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Estimation of Seismic Hazard Parameters for Uttarakhand Region

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ABSTRACT

Seismic hazard is a natural phenomenon provoked by an inevitable earthquake that causes rupture of faults, ground shaking or soil liquefaction. It incorporates the quantitative estimation of ground shaking at the particular region for use of engineering planning as well as to protect human life and ecological system to getting damaged. Due to the continuous collision of Eurasian and Indian plates within the last 100 years, the Himalayan region has experienced moderate to severe ground shaking. By keeping this in mind Indian state Uttarakhand is considered as region of study for potential earthquake hazard analyses. This region is comprised of a large earthquakes of Chamoli (1999, M_w=6.6) and Uttarkashi (1991, M_w=6.8). This state has a high potential for river valley and hydropower projects. Uttarakhand, lies on the southern slope of the Himalayan range lies between 28.7°N-31.1°N latitudes and 77.6°E-81°E longitudes. It is a seismically active region with numerous major seismic faults. In the present study, all earthquakes took place during 1976-2018 (44 years) in Uttarakhand region have been analysed using Gumbel type-I extreme value theory. The dataset was taken from United States Geological Survey (USGS) with regional magnitude. The extreme distribution function is applied to the earthquake record for computation of hazard parameters viz. '*a*' and '*b*' values, return periods, the most probable maximum magnitude and probabilities of occurrence related to medium and large earthquakes for the study area. The values of hazard parameters *a* and *b,* are 3.81, 0.83 respectively. The line of expected extremes (LEE) based on the data has been plotted and the return period is calculated. The analysis indicates that the most probable largest annual earthquakes are close to 4.6 and *the most probable earthquake that may occur in an interval of 50 years is 6.6 with effect from 2018.*

Keywords: Hazard parameters; The Gumbel's type-I extreme distribution; LEE; Return period.

1. INTRODUCTION

Earthquakes are most inevitable tremor among all the natural disasters with terrible aftereffects. But its disastrous effects can be minimized considerably through scientific understating of their nature, causes, frequency, magnitude, and area of influence. Seismic hazard assessment is carried out by complex analysis of seismological knowledge and the use of experience for predicting seismic parameters to minimize the seismic risk by providing earthquake resistant design of the structure and to predict earthquakes accurately. The most important factors that affect seismic hazard in a particular region are: Magnitude of an earthquake, the distances of site to the source, Return period of an earthquake (Rate of occurrence) and Duration of ground shaking. Movement of Indian plate and Eurasian plate along the plate boundary region progressively accumulates strain energy which makes the Himalayan region more vulnerable to large earthquakes in the future (Kumar et al., 2012). The extreme value theory is a well-known and commonly used method to assess the seismic hazard parameters like return periods and probability of earthquake occurrences. It has major advantage that it requires only the extreme value magnitude. The extreme value theory was proposed by Gumbel for the flood analysis and applied by various workers in the world for the estimation of seismic hazard parameters. Gumbel's theory of extreme value distributions has been used to analyse the observed extremes of an earthquake and to forecast further extremes in a particular area (Gumbel, 1958). The beauty of this theory is, it does not require analysis of the complete record of earthquake occurrence but uses the sequence of earthquakes constructed from the largest values of the magnitude over a set of predetermined intervals. But this theory does not reveal about characteristics of an earthquake. In this study, the return periods and probability of earthquake occurrence are calculated, which would be very helpful for future preparedness, planning and even construction practices in the considered area.

2. DETAILS OF STUDY AREA

The state, Uttarakhand is situated in northern part of India, which shares an international boundary with China in the north and Nepal in the east. The Indian state, Uttar Pradesh, touches the state to the south and Himachal Pradesh to the west and north-west and Haryana on its south-western corner. Map of Uttarakhand is shown in Fig. 1.

Fig. 1 - Location of Uttarakhand in India (Map of Uttarakhand, 2017)

This nascent State lies between latitude 28°43′N and 31°28′N and longitude 77°34′E and 81°03′E and contains an area of 53,483 km^2. This State can be divided into three physiographic zones namely, the Shiwaliks, the Himalaya, and the Terrai region. Most of the northern part of the state is covered by high Himalayan peaks and 19% of geographic area is under glacier, permanent snow and steep slopes (Forest Report, 2005). The state has 13 districts and is divided into two divisions i.e. Garhwal and Kumaon regions. Capital of Uttarakhand is Dehradun which is the largest city of the state.

As the Uttarakhand experienced moderate to severe earthquakes and most earthquakes are located between part of Lesser Himalayan and immediate south of Higher Himalayan. Districts along the borders with Nepal and China i.e. Kumaon region lie in Zone V (IS 1893, 2016) with MSK intensities in excess of IX can be expected in these districts. The rest of the state i.e. Garhwal, including the city of Dehradun lie in IS-1893:2016 Zone IV (IS 1893, 2016), where the maximum intensity expected could reach MSK VIII. This region has experienced numbers of largest instrumented earthquakes in Uttarakhand on 19 October 1991-Pilang-Bhatwari, Uttarakashi (M_w=6.8), 05 January 1997 in Dharchula area of Pithoragarh district (M_w=5.6), 28 March 1999 at Chamoli-Pipalkoti area (M_w=6.4), on 14 December 2005 at Pokhri-Gopeshwar (M_b=5.0) and on 22 July 2007 at Surka Ridge, Yamnotri region, Uttarkashi district (M_b=5.0) (Source: ASC Website).

3. PREPARATION OF EARTHQUAKE CATALOGUE

In this study an updated instrumental earthquake catalogue has been prepared for the time period since 1976 to 2018 and collected from international agency U.S. Geological Survey (USGS, 2018). Present catalogue is heterogeneous with different scales such as local magnitude, surface wave magnitude, body wave magnitude and moment magnitude (Fig. 2). So it is necessary to convert all different magnitude scales to a unified scale to achieve homogeneity in catalogue using region specific empirical correlation. For this purpose, all the reported magnitude scales are converted in advance and most widely accepted moment magnitude (M_w) scale to avoid the problem of saturation for higher magnitudes. This represents the actual seismic energy released in an earthquake. For Indian subcontinent, the conversion of M_b to M_w was achieved using general orthogonal regression analysis correction given by Das et al., (2012). In the dataset minimum moment magnitude of 3.5 and a maximum of 6.8 were presented. These collected earthquake events are used to prepare the Seismotectonic map for the region by ArcGIS software using SEISAT sheet 2000 (GSI, 2000).

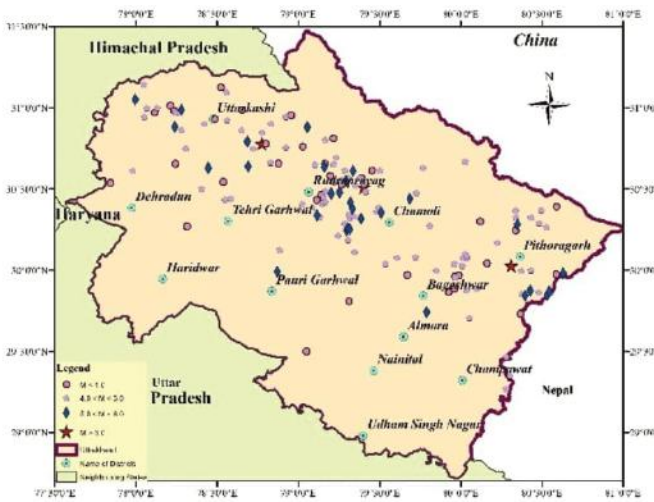

Fig. 2 - Distribution of earthquake catalogue around study area

4. GEOLOGY AND SEISMO-TECTONIC SETUP OF UTTARAKHAND

The Himalayan Mountains have formed due to continuous thrusting of the Indian plate under Eurasian plate since cretaceous time. This region is characterised by three major north dipping thrust zones separated by geographical sub-provinces. The Greater Himalaya lies in northern territory which has an average elevation of 5 km and composed of crystalline metamorphic and igneous rocks brought up along Main Central Thrust (MCT). The Lesser Himalayan sub-province is in south, which are sedimentary rocks with average elevation of 2.5 km delimited by the Main Boundary Thrust (MBT) (Valdiya, 1988). These slightly metamorphosed sediments are overlain, in places, by a thrust sheet of the crystalline rocks. South of MBT lies in outer Himalaya or Sub-Himalaya with average elevation of few hundred meters. This zone consists of folded and faulted Siwalik mollase sediments of Miocene age. The Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT) are the main active features in Uttarakhand (Mittal and Chakraverty, 2005) as shown in Fig. 3. The region of potential danger is known as the Central Seismic Gap, and underlies Uttarakhand and western Nepal. Smaller faults such as the Yamuna Fault near Haridwar and Alaknanda Fault near Rudraprayag have been active during the Holocene period (Dasgupta et al., 2000).

Fig. 3 - Tectonic map of Uttarakhand with neighbouring state, countries, major thrust and faults

A seismotectonic map is superimposition of all prominent features with seismicity. This is prepared by using SEISAT 2000 sheets. The study area covers sheet no. 5 and 6 of SEISAT. These are georeferenced and digitized in ArcGIS software. The Seismotectonic map is prepared as shown in Figure 4.

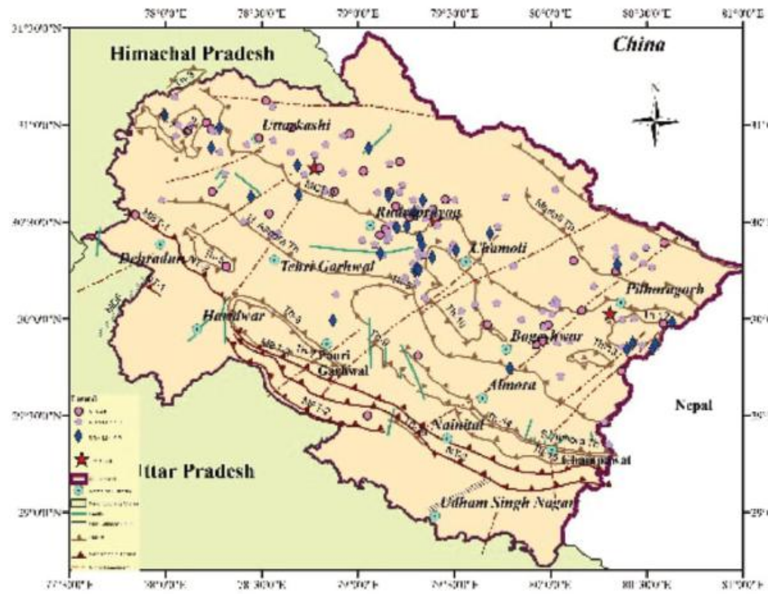

Fig. 4 - Seismotectonic map of study area depicting Seismicity on GIS platform

5. FORMULATION OF ANALYSIS

As we know various statistical models have been proposed to the analysis of earthquake occurrence with different degrees of success. Gumbel's model based on the extreme value theory is used in the calculations, which use extreme value statistics, need only part of the data i.e. largest earthquakes. Gumbel's extreme value theory (1958) suggests that if the earthquake magnitude is unlimited, individual events are unrelated and the number of earthquakes per year decreases with their increase in size, then the largest annual earthquake magnitude is distributed by cumulative distribution function G(m),

$$G(m;\ \alpha,\ \beta) = \exp[-\alpha \exp(-\beta m)] \quad m \geq 0 \tag{1}$$

Where α is the average number of earthquakes with magnitude > 0 per year and β is the inverse of the average magnitude of earthquakes under the considered region, and m is the maximum annual earthquake magnitude.

In order to study the earthquake risk, probability of occurrence and return periods, the earthquake data distributed over 44 years periods has been divided into one year time interval such that at least one event in each year duration is observed, which is necessary condition of the validity of the approach. For the continuity of the data M_w=4.8 is assigned for those years which have not reported any type of earthquake. It is an average value of events which is recorded for the study region. The probability integral transformation theorem and manipulation of equation (1) gives the relation:

$$-\ln[-\ln(p_m)] = \beta m_i - \ln(\alpha) \tag{2}$$

Where, p_m represents the plotting position. The mean frequency of i^{th} observation in the ordered set of extremes may be represented as

$$p_m = \frac{i}{N+1} \tag{3}$$

Where, N is the total number of observed data. The relationship between Gumbel parameters α and β and Gutenberg-Richter parameters a and b can be given by following expression, where a and b are constants.

$$a = log_{10}\,\alpha \tag{4}$$
$$b = \beta\, log_{10}\, e \tag{5}$$

The expected number of earthquakes, N_m, in a given year having magnitude exceeding M can be expressed by the Gutenberg- Richter seismicity relation as

$$log_{10} N_m = a - bM \tag{6}$$
$$N_m = 10^{a-bM} \tag{7}$$

Equation 7 is obtained from rearrangement of Equation 6.

The probability of at least one earthquake of magnitude $\geq M$ occurring within one year is given by the Poisson process as

$$p = 1 - e^{-N_m} = 1 - e^{-10^{a-bM}} = 1 - e^{-e^{\ln 10^{a-bM}}} \tag{8}$$

After derivation Equation 8 becomes

$$M = \frac{a}{b} - \frac{1}{b \ln 10} \ln\left[-\ln(1-p)\right] \tag{9}$$

where p lies in the interval (0,1).

The probability of at least one earthquake of magnitude $\geq M$ within t years can be given by the equation,

$$p = 1 - e^{-Nt} = 1 - e^{-(10^{a-bM})*t} \tag{10}$$

The expected number of earthquakes in a given year which have magnitude exceeding m can be found using the following equation:

$$\ln N_m = \ln \alpha - \beta m \tag{11}$$

The return period of earthquakes having magnitude greater than m is given in below equation

$$T_m = \frac{1}{N_m} = \exp(\beta m)/\alpha \tag{12}$$

Several other formulae can be obtained from the model expressed by Equation (1). For example, the most probable annual maximum magnitude (U) can be estimated using α and β as

$$U = \ln \alpha / \beta \tag{13}$$

The most probable earthquake magnitude, U_t in 't' year periods can be written as given below

$$U_t = \ln(\alpha * t) / \beta = U + \ln(t)/\beta \tag{14}$$

By using the above formulae and method in considered region earthquake hazard parameters are estimated in terms of an expected time interval for the occurrence of an earthquake, the most probable magnitude of an earthquake in a given time period and the occurrence probability of an earthquake in the specified time interval of 44 years.

Earthquake Hazard can be calculated for various time duration (D), which represents the probability of recurrence of an earthquake of magnitude 'm' within a period of D years and is given by Equation 15

$$H_{D(m)} = 1\text{-}exp\,(-\,\alpha\, D\, e^{(-\beta m)}) \tag{15}$$

6. RESULTS AND DISCUSSION

The annual maximum magnitudes of seismic events observed in the considered region from the year 1974 to 2018 are arranged in increasing fashion and assigning order number to each event to calculate plotting position and the values of the Extreme Event Type-I reduced variate. The obtained results from this process are shown in Table 1.

From above obtained results a graph between plotting position and maximum magnitude is plotted and the line of expected extremes (LEE) based on 44 years (1974-2018) of seismicity for the region has been shown in Fig. 4.

Table 1 - Frequency and reduced variate with increasing earthquake magnitude

Extreme	Order	Plotting Position	Reduced Variate
3.5	1	0.0217	1.343
3.8	2	0.0435	1.143
3.9	3	0.0652	1.004
4.3	4	0.087	0.893
4.4	5	0.1087	0.797
4.4	6	0.1304	0.711
4.5	7	0.1522	0.633
4.5	8	0.1739	0.559
4.5	9	0.1957	0.489
4.5	10	0.2174	0.423
4.5	11	0.2391	0.358
4.5	12	0.2609	0.295
4.6	13	0.2826	0.234
4.6	14	0.3043	0.174
4.6	15	0.3261	0.114
4.7	16	0.3478	0.055
4.7	17	0.3696	-0.005
4.8	18	0.3913	-0.064
4.8	19	0.413	-0.123
4.8	20	0.4348	-0.183
4.8	21	0.4565	-0.243
4.8	22	0.4783	-0.304
4.8	23	0.5	-0.367
5	24	0.5217	-0.43
5	25	0.5435	-0.495
5	26	0.5652	-0.561
5	27	0.587	-0.63
5	28	0.6087	-0.7
5	29	0.6304	-0.774
5	30	0.6522	-0.85
5	31	0.6739	-0.93
5.1	32	0.6957	-1.014
5.1	33	0.7174	-1.102
5.1	34	0.7391	-1.196
5.2	35	0.7609	-1.297
5.2	36	0.7826	-1.406
5.2	37	0.8043	-1.525
5.2	38	0.8261	-1.655
5.2	39	0.8478	-1.801
5.3	40	0.8696	-1.968
5.3	41	0.8913	-2.162
5.5	42	0.913	-2.397
5.6	43	0.9348	-2.696
6.6	44	0.9565	-3.113
6.8	45	0.9783	-3.818

To estimate α and β values a plot between Reduced Variate [ln (-ln (P_m))] with Maximum magnitudes '*M*' as shown in Fig. 5.

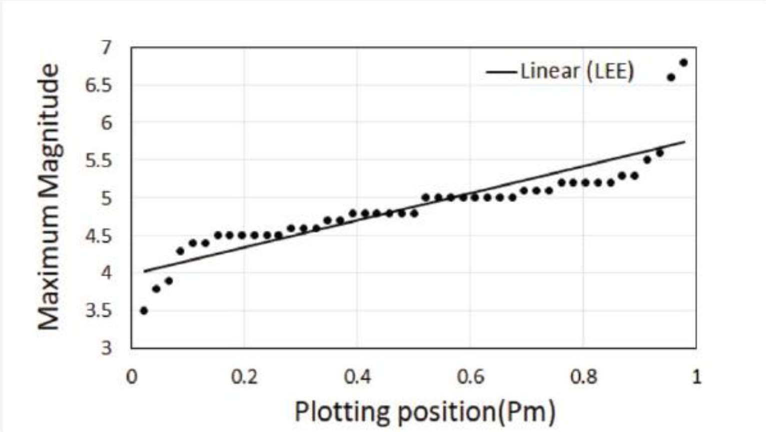

Fig. 4 – Mean line of expected extreme to study the probability of the largest earthquake

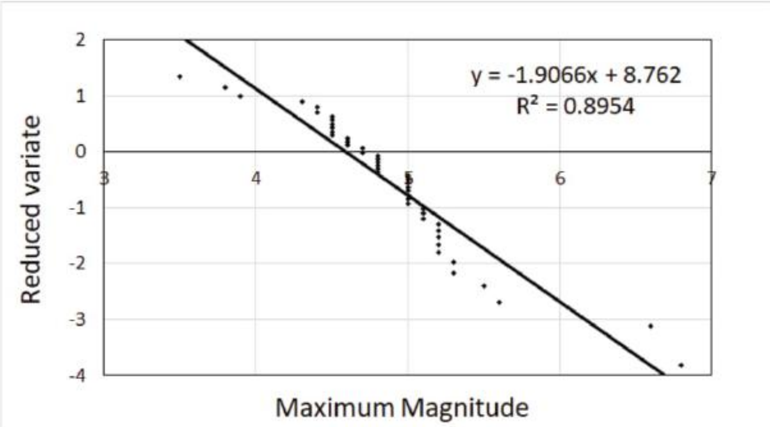

Fig. 5 - The plot of reduced variate with maximum magnitudes for considered region

Estimation of Gumbel's parameters α and β are basically slope and intercept of equation of line which obtained by plotting maximum magnitude verses reduced variate. This equation (y = -1.9066x + 8.762) is obtained using least square fitting of data and the value α and β obtained are stated in Table 2.

Table 2 - Estimated Gumbel's parameters

Statistics	Value	Interpretation
Slope ($-\beta$)	-1.9066	
β	1.9066	β is the inverse of the average magnitude of earthquakes under the region.
Intercept [ln (α)]	8.762	
α	6386.873	α is the average number of earthquakes with magnitude > 0 per year.

The values of α and β are 6386.873 and 1.9066 respectively, which do not vary much if one uses a long or short duration of data. Using Equations 4 and 5 values of '*a*' and '*b*' are calculated as 3.81 and 0.83 respectively. Where, '*a*' is a measure of the level of seismicity and '*b*' is size distribution, typically close to 1 (Richter, 1958). The value of '*b*' is the gradient of Gutenberg and Richter equation, where higher '*b*' indicates a larger proportion of small earthquakes, and lower '*b*' a smaller proportion of small earthquakes. The Yearly Expected Number (N_m) and their return period for different magnitude are summarized in Table 3.

Table 3 - Predicted yearly number of earthquakes with their return periods

Magnitude	Yearly expected number (N_m)	Return period (T_m) (Years)	Probability of occurrence
3.5	8.035	0.124	1
4	3.09	0.324	0.955
4.5	1.189	0.841	0.695
5	0.457	2.188	0.367
5.5	0.176	5.689	0.161
6	0.068	14.791	0.065
6.5	0.026	38.459	0.026
7	0.01	100	0.01
7.5	0.004	260.016	0.004

These values indicate that as return period increases, the frequency of earthquake occurrences decreases. In continuation with this, probability of occurrence in different time periods are calculated which are shown in Table 4.

Table 4 - Extreme magnitude and probability of their occurrence in different periods using Gumbel's method

Magnitude	5yrs	10yrs	15yrs	20yrs	30yrs	50yrs	75yrs	100yrs
3.5	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1
4.5	0.997	1	1	1	1	1	1	1
5	0.898	0.99	0.999	1	1	1	1	1
5.5	0.585	0.828	0.929	0.97	0.995	1	1	1
6	0.288	0.493	0.639	0.743	0.87	0.967	0.994	0.999
6.5	0.122	0.229	0.323	0.405	0.542	0.727	0.858	0.926
7	0.049	0.095	0.139	0.181	0.259	0.393	0.528	0.632
7.5	0.02	0.039	0.058	0.077	0.113	0.181	0.259	0.33

By using the above obtained values, variation of probability with year and probability of occurrence versus magnitude of earthquake for Uttarakhand are plotted in Figs. 6 and 7 respectively.

Table 5 shows the 20-years and 50-years earthquake hazard for Uttarakhand region, based on the analysis carried out in this study which is calculated from Equation 15 and on the basis of the data calculated graph is also plotted in Fig. 8.

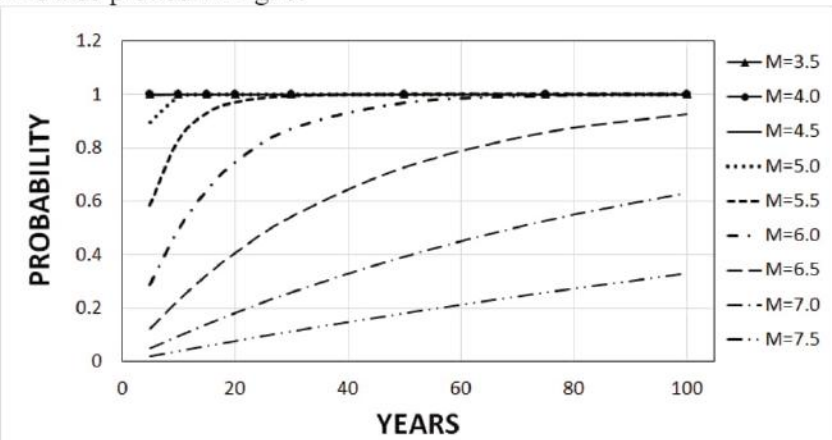

Fig. 6 - Variation of Probability with Years

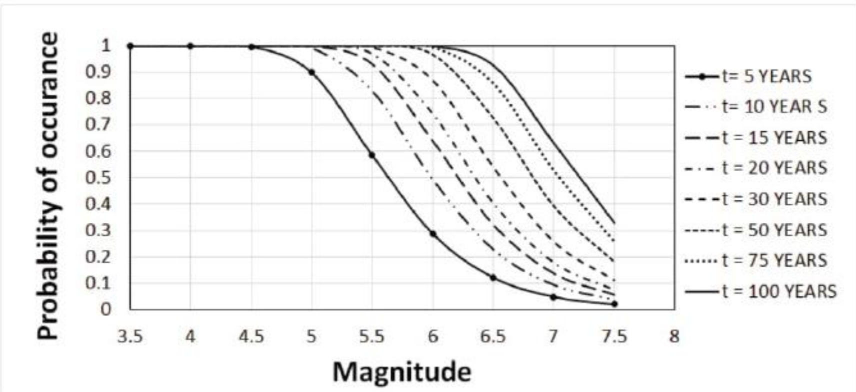

Fig. 7 - Probability of occurrence with magnitudes for different time periods

Table 5 - Earthquake hazard ($H_{D(m)}$) for D=20 year and D=50 year

Magnitude (m)	Probability of recurrence	Probability of recurrence
3.5	1	1
4	1	1
4.5	1	1
5	0.9999	1
5.5	0.9717	0.9999
6	0.747	0.9676
6.5	0.4113	0.7335
7	0.1847	0.3994
7.5	0.0757	0.1784

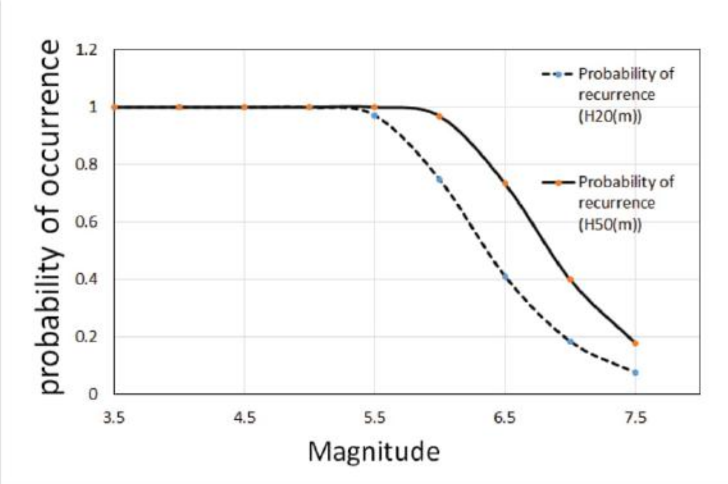

Fig. 8 - 20-years and 50-years earthquake hazard for Uttarakhand region

These observations suggest that within hundred year period probability of occurrence of larger magnitude earthquakes decrease with time.

7. CONCLUSIONS

Using Gumbel's type-I extreme value theory, values of Gumbel's parameters (α and β) are calculated as 6386.873 and 1.9066 respectively and hazard parameters i.e. 'a' and 'b' are calculated as 3.81 and 0.83 respectively. Yearly expected number, return period and Probability of occurrence are also calculated. Results advocate that as return period increases, the frequency of earthquake occurrences decreases and probability of occurrence of larger magnitude earthquakes decrease with time. For the considered region the most probable largest annual earthquakes are close to 4.6, which is calculated using Equation 14 and the most probable earthquake that may occur in an interval of 50 years using Equation 15 is estimated to be 6.6. This study is useful for engineering investigations at a particular site and decision making problems for planning to develop a certain region for infrastructural activities. By seeing the importance of economics as well as a safety before making any investment for the development in an area, seismic hazard and risk update is decisive. Yearly expected number is more for lower magnitude rather than higher magnitude. This indicates frequent occurrence of earthquakes. It suggests that tectonic stresses in this region are releasing frequently in the form of small-small earthquakes. Therefore, there is less possibility for the large earthquake. This is comparable to the results of the probability of occurrence which decreases with increase in magnitude of earthquake.

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