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Seismic Hazard Assessment in Hindukush-Pamir Himalaya Using IMS Network

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Abstract Hindukush–Pamir Himalaya and their vicinity bounded by 25–40°N and 65–85°E have been considered for future earthquake hazard. This is one of the most seismically active continent – continent collision-type active plate regions of the world where earthquakes of magnitude 8.6 have occurred during the past hundred years. Seventeen years earthquake data from June 13, 1999 to March 12, 2015 have been taken from International Monitoring System (IMS) Network setup by Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), Vienna Austria. Gumbel's Type I extreme event statistics [1] has been applied to analyses those maximum magnitude data with a satisfactory degree of correlation (0.92). The result of analysis has enabled earthquake hazard that exist in the Hindukush-Pamir Himalayan belt to be quantified in terms of recurrence periods and probabilities of occurrence of earthquake of any given magnitude. The line of expected extremes (LEE) which is based on 17 years (1999-2015) of seismicity data of yearly extreme values of earthquakes for the region has been plotted. The medium to large size earthquakes which is expected to occur in this region has been predicted. Study indicates that the most probable largest annual earthquakes are close to 5.5. The most probable earthquakes that may occur in an interval of 50 years are estimated as 6.6.

Keywords Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), The line of expected extremes (LEE), International Monitoring System (IMS) Network, Seismic Hazard

1. Introduction

Seismic hazard and related earthquake engineering determinations usually need estimate of return periods or probabilities of exceedance of specific levels of design load criteria or extremal safety conditions. Assessment of seismic hazard holds a major problem in earthquake engineering. There are several validations for adopting extreme value distributions [2-16]. There is the real believed in any analysis of seismic risk that it is the extreme or maximum events which are of most interest and important that impact on in day to day life of the people and their environment. Therefore effective engineering solutions are required to meet the challenges in this area regarding earthquakes and its impacts on civil society. This study will be very helpful for future preparedness and planning and even construction practices in the area because through this we can estimate the probable return periods of the earthquakes and their probable magnitudes occurrence[1].

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2. Regional Characteristics

Hindukush–Pamir Himalaya and their vicinity bounded by 25–40°N and 65–85°E have been considered for future earthquake hazard (Figure 1). This region is situated on the northern boundary of the Indian Plate along its northwestern flanks. In the past few decades there have been major advances in understanding the seismic and tectonic characteristics of this zone. It is believed that the current tectonic and seismic activity in central Asia is often considered to be the consequence of continental collision between India and Eurasia. However, the tectonic and seismic characteristics of the Hindukush can not be explained solely by the collision between the two plates, but thermal convection below the Indian Plate and the flow of the upper mantle in the Tibetan plateau region would affect earthquake activity and stress in the subducted lithosphere [8].

[1] The views expressed herein are those of the authors and do not necessarily reflect the views of the CTBTO Preparatory Commission nor those of the Galgotias University and Indian Institute of Technology, Roorkee.

Extreme value theory was proposed by [2] for flood analysis and has been applied for seismic risk assessment. Using this theory [2] attempted for the first time for earthquakes in southern California and for the largest earthquakes in the world. Since then several researchers have applied this method in different regions [3]. This study estimates the probability of occurrence of extremes, their return periods and the seismic risk of earthquakes in the region considered.

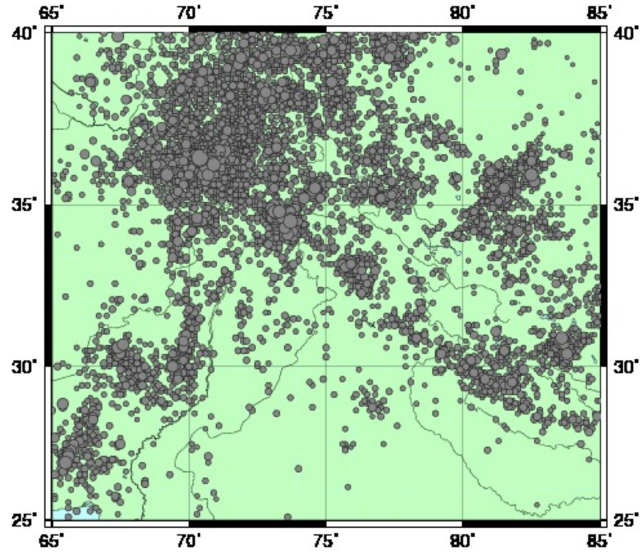

Figure 1. Seismic activity recorded by (IMS) from 1999 to 2015 at the considered region

3. The Data and Method of Analysis

Seismic technology is one of three waveform technologies which are part of the Comprehensive Nuclear Test Ban Treaty (CTBT) verification regime. The International Monitoring System (IMS) of the CTBT consists of 337 monitoring stations and laboratories world-wide. These facilities include 50 Primary and 120 Auxiliary seismic stations, installed world-wide and transmitting data to the International Data Centre (IDC). Since June 1999, the IDC began routine automatic and interactive processing of seismic data; the detected and located events are systematically included in the Reviewed Event Bulletin (REB).

Study investigates Seventeen years earthquake data from June 13, 1999 to March 12, 2015 with M ≥ 5.0 for the considered region (25–40°N and 65–85°E) taken from International Monitoring System (IMS) Network setup by Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), Vienna Austria. In order to study the earthquake risk, probability of occurrence and return periods, the earthquake data distributed over 17 years periods has been divide into one year time interval such as at least one event in each year duration is observed, which is necessary condition of the validity of the approach.

Gumbel's [1] extreme value theory postulates that if the earthquake magnitude is unlimited, if the number of earthquakes per year decreases with their increase in size, and if individual events are unrelated, then the largest annual earthquake magnitude is distributed by cumulative distribution function G(m), where

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

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

$$b = \beta\log_{10} e \tag{4}$$

and

$$a = \log_{10}\alpha \tag{5}$$

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

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

Where, a and b are constants.

From equation (6)

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

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

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

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 Eq (11)

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

and the return period of earthquakes having magnitude greater than m is given by:

$$T_m = {}^{1}/_{N_m} = \exp\,(\beta m)/\alpha \qquad (12)$$

4. Results and Discussion

Based on these, estimated results are summarised in tables and figures.

The annual maximum magnitudes of seismic events recorded in the considered region from the year 1999 to 2015 are shown in Table 1. The events are arranged in rank order, and the values of cumulative frequency probability, are calculated using Eq (3). The Extreme Event Type I reduced variate, is then calculated as per Eq (2). The obtained data from this process is given in Table 1. The values of α and β are then estimated from a least-square fit to the reduced variate linear equation (Fig. 4) and given in Table 2. The figure 3 shows the mean Line of Expected Extreme (LEE) to study the probability of largest extreme in the considered region.

Table 1. Calculation for Gumbel's Annual Maximum Distribution & Estimation of α and β

Extremes	Rank(j)	Plotting Position G(m)	Reduced Statics Ln(-ln (G(m)))
5.1	1	0.0555556	1.061385
5.2	2	0.1111111	0.787195
5.4	3	0.1666667	0.583198
5.5	4	0.2222222	0.40818
5.5	5	0.2777778	0.247589
5.6	6	0.3333333	0.094048
5.6	7	0.3888889	-0.05714
5.6	8	0.4444444	-0.20957
5.7	9	0.5	-0.36651
5.8	10	0.5555556	-0.53139
5.8	11	0.6111111	-0.70831
5.8	12	0.6666667	-0.90272
5.8	13	0.7222222	-1.12263
5.8	14	0.7777778	-1.38105
5.9	15	0.8333333	-1.70198
6	16	0.8888889	-2.13891
6.3	17	0.9444444	-2.86193

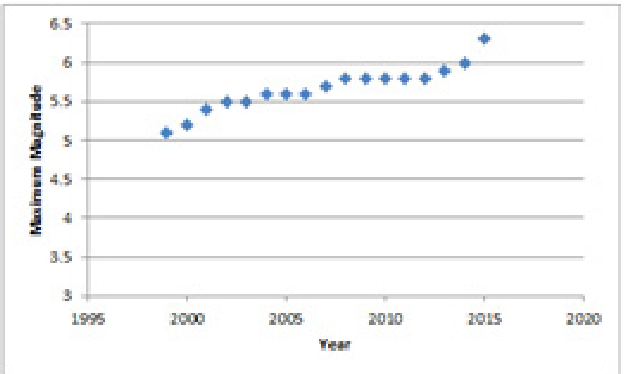

Figure 2. Variation maximum magnitude with year

Table 2. Estimated Gumbel's Parameters α and β

Statistics	Value
Slope (-β)	-3.551
β	3.55
Intercept (ln(α))	19.62
α	331785754.23

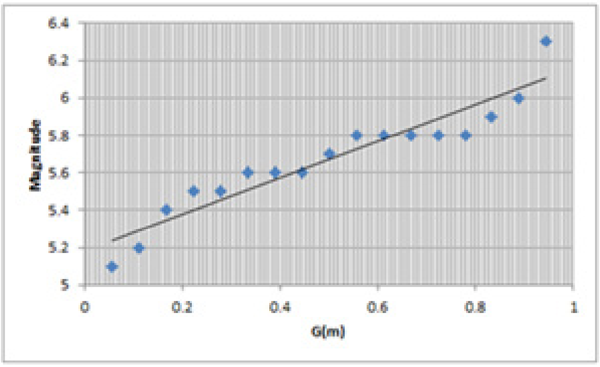

Figure 3. Variation of extremes magnitude with probability

Table 3. Predicted Annual number of earthquakes and its return period

Magnitude	N_m	T_m
5.1	4.549421127	0.219808
5.2	3.189933276	0.313486
5.4	1.568312185	0.637628
5.5	1.099658855	0.909373
5.5	1.099658855	0.909373
5.6	0.771051586	1.29693
5.6	0.771051586	1.29693
5.6	0.771051586	1.29693
5.7	0.540640895	1.849657
5.8	0.379083038	2.637944
5.8	0.379083038	2.637944
5.8	0.379083038	2.637944
5.8	0.379083038	2.637944
5.8	0.379083038	2.637944
5.9	0.265802959	3.762185
6	0.186373976	5.365556
6.3	0.064248301	15.56461
6.5	0.031587304	31.65829
7	0.005353525	186.7928
7.5	0.000907334	1102.13
8	0.000153778	6502.877
8.5	2.60628E-05	38368.8

The variation of maximum magnitude with year has been shown in Fig 2. Which indicates that maximum magnitude increases with time in the considered region.

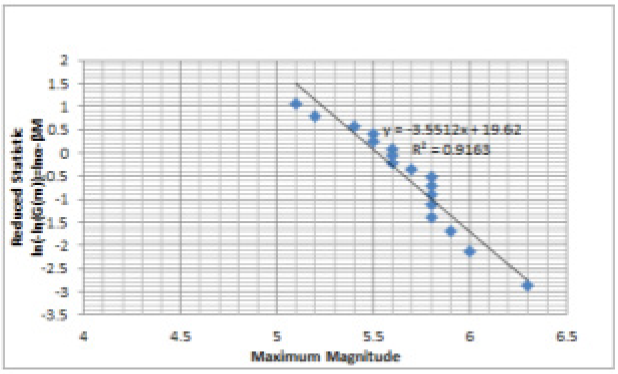

Figure 4. Display the reduced Variate versus maximum magnitude and to calculate α and β using linear regression of data

Table 4. Most probable largest earthquake hazard H_t (m) for Different Magnitude and Time Periods (t=10, 20, 30) years

Mag. (m)	$H_{50(m)}$	$H_{75(m)}$	$H_{100(m)}$
5.1	1	1	1
5.2	1	1	1
5.4	1	1	1
5.5	1	1	1
5.5	1	1	1
5.6	1	1	1
5.6	1	1	1
5.6	1	1	1
5.7	1	1	1
5.8	0.999999994	1	1
5.8	0.999999994	1	1
5.8	0.999999994	1	1
5.8	0.999999994	1	1
5.8	0.999999994	1	1
5.9	0.999998309	0.999999998	1
6	0.999910269	0.99999915	0.999999992
6.3	0.959740732	0.991922094	0.998379191

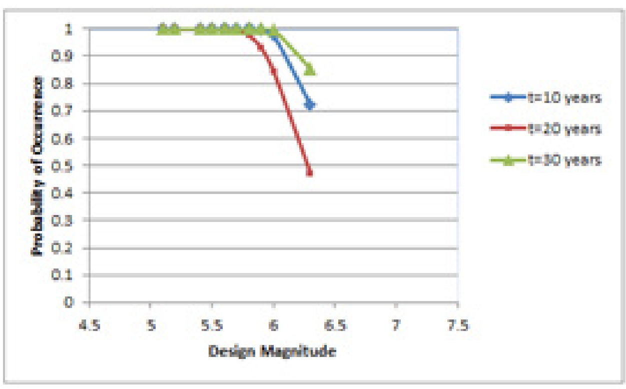

Figure 5. Earthquake Hazard in Hindukush-Pamir-Himalaya for different period

The proper risk evaluation is important from economic as well as safety point of view before making development and making investment in the region. Seismic threat and related earthquake engineering determinations usually require estimation of return periods or probabilities of exceedance of specific levels of design load criteria or extremal safety conditions. Assessment of seismic hazard cliques a major problem in earthquake engineering. The best of maximum earthquake magnitude recorded by IMS networks data base has been considered for quantifying the earthquake hazard in Hindukush-Pamir-Himalayas. The earthquake hazard H_t (m) is the probability of occurrence of earthquake of magnitude m within a period of t year and define as following equation.

Table 5. Most probable largest earthquake hazard H_t (m) for Different Magnitude and Time Periods (t=50,75, 100) years

Mag. (m)	$H_{10(m)}$	$H_{20(m)}$	$H_{30(m)}$
5.1	1	1	1
5.2	1	1	1
5.4	0.999999846	1	1
5.5	0.999983241	1	1
5.5	0.999983241	1	1
5.6	0.99955191	0.999999799	1
5.6	0.99955191	0.999999799	1
5.6	0.99955191	0.999999799	1
5.7	0.995512273	0.99997986	0.99999991
5.8	0.977423153	0.999490286	0.999988492
5.8	0.977423153	0.999490286	0.999988492
5.8	0.977423153	0.999490286	0.999988492
5.8	0.977423153	0.999490286	0.999988492
5.8	0.977423153	0.999490286	0.999988492
5.9	0.929913816	0.995087927	0.999655732
6	0.844908461	0.975946614	0.996269523
6.3	0.474015224	0.723340015	0.85448106

Table 6. Design earthquake Recurrence Period with 89% probability

Magnitude (m)	Return Period (Years)	Recurrence Periods (years)
5.5	0.90	1.986547422
6	5.37	11.85306628
6.5	31.65828868	69.8785464
7	186.7928035	412.3030692
7.5	1102.130055	2432.704022
8	6502.877173	14353.63765
8.5	38368.80352	84690.49745

$H_t(m) = 1 - \exp\left(-\alpha t e^{-\beta m}\right)$. The earthquake hazard for different magnitude and different time period are estimated and summarized in Table 4 & 5. The earthquake hazard probabilities are also offered in Figure 5, for 10-years, 20-years and 30-years periods. The general interpretation of this curve reveals that the probability of an earthquake of magnitude 5.5 occurring in the considered region with 20-years period is estimated to be 0.999 (Although, probability of any particular event is never absolutely certain). This means that at least one earthquake of magnitude 5.5 will surely occur within that period of time.

The statistics have been use to forecast and discussed, with any given confidence, recurrence periods in the considered region, for earthquake of any given magnitude. Equally, it could be also used to estimate the probability of any number of given magnitude earthquake occurring within any given time period (Fig 5). b-value of the considered area was reported 1.43 by [20] while, estimate presented here is b=1.54 and a=8.52 (equations 4 & 5). Our estimates well approve with other authors. The results are potentially useful for probabilistic seismic hazard assessment in the region. The estimates can be considered to be two ways reliable because on one way, the value of α and β which have been used to estimate the earthquake hazard and return periods do not change much for the short or long duration of data used and other, complete and reliable IMS data recording. The most probable annual maximum magnitude is equal to 5.5, which very much comparable with 6.0 by [20] and most probable 50-years maximum magnitude equal to 6.6. Further, the probability P (t ≥ T) that the recurrence period of the design earthquake of magnitude m exceeds an random recurrence period of T years is given by [14]; $P(t \geq T) = \exp(-T/T_m)$. Therefore, the probability of recurrence period being less than random time T is given by $P(t \leq T) = 1 - \exp(-T/T_m)$; from which one can deduce that period T within which at least one earthquake of magnitude m will occur with probability P express as $T = -T_m \ln(1\text{-}P)$. By which one can estimate expected period within which at least one earthquake of any given magnitude will occur with any specified probability. For example; recurrence period for at least one earthquake of magnitude m within a probability of 89% is given by $T_{89} = -T_m \ln(1\text{-}89)$. Here design earthquake Recurrence Period with 89% probability is estimated using Table 3 and its values are reported in Table 6. The 89% probability is taken because it is at that level of probability the estimated return periods follow to the observed return periods. The general interpretation of the 89% probability recurrence period could be understood that in the Hindukush-Pamir-Himalaya, there is 89% probability that, in any given time say 69 years period, at least one earthquake of magnitude 6.5 or greater will occur and conversely that 11% probability that an earthquake of M 6.5 or more will not occur (Table 6). The predicted values are also useful for engineering application and decision making for planning human settlement or societal infrastructure development in the region.

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