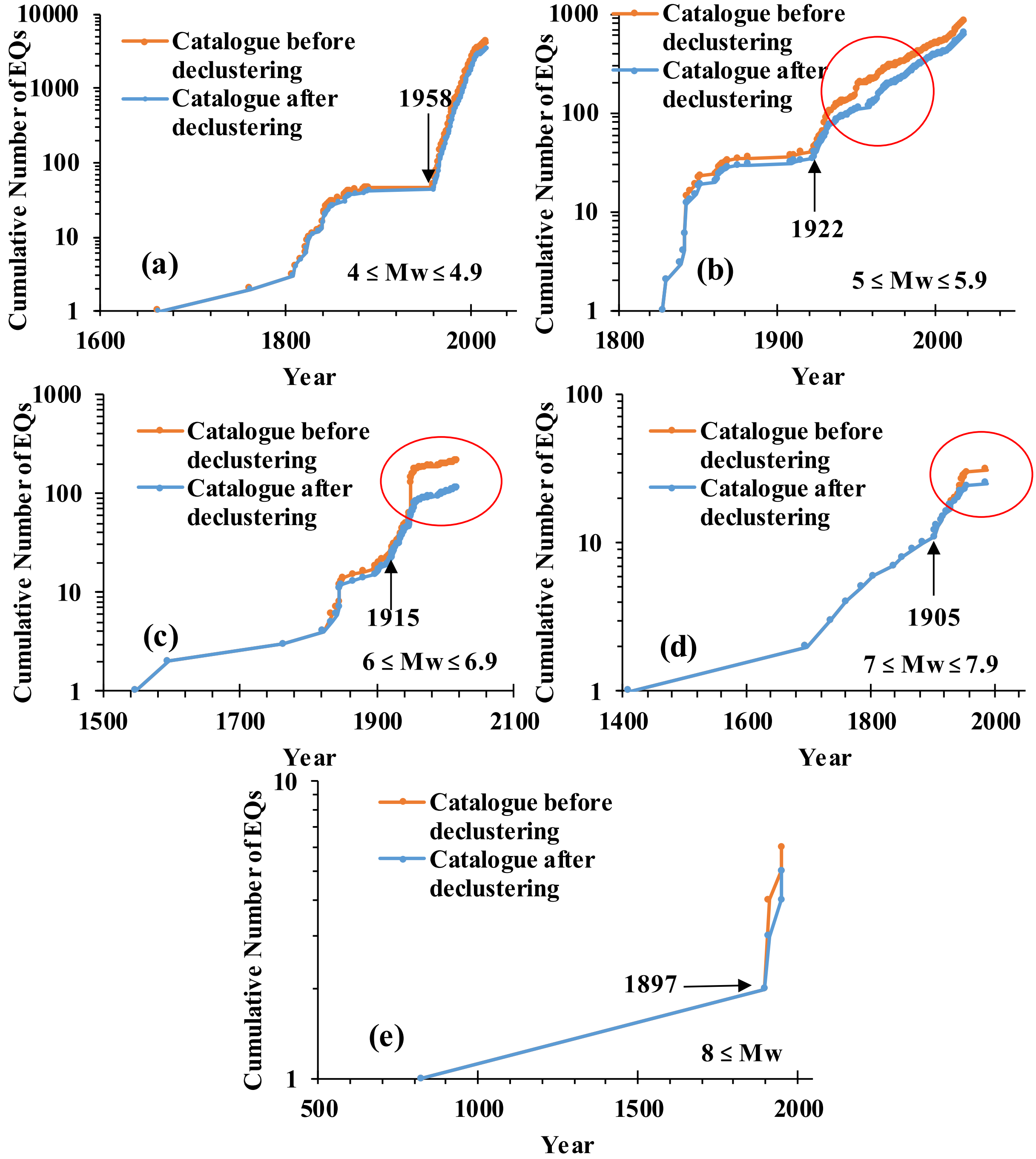

Fig. 5 – CUVI method for determining catalogue completeness (arrow showing the point after which the data are complete with respect to time)

6 Effect of declustering on the estimation of Mmax

Knowledge of maximum magnitude (Mmax) on a particular seismic source, which had occurred so far is very important for seismic hazard analysis. Fig.6 shows the seismic sources (total 121 in numbers) in and around NE India as well as the past seismic events (Fig.1) both main events (red dots) and dependent events (blue dots). In here, main events represent the EQ events from the catalogue after declustering and combination of both main events and dependent events represent EQ events from the catalogue before declustering. The seismic source information is taken from past literature [24, 25] and SEISAT 2000 [26].

Considering both the catalogues separately, all the EQ events are assigned to the nearest seismic source. After assigning the EQ events, the Mmax values for all the seismic sources using both the catalogues are found separately. It is seen that for 112 numbers of seismic sources (one seismic source with no EQ reported), Mmax observed are same from both the catalogues. Further, for 8 other seismic sources, Mmax values obtained from both the catalogues are different. In these 8 seismic sources, the total numbers of sources having the differences in Mmax to be 0.1, 0.4, 0.5, 0.8, 0.9 and 2.5 are 2, 1, 2, 1, 1 and 1 respectively. Comparison of both EQ catalogues for these 8 seismic sources show that Mmax after declustering has become lesser then what was there before declustering. This indicates that the declustering has lead to underestimation of Mmax value for a particular seismic source. Observing the locations of above 8 seismic sources show closer proximity of many of them with respect to each other. Thus, declustering for a particular seismic source, based on spatial and temporal window, has considered EQs happened on adjacent

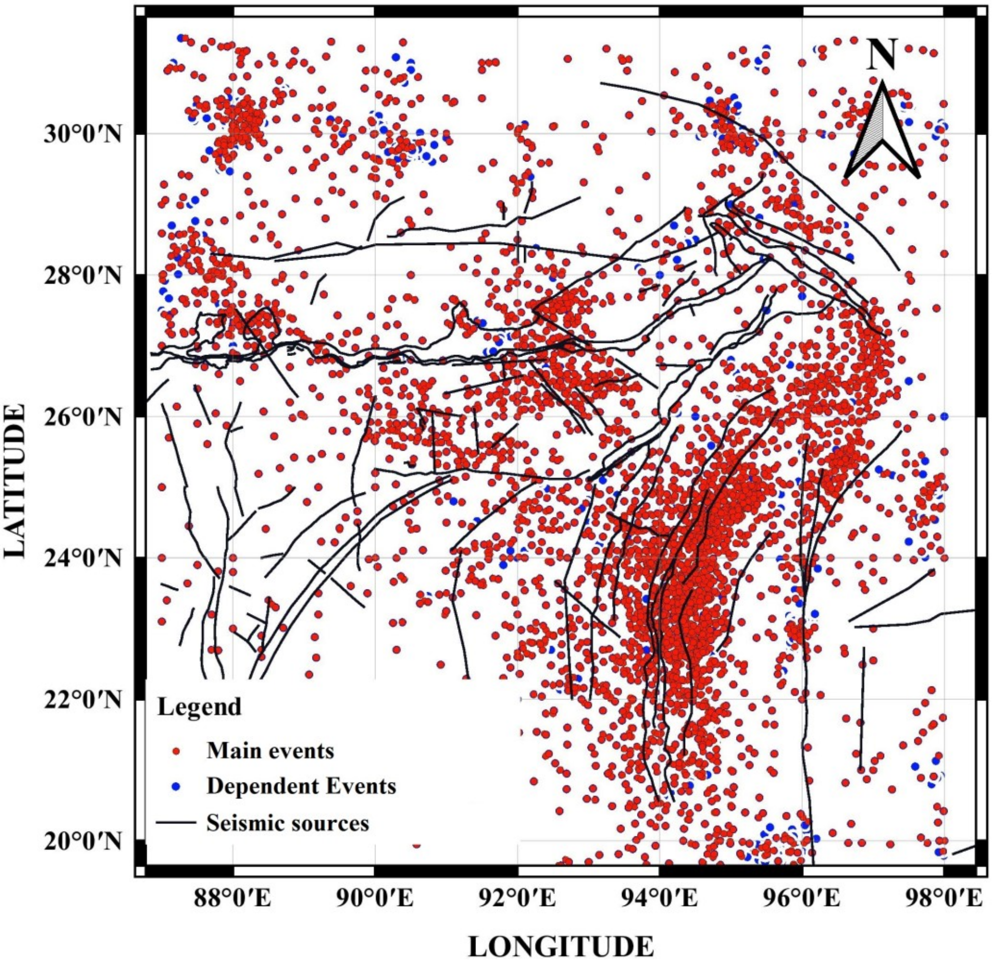

Fig. 6 – Seismic sources in NE India region along with EQ data from both catalogue before declustering and catalogue after declustering

seismic source (having Mmax of lower magnitude than the Mmax of seismic source under consideration) as dependent EQ and removed it. As a result, during declustering Mmax of adjacent source available will be different value since actual Mmax has been removed as discussed earlier. This scenario of underestimating Mmax of seismic source based on declustering, is possible when seismic sourcs are close to each other. Thus, in such scenario, present work recommends Mmax of each seismic source to be considered before declustering. Further, above analysis also suggests that a larger EQ can trigger EQs on adjacent seismic sources as well, as a result, such secondary EQs are found to be dependent events.

7 Dependent events of major to great EQs

Based on the currently adopted method for declustering (Urhammer [6]), more than 115 numbers of aftershocks for 1950 Assam EQ are obtained. It must also be mentioned here that based on the declustering method, no foreshocks is observed from 1950 Assam EQ. Fig.7 shows the location of the main event of 1950 Assam EQ, along with the aftershocks locations. It can be observed from Fig.7 that the aftershocks of 1950 Assam EQ are not located on seismic source responsible for the main event but on other nearby sources. Thus, based on the locations of epicentres and nearby seismic sources, the events which are identified as aftershocks of 1950 Assam EQ, might be independent events. Three of such identified aftershocks had Mw > 7 while many had Mw > 6. These so identified dependent events are indicating the seismic activity of nearby sources and can cause significant seismic hazard in the region. As mentioned in section 5 earlier (Fig.5 b-d), 1950 Assam EQ might had resulted in triggering EQs on other seismic sources before their actual time of occurrence. Hence, care should be taken while removing high magnitude EQs from the EQ catalogue, else the EQ catalogue will underestimate the true potential of many seismic sources while quantifying the seismic hazard of the region.

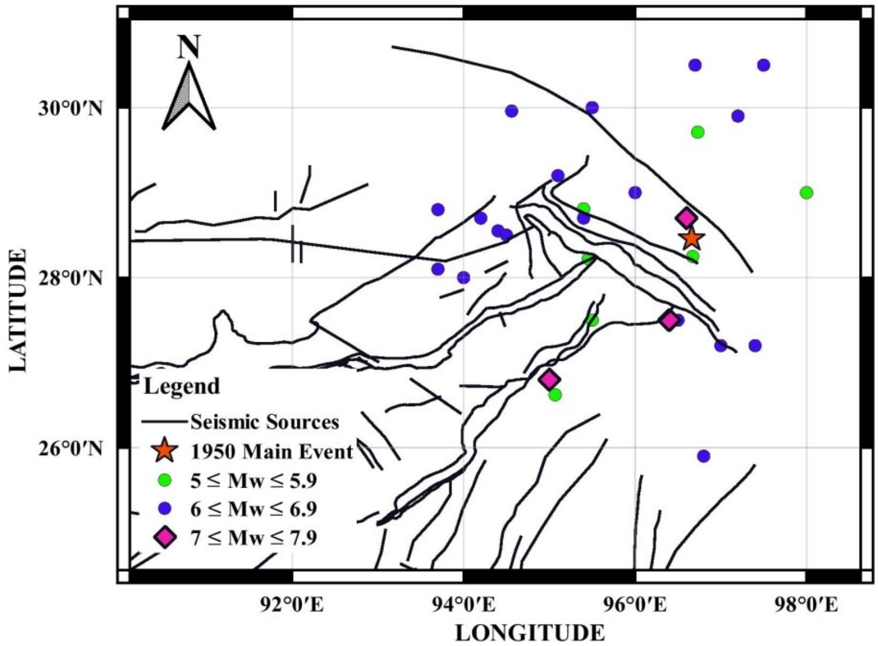

Fig. 7 – The great 1950 Assam EQ and its aftershocks location along with the seismic sources

Similar observations can be made for other EQs occurred after 1950 Assam EQ as well. In 1954, 1957 and 1988, three EQs having magnitudes of 7.3 Mw, 7.2 Mw and 7 Mw occurred in the region. Out of which only 1988 EQ had a significant numbers (22) of aftershocks. It can also be mentioned here that not all higher magnitude events are causing a significant number of aftershocks. Fig.8 shows the main event and aftershocks of the 1988 EQ events. Here it can be seen that most of the aftershocks had occurred within the seismic source. Further, a fewer aftershocks had occurred on different seismic sources as well. The magnitudes of these aftershocks events were not that high (maximum Mw = 5.3). However, this may also contribute to the seismicity of nearby sources.

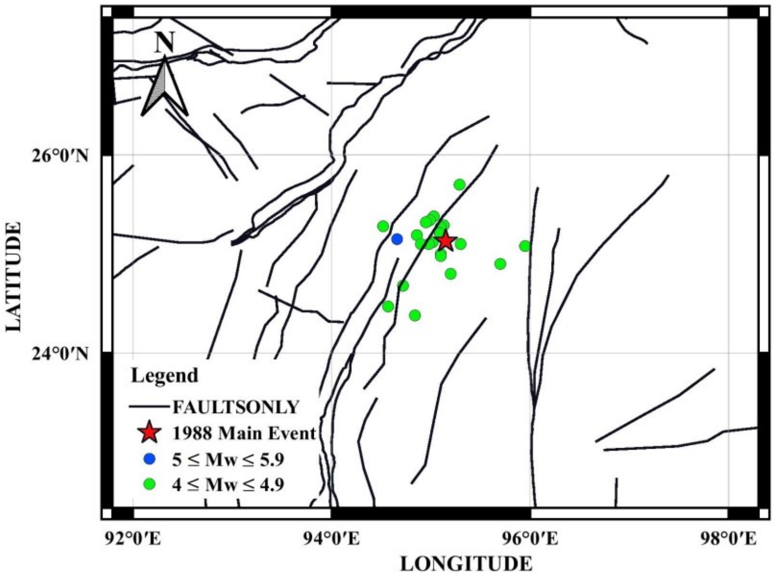

Fig. 8 – 1988 EQ and its aftershocks location along with the seismic sources

8 Conclusion

Current practice while preparing EQ catalogue for seismic hazard analysis is to develop EQ catalogue based on past EQ information, then removed dependent events and determine seismic activity parameters from complete part of the EQ catalogue. This way, while declustering, suitable method is applied to the EQ catalogue and no due consideration is given to the location of nearby seismic sources. In the present work, initially, the EQ catalogue for NE India is developed based on collected past EQ information from various sources. When the catalogues before and after declustering are analysed for completeness, both show the duration of completeness to be same for all the magnitude classes. This indicates that the duration of complete portion of catalogue is independent of declustering. Further, while examining cumulative number of EQs per year from both the catalogues, a sudden decrease in number of EQs after 1950 in the declustered catalogue is observed. It must be mentioned here that EQ catalogues for all magnitude classes are found complete after 1950 and thus such a reduction in cumulative number of EQs per year since 1950 indicates either of the two possibilities. First possibility is that the 1950 Assam EQ has triggered EQs on other seismic sources which actually should have happened later, resulting in lesser number of EQs in declustered catalogue. Second possibility is that the events which though occurred on different seismic sources but due to larger spatial and distance windows during declustering, were considered as dependent events of EQ happened on nearby sources. Later, it is found that as a result of second observation, Mmax of nearby seismic sources have been underestimated after declustering which is validated for 8 seismic sources. First reason mentioned above has also been validated for two EQs namely in the year 1950 and 1988. Whether going with the first reason or the second reason mentioned above, declustering leads to underestimation of actual seismic activity and subsequently the seismic hazard of seismic sources. Thus, in addition to past EQ information, the relative locations of seismic sources should also be given due importance in declustering. Further, Mmax of each seismic source should be determined before declustering is another important observation from this work.

Keeping in mind the large density of seismic sources in seismically active regions, above two observations may be useful in arriving at true seismic activity as well as seismic hazard for a region.

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