A Statistical Analysis of Completeness of Earthquake Data around Dehradun city and its Implications for Seismicity Evaluation

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SUMMARY:
A catalog for a rectangular area around Dehradun city for the period 1720-2010 with 1777 historical and instrumental earthquakes events is compiled from different sources. This catalog has been further processed for removal of duplicate events, foreshocks and aftershocks of main events and then subjected to conversion of different magnitude types to $M_{w,\,GCMT}$ for homogenisation. Relations for conversion of m_b and M_s magnitudes to $M_{w,GCMT}$ are derived using three different methods, namely, linear Standard Regression (SR), Inverted Standard Regression (ISR) and Orthogonal Standard Regression (OSR), for different magnitude ranges based on events data for the period 1964-2007. The relations obtained from orthogonal regressions found to be better compared to the corresponding SR and ISR regression fits and, hence, are used for homogenisation of the catalog. Completeness tests have been performed to determine time –intervals in which data sets are complete in different magnitude ranges (classes) using various statistical techniques. The analysis reveals that the events data are complete for last 20 , 35 , 45 , 50 , 65 , 75 and 160 years from present in the magnitude classes $4.0 < M \leq 4.5$, $4.5 < M \leq 5.0$, $5.0 < M \leq 5.5$, $5.5 < M \leq 6.0$, $6.0 < M \leq 6.5$, $6.5 < M \leq 7.0$, and $M \geq 7.0$, respectively. The two significant parametric constants of Seismicity *(a- and b- values)* obtained by regression analysis of these data sets turns out to be 4.79 and 0.84, respectively, that are typically indicative of highly active zone. The homogenized catalog prepared in this study shall be used for PSHA of important cities (e.g. Dehradun city) falling in the Western Himalayan region.

Keywords: Moment magnitude, Orthogonal Regression, magnitude of completeness, b-value

1. INTRODUCTION

Historical and instrumental earthquake catalog describes the historical seismicity of a seismic region. Such catalogs compiled from several different sources, are in general, encompass duplicate events, foreshocks and aftershocks, and heterogeneity in magnitude types. Also, most magnitude determinations are beset with inherent errors because of the complex nature of the earthquake phenomena as well as variations in instrumental characteristics and azimuthal coverage of seismometers within a seismic region.

A homogeneous earthquake catalog is a basic requirement for studying the earthquake occurrence patterns in space and time and in Probabilistic Seismic Hazard Assessment (PSHA) for any seismic region. In order to compile a homogeneous earthquake catalog for a seismic region, appropriate processing of catalog- for identification and removal of duplicate events, removal of foreshocks and aftershocks, and conversion of different magnitude types to a preferred magnitude scale, is required.

The regression relations used for conversion of magnitudes on different magnitude scales are of critical importance since any bias introduced during the conversion process propagates errors in the seismicity parameters (a- and b- values) of the frequency-magnitude (F-M) distribution and consequently in the seismic hazard estimates. A majority of such regression relations are derived based on the assumption that one of the magnitudes (independent variable) is either error free or the order of its error is small compared to the measurement errors of the dependent variable. In the linear least-squares regression, those estimates are unbiased that are linear function of the observations (Hald, 1952). As both the magnitudes types used in a regression conversion relation may have measurement errors of similar order, the use of the standard least-squares regression procedure is found to be inadequate. In such a case, considering both the variables having errors, the use of orthogonal regression analysis is most appropriate to estimate regression relationships between different magnitudes (Castellaro *et al.,* 2006).

The Dehradun city and adjoining region is seismically one of the most active regions of the Himalayan seismic belt, stretching from the Pamir-Hindukush to the Arkans in Burma. The seismicity in this region is considered to be related to the continent collision of the Indian plate with Tibet in the north and Burmese landmass towards the east. The ongoing northward drift of the Indian plate makes the Himalayan region geodynamically active, where seismicity is concentrated along major thrusts, viz., Main Central Thrust (MCT), Main Boundary Fault (MBT), and Main Frontal Thrust (MCT).

Available earthquake catalogs for Dehradun city and adjoining region covering the seismicity from historical times (1720 onwards) to the period up to 1962 are heterogeneous in magnitude types (e.g., Gupta, 1986, Chandra, 1992). Recently, some studies are devoted to develop regression relations for converting different magnitude types to moment magnitude M_w (e.g.Thingbaijam *et al.*, 2008; Yadav *et al.*, 2009; Das et al., 2012). But these conversion relations do not specific for the study area and based on the assumption that one of the magnitudes involved is error free. Although some of them used OSR but not used proper error variance ratio.

In this paper, we have derived different regression relations for conversion of m_b and M_s to M_w. The regression relations obtained are the first relations for this region. No independent M_w determinations are attempted but instead we rely on the M_w values as reported by HRVD/CGMT databases. The m_b and M_s Values of events are taken mainly from ISC, NEIC, and ISET databases. A unified earthquake catalog in terms of $M_{w,GCMT}$ has been prepared based on the OSR conversion relations for the Dehradun city and adjoining region.

Further, in this paper, completeness tests have been performed to determine time –intervals in which data sets are complete in different magnitude ranges (classes) using various statistical techniques and estimation of seismicity parameters has been attempted.

2. STUDY AREA, TECTONIC SETUP, AND DATA SOURCES

The Dehradun city and adjoining area in western Himalayas is part of a very active seismic region bounded by latitudes 26^0-35^0 N and longitudes 72^0-83^0 E (Figure-1). The city is located at the foothills of Garhwal Himalaya and between two major active fault systems- the MBT in the north and MFT the south, where sedimentary plains hide the exact outcrop of the MFT. The region has experienced many damaging earthquakes in the historical past (Figure-1).

In this study, earthquake occurrence data for the period 1720 to 2010 has been compiled from different sources. For the historical seismicity period 1720 to 1963, events are taken from the catalogs published by ISET (1983), USGS, NEIC, Chandra (1992), Ambraseys and Douglas (2004). The earthquake events which do not have any specific magnitude unit assigned in this catalog are taken as surface wave magnitude (Thingbaijam et al., 2008; Yadav et al., 2009; Das et al, 2012).

For the period 1964 to 2010**,** events data has been compiled from International Seismological Center (ISC), U.K. (http://www.isc.ac.uk/search/Bulletin), National Earthquake Information Center (NEIC), (http://neic.usgs.gov/neis/epic/epic-global.htm) USGS, USA and HRVD (HRVD is presently addressed as GCMT http://www.globalcmt.org/CMTsearch.html) earthquake data bulletins. Further, m_b magnitudes data for the year 2007 to 2010 from NEIC has also been used for homogenization of magnitudes to moment magnitudes. The complete catalog period (1720-2010) contains total 1777 events out of which 7 events have M > 7 and 64 events are with M ≥6. Conversion relations have been developed using the data for the period 1964 to 2007.

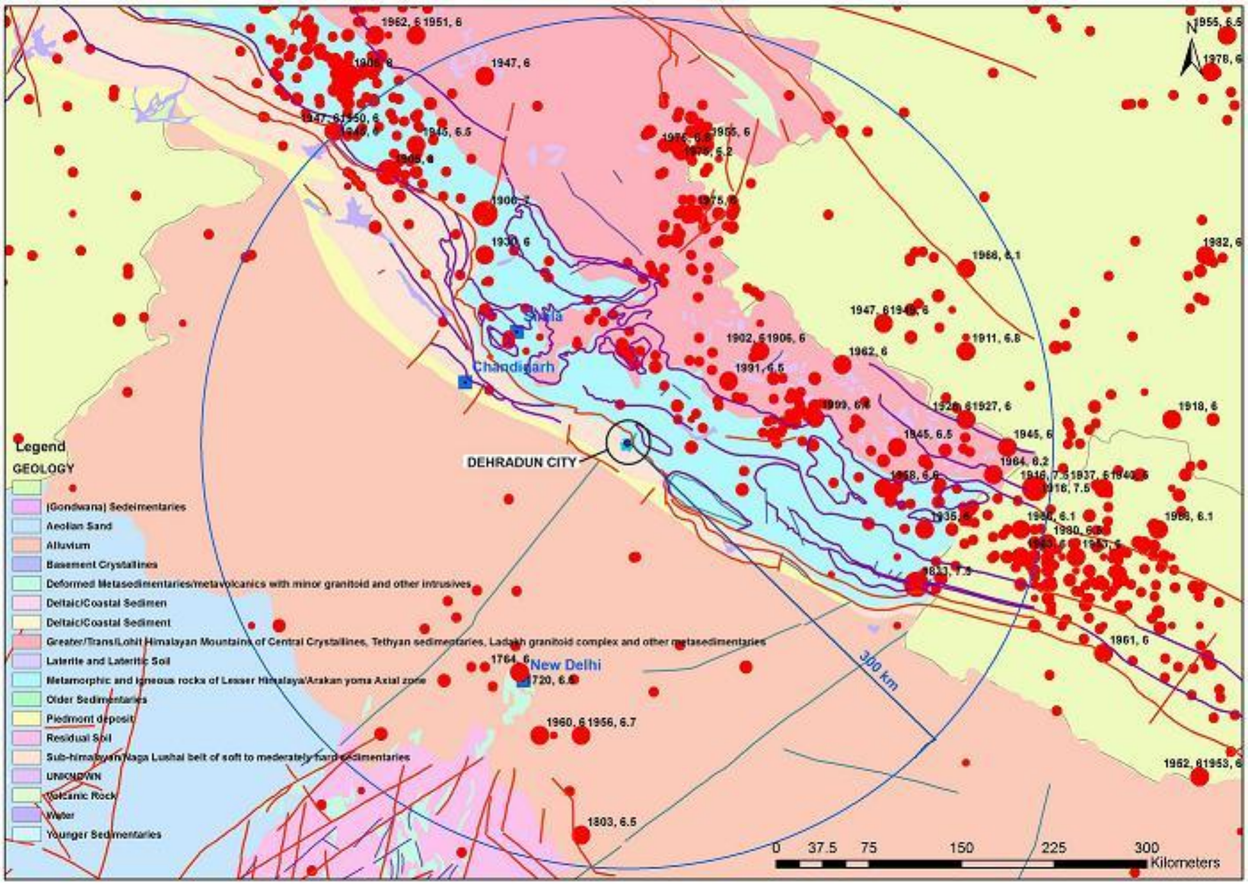

Figure -1: A seismotectonic map of Dehradun city and adjoining area on GIS platform depicting seismicity for $M_w \geq 3.5$ from the earthquake catalog prepared in this study

3. REGRESSION PROCEDURES

When both the dependent and independent variables contain measurement errors, the use of least-squares linear regression procedure is not correct. In such situation, it is appropriate to use OSR relation (Stromeyer *et al.*, 2004; Castellaro *et al.*, 2006, 2007; Thingbaijam *et al.*, 2008; Ristau, 2009). However, this relation requires the error variance ratio for the two magnitudes which is usually not known. In an orthogonal fit with a large error ratio, the fitted line approaches the standard least-squares line of fit.The procedure for orthogonal standard regression is described in detail in the literature (Madansky, 1959; Fuller, 1987; Kendall and Stuart, 1979; Carroll and Ruppert, 1996, Das et al., 2011; Das et al., 2012) and is not included here.

Inverted standard least-squares regression approach is same to the standard least -squares regression but minimizes the horizontal offsets to the best fit line. In this regression the function of the dependent and independent variables gets reversed. The methodology for ISR is given in literature (e.g., Draper and Smith, 1998) and is not described here.

4. MAGNITUDE CONVERSION RELATIONS

For conversion of surface and body wave magnitudes to moment magnitudes, we have considered events in the period 1964-2007 in specified magnitude ranges. $m_{b,ISC}$,$m_{b,NEIC}$, $M_{s,ISC}$ and $M_{s,NEIC}$ values with focal depths $\leq$ 50 km only are considered for deriving the conversion. The error variance ratio has been considered from Das et al. (2011).

4.1. Relationship between $m_{b,ISC}$/ $m_{b,NEIC}$ and $M_{w,GCMT}$

For the conversions of $m_{b,ISC}$ to $M_{w,GCMT}$ in the magnitude range $4.8 \leq$ magnitude ≤ 6.1, and $m_{b,NEIC}$ to $M_{w,GCMT}$ in the magnitude range $4.9 \leq$ magnitude ≤ 6.1, we follow the same approach using data set of 23 and 24 events, respectively, for the period 1964-2007. The regression parameters obtained for these two conversions are given in Table 1 and the plots are shown in Figures 2a and Figures 2b respectively.

4.2. Relationship between $M_{S,ISC}$/ $M_{S,NEIC}$ and $M_{w,GCMT}$

For the regression relations between $M_{s,ISC}$ and $M_{w,GCMT}$ we used 19 events within the range $4.0 \leq M_{s,ISC} \leq 6.1$, and the derived OSR, SR and ISR conversion relations are given in Table 1 and Figure. 2c. Similarly, for conversion of $M_{s,NEIC}$ to $M_{w,GCMT}$, we considered 12 events for the range $4.6 \leq M_{s,NEIC} \leq 6.5$, and the derived OSR, SR and ISR conversion relations are given in Table 1 and Fig. 2d.

Table 1: Regression parameters for different magnitude conversion relations

Regression Relation	Magnitude Range	Slope	Error (slope)	Intercept	Error (Intercept)	R^2	σ(SD)
$M_{s,ISC}$ to $M_{w,GCMT}$ (OSR), η=.56	$4.0 \leq M_{s,ISC} \leq 6.1$, n=19	0.688	0.054	1.888	0.27	0.84	0.12
$M_{s,ISC}$ to $M_{w,GCMT}$ (SR)		0.722	0.003	1.718	0.081		0.16
$M_{s,ISC}$ to $M_{w,GCMT}$ (ISR)		1.316	0.104	-2.009	0.55		0.19
$M_{s,NEIC}$ to $M_{w,GCMT}$(OSR), η=0.56	$4.6 \leq M_{s,NEIC} \leq 6.5$, n=12	0.662	0.054	2.053	0.295	0.85	0.13
$M_{s,NEIC}$ to $M_{w,GCMT}$(SR)		0.682	0.003	1.945	0.093		0.12
$M_{s,NEIC}$ to $M_{w,GCMT}$(ISR)		1.416	0.116	-2.568	0.655		0.14
$m_{b,ISC}$ to $M_{w,GCMT}$ (OSR), η=0.2	**$4.8 \leq m_{b,ISC} \leq 6.1$, n=23**	**1.478**	**0.05**	**-2.525**	**1.460**	**0.68**	**0.18**
$m_{b,ISC}$ to $M_{w,GCMT}$ (SR)		**1.042**	**0.156**	**-0.172**	**0.843**		**0.26**
$m_{b,ISC}$ to $M_{w,GCMT}$ (ISR)		**0.652**	**0.098**	**1.844**	**0.533**		**0.22**
$m_{b,NEIC}$ to $M_{w,GCMT}$(OSR), η=0.2	$4.9 \leq m_{b,NEIC} \leq 6.1$,n=24	1.526	0.0231	-2.899	0.668	0.75	0.14
$m_{b,NEIC}$ to $M_{w,GCMT}$(SR)		1.277	0.126	-1.558	0.681		0.27
$m_{b,NEIC}$ to $M_{w,GCMT}$(ISR)		0.644	0.064	1.957	0.339		0.24

5. CATALOG COMPLETENESS AND ESTIMATION OF SEISMICITY PARAMERTS

The homogenized catalog in terms of $M_{w,GCMT}$ has been used for completeness test for different magnitude interval and estimation of seismicity parameters, which will be used in subsequent study for the PSHA of Dehradun city and surrounding areas.

The analysis reveals that the events data are complete for last 20 , 35 , 45 , 50 , 65 , 75 and 160 years from present in the magnitude classes $4.0 < M \leq 4.5$, $4.5 < M \leq 5.0$, $5.0 < M \leq 5.5$, $5.5 < M \leq 6.0$, $6.0 < M \leq 6.5$, $6.5 < M \leq 7.0$, and $M \geq 7.0$, respectively. The two significant parametric constants of Seismicity (a- and b- values) obtained by regression analysis of these data sets turns out to be 4.79 and 0.84, respectively, that are typically indicative of highly active zone. The homogenized catalog prepared in this study shall be used for PSHA of important cities (e.g. Dehradun city) falling in the Western Himalayan region.

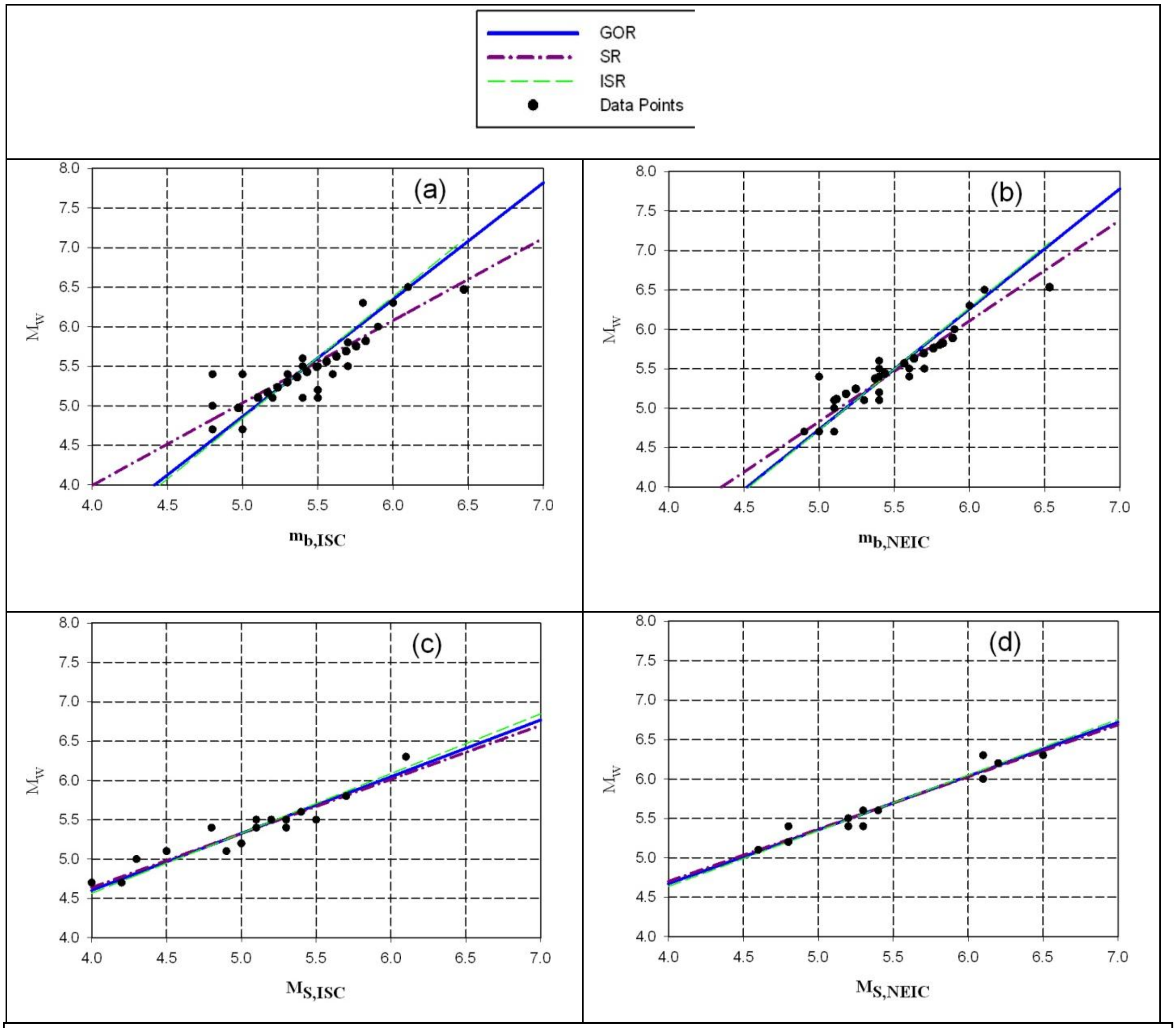

Figure 2. Regression relations (OSR, SR, ISR) for different magnitude conversions using using GOR, SR and ISR: (a) $m_{b,\ ISC}$ | $M_{w,\ GCMT}$ relation, (b) $m_{b,\ NEIC}$ | $M_{w,\ GCMT}$ relation, (f) $M_{s,\ ISC}$ | $M_{w,\ GCMT}$ relation, (d) $M_{s,\ NEIC}$ | $M_{w,\ GCMT}$ relation

6. DISCUSSION AND CONCLUSIONS

The regression relations used in various studies for conversion of different magnitude types to the unified $M_{w,GCMT}$ are generally based on the standard linear least-square approach (SR). Yet SR is not a good estimator when both the dependent and independent magnitude variables contain measurement errors.

In this study, earthquake occurrence data for 1777 events pertaining to the Dehradun city and adjoining region (Lat. 26^0-35^0N & Long. 72^0-83^0E) has been compiled for the time period 1720 to 2010, combining the historical and instrumental periods. As the events catalog is heterogeneous in magnitude types, regression relationships for conversion of body and surface wave magnitudes to $M_{w,GCMT}$ have been derived using three different methods, namely OSR, SR and ISR approaches. The $m_{b,ISC}$ to $M_{w,GCMT}$ conversion relations have been derived using 23 events data for the magnitude range $4.8 \leq m_{b,ISC} \leq 6.1$. Similarly, $m_{b,NEIC}$ to $M_{w,GCMT}$ conversion relations have been derived for the range $4.9 \leq m_{b,NEIC} \leq 6.1$, based on 24 events data. For smaller body wave magnitudes mb < 4.6, the data being very scarce, no regression relation is attempted it is advisable to use Das et al.(2011) relation which has wider magnitude range based on large data set. Further, $M_{s,ISC}$ to $M_{w, GCMT}$ and $M_{s,NEIC}$ to $M_{w, GCMT}$ conversion relations have also been derived for magnitude ranges $4.0 \leq M_{s, ISC} \leq 6.1$ and $4.6 \leq M_{s,NEIC} \leq 6.5$, respectively. The relationships derived in this paper are the first such relations for conversion for the study region. A homogenized catalog prepared using the derived relations in unified moment magnitude values which is an important input for seismic hazard estimation and other seismological studies.

The analysis reveals that the events data are complete for last 20 , 35 , 45 , 50 , 65 , 75 and 160 years from present in the magnitude classes $4.0 < M \leq 4.5$, $4.5 < M \leq 5.0$, $5.0 < M \leq 5.5$, $5.5 < M \leq 6.0$, $6.0 < M \leq 6.5$, $6.5 < M \leq 7.0$, and $M \geq 7.0$, respectively. The two significant parametric constants of Seismicity (a- and b- values) obtained by regression analysis of these data sets turns out to be 4.79 and 0.84, respectively, that are typically indicative of highly active zone. The homogenized catalog prepared in this study shall be used for PSHA of important cities (e.g. Dehradun city) falling in the Western Himalayan region.

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