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Applicability of surface wave magnitude scale, Ms, and body wave magnitude scale, mb, in the study of seismicity of Northeast India and its adjoining region

Anupama Devi[1] , Dr. S. Kalita[2]
[1.] Department of Physics, Arya Vidyapeeth College, Guwahati, Assam, India
[2.] Dept. of Environmental Science, Gauhati University, Guwahati,Assam,India

Abstract: *Richter gave an empirical relation between surface wave (Rayleigh Waves) magnitude , Ms, and body wave magnitude, mb, (generally short P type body waves of period 1 sec). At the outset, we have tried to modify the Richter's relation by taking into account of the earthquake data of the North-East India and its adjoining region. Then we analyse the applicability of surface wave magnitude scale and body wave magnitude scale for the seismicity study of the region. Lastly the completeness of the earthquake datafile is checked. Various statistical methods are adopted in this present study. It has been seen that there is not much difference between the values of surface wave magnitude obtained from Richter's relation and modified Richter's relation. Since error is less,it would be better if modified Richter's relation is applied. From the study of applicability it is found that error is less if body wave magnitude is taken in the seismicity study. From the completeness analysis of the datafile it has been found that the datafile is complete from different period onwards for different magnitudes.*
Key words: *Surface wave magnitude, Body wave magnitude, Richter's relation, Seismicity.*

I. INTRODUCTION

Measurement of the size of an earthquake is done in terms of amount of energy released in its focus. Various magnitude scales have been developed to account for different type of seismic waves, distribution of teleseismic stations, different depth of the focus of an earthquake etc. The amplitude of seismic waves produced due to an earthquake depends on the amount of energy released at the focus after they has been corrected for their attenuation during their propagation. Using this concept, the earthquake magnitude scale, M_L, was first introduced by Richter[1] The Richter magnitude scale accurately reflects the amount of seismic energy released by an earthquake up to about M_L 6.5, but for increasingly larger earthquakes, the Richter scale progressively underestimates the actual energy release. Again, this scale can be used only when the seismographic stations are located within 600 km from the epicentre of an earthquake. The extension of the definition of magnitude of earthquakes at large distances (>600 km) was done by Gutenberg and Richter between 1936 and 1956. Two magnitude scales were defined in terms of ground motion recorded at a distance, one for surface waves, Ms, (Rayleigh waves) [2,3] of period 20 sec. and the other for body waves, mb, of period 1 sec. The surface-wave magnitude calculation does not require a seismograph record within 100 km (or nearby) of the epicenter, so the teleseismic records of many large-to-moderate magnitude earthquakes worldwide have been assigned surface-wave magnitudes. Because of this large data set, Ms is the typical magnitude used in empirical comparisons of magnitude versus earthquake rupture length or displacement [4] However, the surface-wave magnitude scale also saturates, at about Ms > 8. The body wave magnitude is measured from peak motions recorded at distances up to 1000 km on instruments. Peak motions usually correspond to the Lg wave. The main merit of mb is its applicability to both shallow and deep events. This scale has been used since the installation of the World – Wide Standardized Seismograph Network. Since mb is determined by the maximum amplitude from the very beginning of the P-wave group, it represents the size of an earthquake at the beginning rather than the magnitude of the earthquake as a whole. Also it is determined from P-waves alone, and is more strongly affected by source mechanism. In general, direct P waves from a strike – slip event are nearly an order of magnitude smaller than those from a dip – slip event. Hence, for earthquakes with a large fault dimension and complex rupture mechanism, the usefulness of this scale is limited. Detailed discussions on the relation between different magnitude scales are done by Geller and Kanamori [5], Abe and Kanamori [6,7], Miyamura [8] , Chung and Bernreuter [9] , Abe [10] , Bath[11] and Kanamori[12]. The variation in the different magnitude scales due to the intrinsic variation in the source properties such as the stress drop, complexity, fault geometry and size, and depth has also been studied. Recent studies have demonstrated that, although a gross scaling relation can be established [13,14,15], significant variations in the source spectral characteristics exist between different earthquakes. Also, it has been found that the heart of creating homogeneous earthquake catalog centers around appropriate correlation equations between the various magnitude scales, Mw, Ms, mb, and M_L.[16] A detailed analysis of the homogeneity of the earthquake catalogs of the study region was done by Das et.al. [17]. Now, Richter gave an empirical relation between surface wave magnitude, Ms, and body wave magnitude, mb.[18] Here we have tried to modify the Richter's relation by taking into account of the earthquake data of the North-East India and its adjoining region and also tried to ascertain statistically the applicability of both the magnitude scale in the study of seismicity of the region together with the completeness of the earthquake datafile.

II. DATASOURCE AND METHODOLOGY

Out of the available earthquake bulletins for North-East India and its adjoining region (between 22^0N – 30^0N latitude and between 89^0E and 98^0E longitude), the bulletins of ISC and USGS are used as data source for the period 1909 – 2012 (31^{st} July).

2.1. Modification of Richter's relation:

Regression analysis has been applied to determine the relationship between surface wave magnitude, Ms, and body wave magnitude, mb. A majority of such regression relations are, however, derived based on the assumption that one of the magnitudes (independent variable) is error free. When both the magnitude types contain measurement errors , the use of the standard least-squares regression procedure is found to be inadequate. In such a case, the use of orthogonal regression analysis is more appropriate to estimate regression relationships between different magnitude types[19]. Some reported regression relations also make use of other approximations, such as taking averages of conversions from mb and Ms to moment magnitude, which limits the accuracy of the converted magnitudes [20].

The relation between two variables is given by,

$$Y - \overline{y} = b(X - \overline{x}) \quad \text{…………….} \ (1)$$

where,

$$b = \frac{cov\,(x,y)}{s_x^2};\ \text{cov}\,(x,y) = \left(\frac{\sum xy}{n} - \overline{x} * \overline{y}\right)$$

and standard deviation,

$$s_x^2 = \left\{\frac{\sum x^2}{n} - \left(\frac{\sum x}{n}\right)^2\right\}.$$

Scatter diagram is used for diagrammatic representation of the bivariate variables Ms and mb. Chi square test is done between the observed values of Ms and the calculated values obtained using both modified Richter's Relation and Richter's Relation. While performing the chi-square test the null hypothesis taken is that both the modified Richter's relation and Richter's relation can be applied in the study region. The equation used for chi-square test is,

$$\chi^2 = \sum \frac{(O-E)^2}{E} \quad \text{…………………} \ (2)$$

where O represents the observed values and E the expected values obtained by applying the hypothesis. Z-test which is the test of significance for the difference of standard deviation is also performed by assuming the null hypothesis to be such that there is not much significant difference between the value of standard deviation obtained by taking the values of Ms from earthquake catalog and from modified Richter's relation and those between the Ms values of earthquake catalog and that from Richter's relation (two – tailed test). The equation used for Z-test is,

$$Z = \frac{s_1 - s_2}{\sqrt{\left(\frac{s_1^2}{2n_1} + \frac{s_2^2}{2n_2}\right)}} \quad \text{………………..} \ (3)$$

Here s_1 and s_2 are the respective standard deviations and n_1 and n_2 are the respective sample size.

2.2 Applicability of surface wave magnitude or body wave magnitude in the seismicity study:

At the outset, the temporal variation of the earthquakes having different ranges of magnitudes is analysed. In this study, earthquakes are grouped having magnitude ranges (3.0 - 3.9), (4.0 - 4.9), (5.0 - 5.9), (6.0 - 6.9) and ≥ 7.0 and then the decadal variation of earthquakes under these ranges is shown graphically.

Next, an efficient estimate of the sample mean is determined by assuming that the earthquake sequences can be modelled as a Poisson Distribution. If $k_1, k_2, k_3, \ldots, k_n$ are the number of earthquakes per unit time interval then an unbiased estimate of the mean rate per unit time interval of this sample [21] is,

$$\lambda = (1/n) \sum_{i=1}^{n} k_i \quad \text{………………} (4)$$

and its variance is,

$$\sigma_\lambda^2 = \lambda/n \quad \text{………………………} (5)$$

where, n is the number of unit time intervals. Considering the unit time interval to be of one year duration, we get,

Standard Deviation, $\delta = (\lambda/T)^{1/2}$ ……….(6)

where T is the length of the sample.

Standard error, $e = \delta/N$ …………(7)

where N is the no of seismic events.

2.3 Analysis of completeness of earthquake datafile:

Completeness of earthquake data is assessed by observing the temporal variation of the earthquakes having different ranges of magnitudes. In this study, earthquakes are grouped having magnitude ranges (3 - 3.9) mb, (4 - 4.9) mb, (5 - 5.9) mb, (6 - 6.9) mb and ≥ 7 mb and then the decadal variation of earthquakes under these ranges are analyzed.

Next, the incompleteness of an earthquake data file that comes in because of the non-uniformity of the seismic networks with time is investigated generally by testing the validity of Gutenberg – Richter recurrence relation [22,23]

Log N (M) = a – bM …………………. (8)

Where log N(M) is the number of earthquakes of magnitude M or greater, 'a' is a constant that represents the number of earthquakes of magnitude larger than zero, and 'b' is the proportion of earthquakes with small and large magnitudes. The value of 'a' and 'b' are generally determined by fitting the observed data sample. The relation has been confirmed for the global seismicity as well as for regional seismicity in different seismic zones of the world [24] . The formula has been shown to hold good for micro – earthquakes [25] and micro – fractures also [26,27]. If the data series is homogenous, equation (8) fits well and it gives considerably stable recurrence rates of earthquakes. But since small earthquake events could not be recorded in earlier times, erroneous results are obtained in finding the recurrence rate using equation (8). It cannot represent the actual long – term recurrence rate for small magnitude earthquakes. Recurrence rates for small magnitude earthquakes may be obtained from a well – documented short period earthquake catalogue. Therefore, it is necessary to use longer data period for larger magnitude earthquakes only to obtain more accurate statistical average.[28] For a long period data set, it is necessary to establish a threshold or lower bound of magnitude above which the catalog can be considered as reasonably complete. Usually the threshold is considered as the value of M where logN clearly depart from the straight line plot represented by equation (1), although a statistical test has been suggested for determining the lower bound of completeness of a sample [29]. Again equation (6) is applied to find the stability of the earthquake data series. Assuming the data series to be stationary, σ_λ behaves as $(1/T)^{1/2}$ in the sub – interval of the 103.58 year sample in which the mean rate of occurrence is constant. If the mean rate of occurrence is constant, stability will occur only in the subinterval that is long enough to give a good estimate of the mean, but short enough that it does not include sub – intervals in which reports are incomplete.

III. RESULTS AND OBSERVATIONS

3.1 Modification of Richter's relation:

Since correlation between Ms scale and mb scale is required to be determined, only those events in which magnitude of earthquake where both the scales have been given is taken. The data is represented as a scatter plot in Fig. 1.

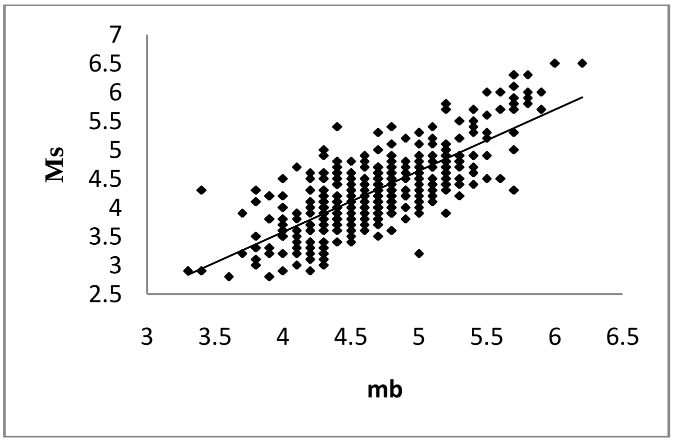

Figure: 1 Scatter diagram of Earthquake data in mb and Ms scale for the period 1978 – 2007

The Covariance = 0.256761 and Standard Deviation , s_x = 0.49295 is obtained from the data. Hence, the relation between surface wave magnitude, Ms, and body wave magnitude, mb , using equation : 1 is,

Ms = 1.05926 *mb – 0.66241 …………..(9)

which is modified Richter's relation.

Now, the Richter's relation [18] between surface wave magnitude, Ms, and body wave magnitude, mb, is given by,

Ms = 1.59*mb – 3.97 …………………(10)

The value of Ms is calculated from relation (9) and (10) by taking different values of mb and compared with the corresponding values of Ms taken from earthquake catalog is represented graphically in Fig. 2 and Fig. 3.

3.1.1.Chi-Square test:

This test is done using equation (2) and observed values are those values of Ms taken from earthquake catalog and the expected values are those values of Ms calculated from modified Richter's relation and from Richter's relation respectively. The result of chi square test by taking Ms values from earthquake catalog and those from modified Richter's Relation is 1.72664 and that obtained by taking Ms values from Richter's relation and from earthquake catalog is 14.53317. The number of degrees of freedom (df) is 27 and the standard tabulated value of χ^2 at 5% level of significance for 27 df is 40.113 .

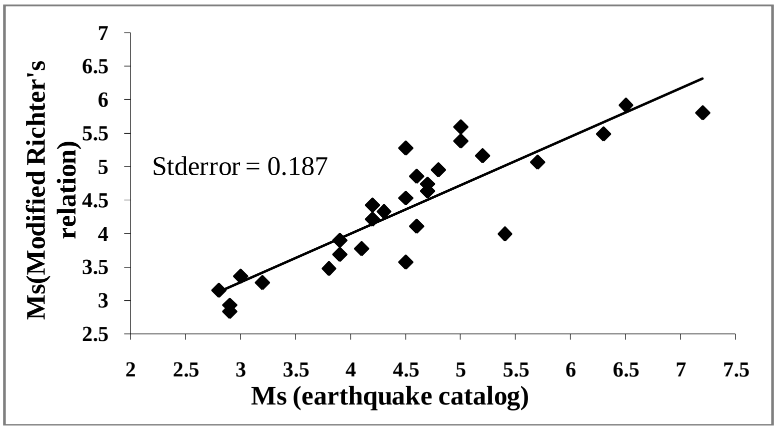

Figure: 2 Graphical representation of values of Ms from earthquake catalog and corresponding calculated values of Ms from modified Richter's Relation

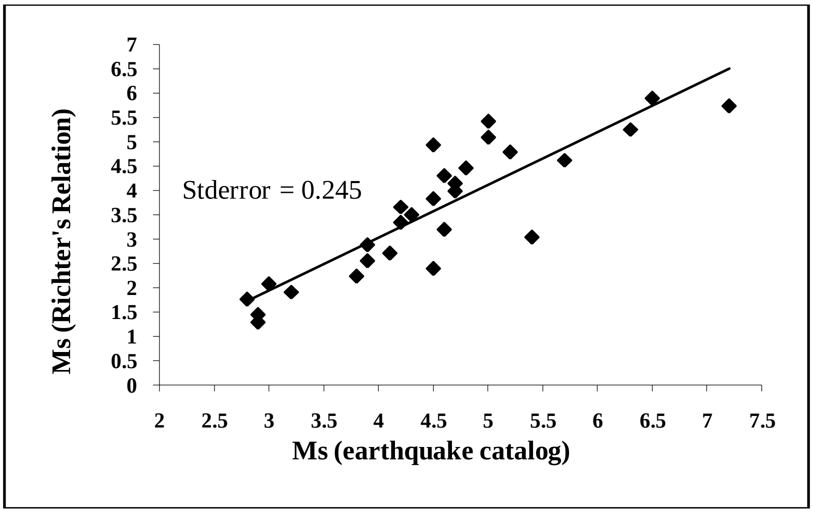

Figure: 3 Graphical representation of values of Ms from earthquake catalog and corresponding calculated values of Ms from Richter's Relation

3.1.2. Z-test:

The values of standard deviation obtained for data used to obtain Fig. 2 and Fig. 3 are 0.987271 and 1.296766 respectively. The test is done for 5% level of significance. Using equation (3) we have obtained the value of Z to be 0.549. This value of Z is less than the tabulated value in case of two- tailed test which is 1.96. Thus, the null hypothesis which was made can be accepted and it is concluded that there is not much significant difference in the value of standard deviation obtained by taking the Ms values from earthquake catalog and modified Richter's relation and those taken again from earthquake catalog and Richter's relation.

But, since the error (0.187) obtained by comparing the values of Ms obtained from modified Richter's relation with those taken from earthquake catalog is less than that (0.245) obtained from the values taken from Richter's relation and from earthquake catalog, it would be better if we apply the modified Richter's relation to study the earthquake catalogs of this region.

3.2. Applicability of surface wave magnitude or body wave magnitude in the seismicity study:

The number of earthquakes per decade from 1909 – 2012 (31st July) are grouped in magnitude ranges (3 - 3.9), (4 - 4.9) , (5 – 5.9), (6 – 6.9) and ≥7 and is presented from fig. 4 to fig. 8 below for surface wave and body wave respectively along with the total number of earthquakes in each decade. The events where either only surface wave magnitude, Ms and body wave magnitude, the modified Richter's relation is applied.

Graphical representation of number of earthquakes reported in each decade from 1909 – 2012 (31st July) for different magnitude classes

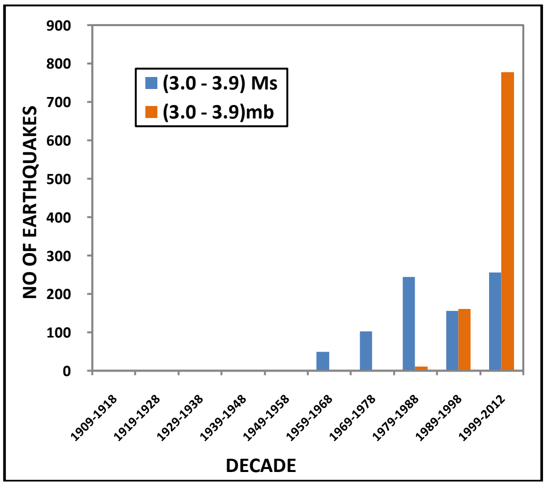

Figure 4: (3.0 – 3.9)

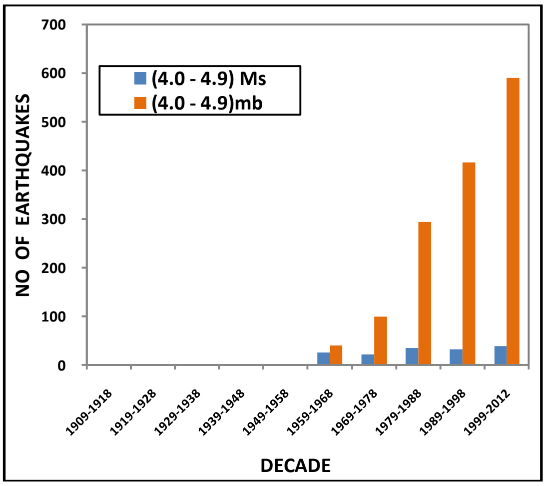

Figure 5: (4.0 – 4.9)

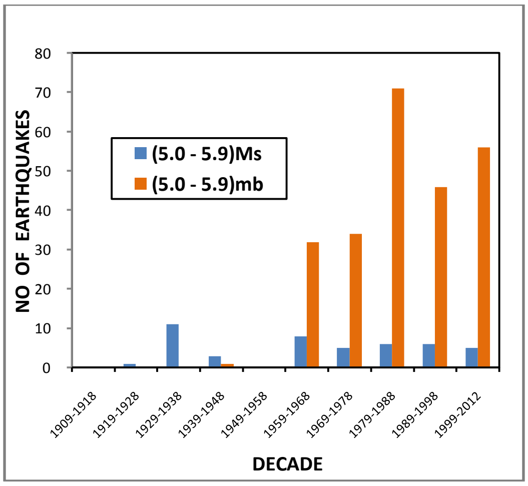

Figure 6: (5.0 – 5.9)

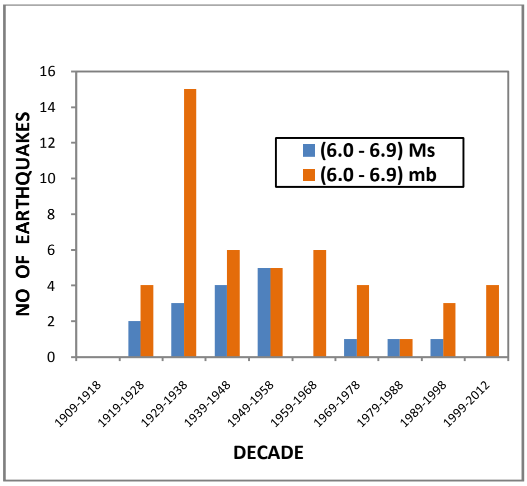

Figure 7: (6.0 – 6.9)

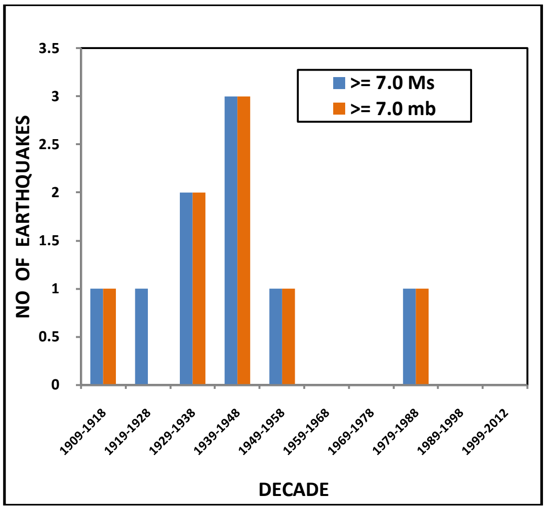

Figure 8: (≥7.0)

From the above graphical representations it is seen that earthquakes of low magnitude were not reported in the early part of 19th century. Moreover after conversion of surface wave magnitude to body wave magnitude using the modified Richter's relation between surface wave magnitude and body wave magnitude there is a variation in the total number of earthquakes. It may be mentioned that only those seismic events are converted whose value in both the scales were not available in the earthquake catalog.

The rates of occurrences of earthquakes of different magnitudes in the study region as a function of time interval both for surface wave magnitude and body wave magnitude is analysed and is represented graphically from fig. 9 to fig. 13.

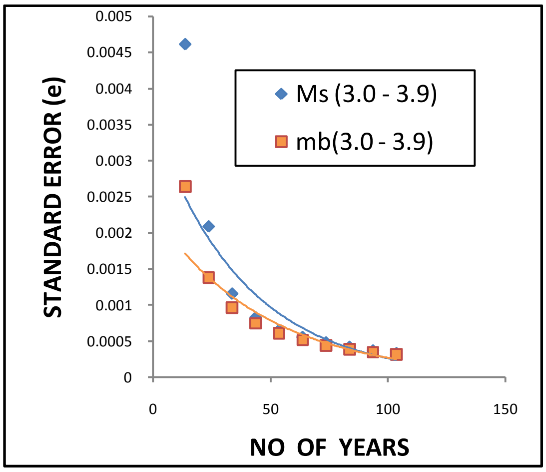

Figure 9. (3.0 – 3.9)

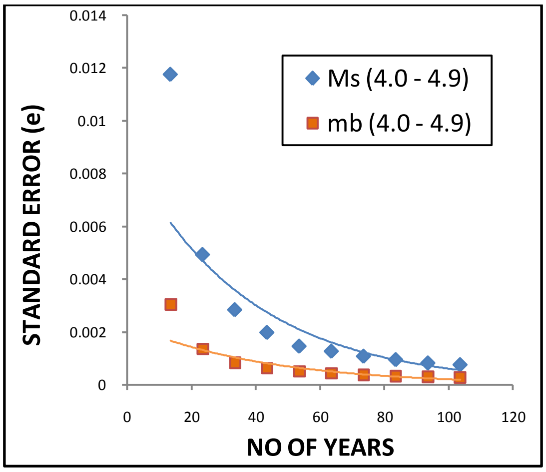

Figure 10. (4.0 – 4.9)

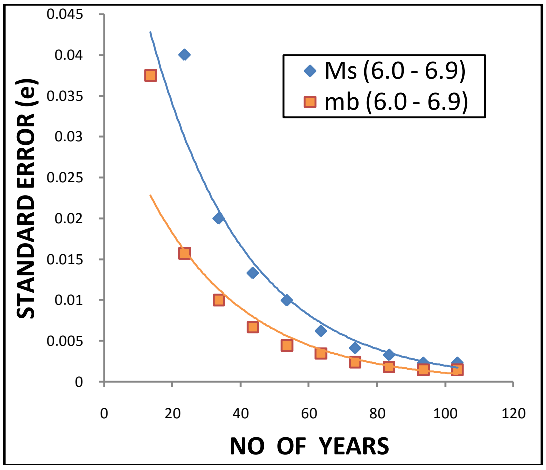

Figure 11. (5.0 – 5.9)

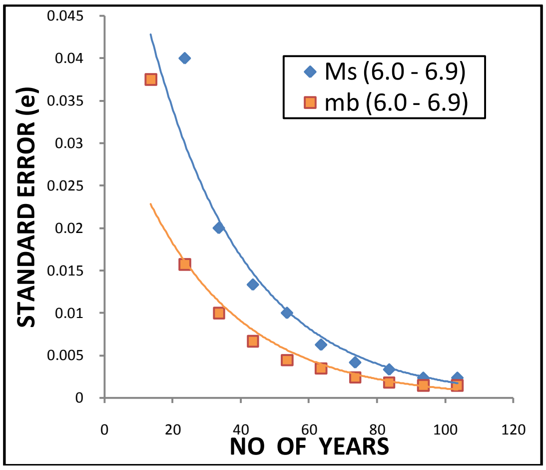

Figure 12. (6.0 – 6.9)

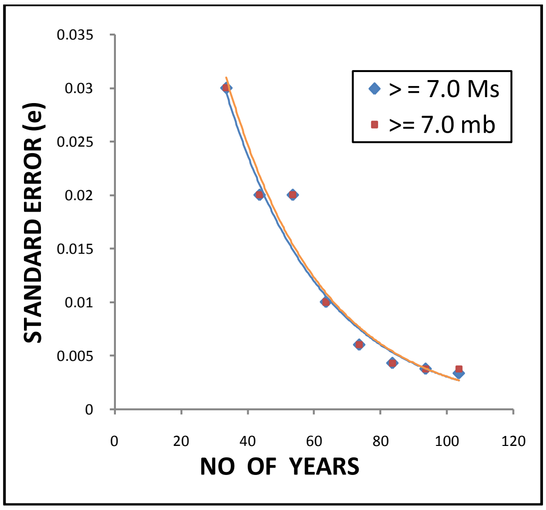

Figure 13. (≥ 7.0)

From the analysis of the fig. 9 to fig. 13 representing the standard error for both surface wave magnitude scale and body wave magnitude scale it is seen that the error incurred will be more if surface wave magnitude is used in analysing seismic parameters of the study region in the magnitude range (3.0 – 6.9). In fig. 13 it is seen that the error of body wave magnitude is more as we know that body wave magnitude of period 1 sec saturates beyond magnitude 7.0. Thus, we can conclude that mb scale will give erroneous result if used to measure earthquakes ≥ 7.0. But since in the study region the number of earthquakes ≥ 7.0 is very less so in this analysis body wave magnitude of earthquakes is considered.

3.3. Analysis of completeness of earthquake datafile:

The numbers of earthquakes per decade from 1909 – 2012(31st July) are grouped in magnitude ranges (3 – 3.9) mb, (4 – 4.9) mb, (5 – 5.9) mb, (6 – 6.9) mb and ≥7 mb and is shown in Figure 14. In case of events where only surface wave magnitude Ms is available it is converted to body wave magnitude,mb, using modified Richter's relation.

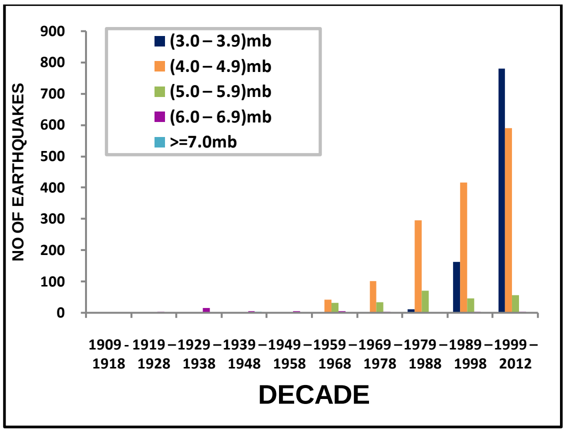

Fig. 14. Graphical representation of number of earthquakes reported in each decade from 1909 – 2012(31st July)

The observations made are:

- The earthquakes of magnitude >= 7 mb have been reported completely during the past 103.58 years.
- Earthquakes having magnitude ranges (6 - 6.9) mb and (5 – 5.9) mb show random distribution from 1919 to 1958.
- From the decade (1959 – 1968) the earthquakes of magnitude range (4 - 4.9) mb has been reported.
- The earthquakes of magnitude range (3.0 – 3.9) mb has been recorded from 1979 onwards.
- There has been a significant increase in the record of earthquakes of lower magnitude since the last four decades.
- The increasing trend in the number of earthquakes between (3 - 3.0) mb and (4 - 4.9) mb indicate incomplete reporting of earthquakes within this range before 1958.

Now, to analyze the completeness of the data file by testing the validity of the Gutenberg – Richter relationship, the cumulative frequency distribution of earthquakes having different ranges of magnitudes are computed out. The cumulative frequencies of earthquakes are plotted in Fig. 15. Here, it has been assumed that the region concerned is sufficiently large to hold good the Gutenberg – Richter relationship and equation (8) is fitted to the cumulative frequency distribution presented in Fig. 15 by using the method of least squares.

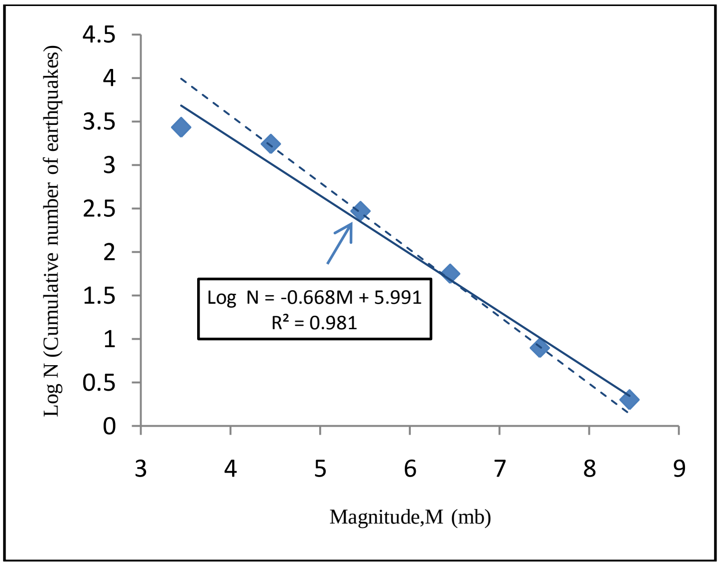

Fig.15: Graphical representation of cumulative magnitude frequency distribution of earthquakes per year for the 103.58 year earthquakes of North-East India and its adjoining region

The constant ‘a’ and ‘b’ are found to be 5.991 and 0.668 respectively. The constant ‘b’ which represents the proportion of small and large magnitude earthquakes, is an important parameter in seismicity study. Values obtained for ‘b’ are very stable within the range 0.6 – 1.4 and its most common value is very near to unity. High values of ‘b’ indicate a high number of small earthquakes, which is to be expected in regions of low strength and large heterogeneity whereas low values of 'b' indicate high resistance and homogeneity.[30] Thus, the low value of 'b' (0.668) obtained for this region indicates that the region is geo-tectonically homogenous having high rigidity.

It has been observed in Fig.15 that the events having magnitude below 5 mb is found to be less than the expected, which indicates incomplete reporting of earthquakes within this range. Earthquakes having magnitude above this range may be considered as reported completely. Further, assuming the validity of Gutenberg – Richter relationship for the region under consideration and considering the earthquakes of higher magnitudes to be well reported as observed from the decadal variation analysis , we may draw a tangential line through the points corresponding to the higher magnitude earthquakes as shown by the dotted line in Fig.15. This reflects that the earthquakes of magnitude greater than 6.5 mb are well reported in the data file throughout the whole period (103.58 years) and the earthquakes of magnitude smaller than 6.5 mb are not completely reported.

The observations made above show that the comprehensive catalog of the earthquakes of the region prepared for last 103.58 years is incomplete, especially for smaller magnitude earthquakes. Thus, determination of the mean rates of occurrence, $\lambda = N/T\ (\text{year})^{-1}$, from the complete 103.58 year sample leads to under-estimation of λ for the middle and lower magnitude of earthquakes. On the other hand, if the recent shorter time interval is taken during which the lowest magnitude group of earthquakes is completely reported, the mean rates of occurrence cannot be determined for the larger earthquakes because of the lack of data. To overcome this problem we seek to determine the subinterval of the total 103.58 year sample in which λ is stable in each magnitude class and assume that this represents the interval of complete reporting for that magnitude class of earthquakes.

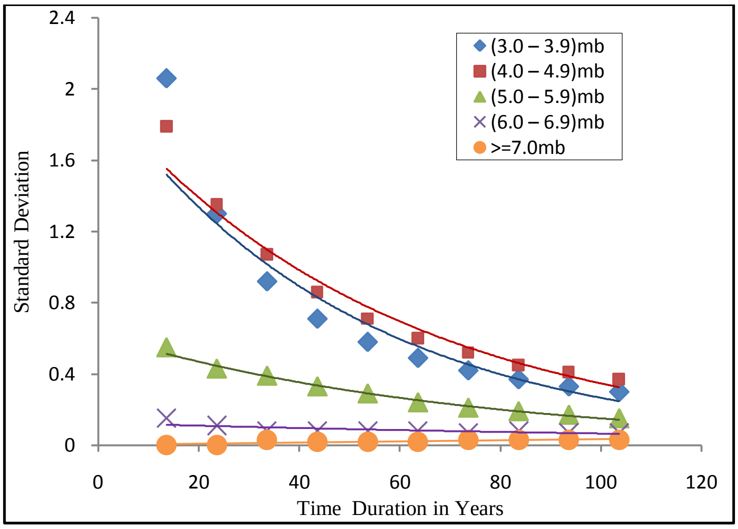

Fig. 16 Graphical representation of Standard Deviation of the Estimate of mean of Annual number of earthquakes as a function of sample length for different magnitude classes

The rates of occurrences of earthquakes of different magnitudes in the study region as a function of time interval are estimated. The rate is given as N/T, where N is the cumulative number of earthquakes in time interval T, for subinterval of 103.58 year sample. Then, the standard deviations of the estimates of mean is computed using equation – (6) and are represented graphically in Fig. 16.

The values of standard deviations decrease with the time interval T, which is obvious from the behavior of the parameter. However, their variation patterns for different magnitude classes are different. This behaviour show that a minimum time interval is required to reach a stable estimate of the mean recurrence rates. This interval is a function of magnitude class being necessarily larger for each higher magnitude class.

The earthquakes for magnitude class (5 - 5.9) mb are observed to be reported completely since 1949 onwards. While a stable estimate of the mean recurrence rate of magnitude class (6 - 6.9) mb is obtained for the period 1919 to 2012 (31st July). For the earthquakes of magnitudes >= 7 mb, the stable recurrence interval is obtained for the entire period. The earthquakes having magnitude less than 4.9 mb are observed to be reported from the decade (1959 – 1968). Thus, it has been observed that the data file for this region should have a minimum length of 100 years for magnitude >=7 mb, 90 years for magnitude (6 – 6.9) mb and 60 years for magnitude (5 – 5.9) mb. Thus, it is seen that one can create an artificially homogenous data sample by determining the interval over which earthquakes with different magnitude classes are completely reported. In this present study, we have found that for all magnitude of earthquakes it can be taken that the earthquake catalog is complete from 1964 onwards.

IV CONCLUSION

From the scatter diagram it is seen that since the points are dense, there is fairly a good amount of correlation between both surface wave magnitude scale, Ms, and body wave magnitude scale, mb. From chi-square test, it is seen that since the calculated values of chi-square in both the cases is much less than the tabulated values, both Modified Richter's relation and Richter's relation can be applied in the study region to use a single scale in order to study the earthquake catalog of the region. The result obtained from Z-test is that there is not much significant difference between the values of standard deviations indicating there is not much significant difference between the standard error obtained in both the cases. But, since the error (0.187) obtained by comparing the values of Ms obtained from modified Richter's relation with those taken from earthquake catalog is less than that (0.245) obtained from the values taken from Richter's relation and from earthquake catalog, it would be better if we apply the modified Richter's relation to study the earthquake catalogs of this region.

Here, an investigation is done on the applicability of body wave magnitude scale and surface wave magnitude scale in seismic hazard analysis of the study region. It is observed that when Richter's relation between surface wave magnitude and body wave magnitude is applied for those events where the events are recorded either only in surface wave magnitude scale or body wave magnitude scale is given there is a vast difference in the number of earthquakes. Also, it has been found that the error of surface wave magnitude scale is more for magnitudes less than 7.0. But beyond 7.0 the body wave magnitude scale would give erroneous result due to saturation. Again it is seen that the number of earthquakes of magnitude greater than 7.0 is very few in number in the region under study. So if body wave magnitude scale is used in analysing various seismic parameters the probability of error would be less.

From completeness analysis it is seen that many earthquakes of low magnitude were not reported in the early periods of the 103.58 years earthquake catalog compared to recent ones as highly sensitive recording instruments were not available and due to sparse distribution of recording stations. The data file can be considered to be complete for earthquakes having magnitude >= 7mb. Earthquakes having magnitudes between (6 – 6.9) mb and (5 – 5.9) mb can be considered to be reported completely since 1919 and 1949 respectively. The earthquakes having magnitude less than 4.9 mb have rarely been reported before the decade (1959 – 1968). Also by observing the period for which the mean recurrence rate is stable, the minimum length of the data file for each magnitude class for which the data file can be assumed to be complete can be determined. This would help in minimizing the error while making an analysis of various seismic parameters of the region by using the datafile.

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