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Seismic Hazard Analyses of Tunnels - Comparisons and Illustration with Statistical Assessment of a Tunnel in Highest Seismic Zone of India

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Abstract

The Himalayan Orogenic belt constitutes the highest seismic hazard zone of the country and experiences moderate, large and great earthquakes since historical times with magnitude of the order of 8.5Mw. Immense developmental activities are taking place in the Himalayas by way of hydroelectric, communication, water supply and storage projects involving construction of tunnels and underground caverns. While, detailed seismic hazard assessment of the surface components of the projects are carried out, seismic vulnerability of underground structures like tunnels and underground caverns are generally not subject to rigorous analyses. The assessment of seismic vulnerability of the underground structures is of equal importance, particularly in higher seismic zones, and hence such studies are warranted. The present study, therefore, was undertaken to assess seismic hazard impacts of an underground tunnel structure in response to seismic activity as adumbrated by different methods. Data gathered for the last 500 years (both historical and instrumental data for the period available) revealed innumerable seismic incidences of magnitude ranging from 3.6 to 7.8 Mw between the years 1500 to 2012 in the Himalayas. This paper highlights the statistical seismology and its application in prognosticating a 7.0 Mw event within 100-year frequency which can lead to provision of corrective and control measures for one of the underground structure contemplated for communication.

Keywords: Seismology, Magnitude Location, Himalayan Region, Frequency Measure, Prognostics

1. Introduction

Aseismic design of civil structures based on seismic risk has gained importance over the past several decades across the Country. While most of the surface structures such as dams, powerhouses, multi-storeyed buildings etc based on their importance, spatial locations and the risk envisaged are subject to rigorous seismic analyses before arriving at seismic co-efficient for respective structures to render the aseismic design. However, in this country particularly large tunnels and underground caverns developed previously have not been included for seismic hazard estimation even in highest seismic zones of the country namely in Himalayas and other adjoining parts of the country. Recently it has become a healthy practice of attempting Seismic hazard assessment of underground structures and other utilities, irrespective of their sub-surface locations. While the approaches to such aseismic design can either be probabilistic or deterministic, several workers have adopted different methodologies to arrive at final measure. In this work, the authors besides compiling data on various methodologies currently in vogue have collected seismic data of 500 year period since 16th Century, for evaluating the seismic risk of a communication tunnel in Northwest Himalayas and arrived at corrective and control measures to be taken into consideration during the course of operation of the tunnel.

2. Study Area

The study area falls in Northwest Himalayan region in India between the latitudes 30°N -36°N and longitudes 72°E-78°E.

The country has been seismically categorised as V zones by Bureau of Indian Standards (BIS: 1893-2002). Zone I is omitted or deleted by BIS according to the latest revision based on the redundancy of Zone I. Zone- II is considered to be the lowest seismic intensity zone where minor damage could occur has a Z value of 0.10. Zone – III which comprises the practical seismic zone, the zone - IV which considered as an severe seismic zone, the zone - V considered as the most severe seismic zone [1,2].

3. Seismic Hazard Analysis Methods

As stated previously, seismic approaches fall in two categories viz., deterministic and probabilistic methods. The deterministic method is to determinately define the most severe earthquake that can occur in a given area causing damages. At present, probabilistic seismic hazard Assessment is more commonly and widely used. It was initially proposed by Cornell [3] and then upgraded by subsequent earthquake engineering specialists and researchers

3.1 Deterministic seismic hazard analysis (DSHA) studies include:

- Identification and classification of all earthquake parameters capable of generating substantial ground movement at the site, including definition of the geometry and size of earthquake. Reiter [4] formulated a wide-range list of features that may constitute critical parameters in a specified region.
- Selection of a monitoring earthquake which creates the severest shocking at the site, triggering ground motion limitation at the site [5].
- The seismic disaster at any site is related to the peak acceleration, velocity and displacement, spectrum response, and ground movement time history of the extreme reliable earthquake [6].

A DSHA delivers a forthright agenda for the assessment of worst-case circumstances at a site. Use the decimal system of headings with no more than three levels.

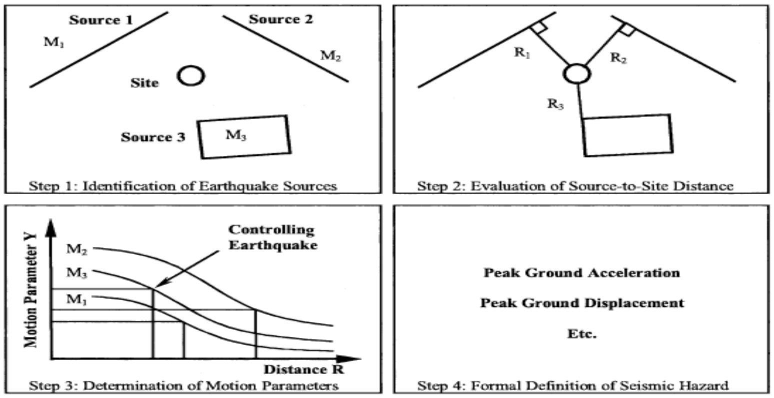

Fig. 1 - Deterministic seismic hazard analysis procedure

Source: Adopted from Wang and Zhao [6]

3.2 Probabilistic seismic hazard analysis (PSHA)

A probabilistic seismic hazard assessment arranges for a structure in which limitations in the scope, location, and reappearance rate of earthquakes can be recognised, calculated, and pooled in an equitable manner. Such an investigation provides a comprehensive portrayal of the seismic hazard at a site, where disparities in ground motion physiognomies can be unambiguously deciphered. For this category of examination, future earthquake events are presumed spatially and temporally self-governing [4].

- Identification and classification of earthquake foundations, comprising the wave propagation of possible breach locations contained in the source zone. Description of the seismicity or chronological dissemination of earthquake recurrences.
- Establishment of the ground motion developed at the site by any size earthquake happening at any source zone using diminution connections. The vagueness intrinsic in the prognostic relationship also measured.
- The amalgamation of these reservations to acquire the chance that a given ground motion stricture will surpass during a given period [6].

The probabilistic methodology integrates the reservations in the source-to-site distance, size, degree of recurrence and the variation in ground motion characteristics into the analyses. In extents where no lively faults can willingly recognise it may be essential to depend on a purely statistical investigation of historical earthquakes in the región [6].

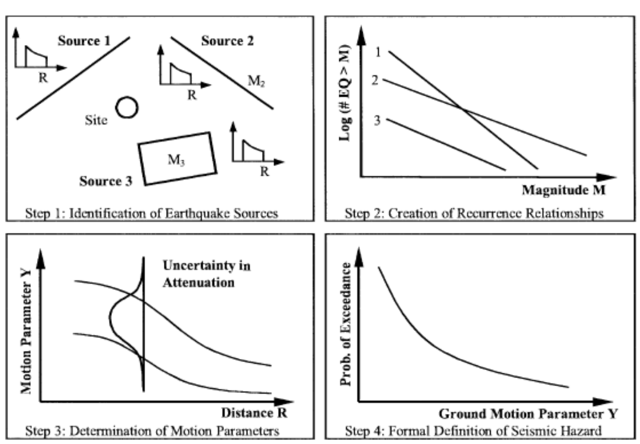

Fig. 2 - Probabilistic seismic hazard analysis procedure

Source: Adopted from Wang and Zhao [6]

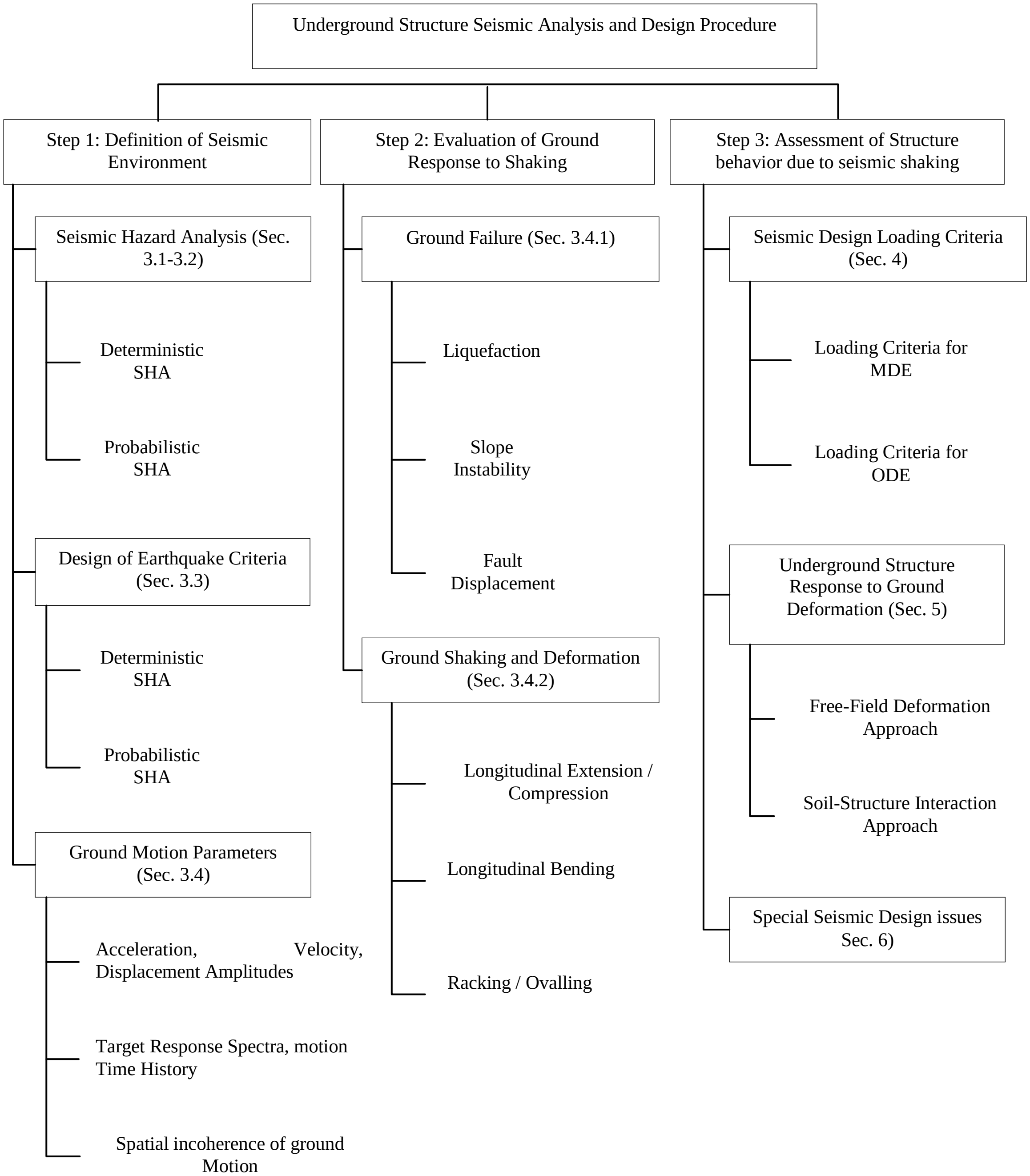

Fig. 3 - Seismic analysis and design procedures

3.3 Design earthquakes criteria

As soon as the seismic threat at the site is considered, the extent of pattern earthquake or seismicity has to be demarcated. The existing seismic design viewpoint for many precarious amenities necessitates dual-level. Design standards, with a progressive design level earthquake intended at life protection and a lesser design level earthquake, proposed for pecuniary risk exposure. Both the design levels are normally defined as ‘maximum design earthquake’ or ‘safety evaluation earthquake.'Besides ‘operational design earthquake’ or ‘function evaluation earthquake.', and have been active in many current transportation tunnel schemes [7].

3.3.1 Maximum Design Earthquake

The Maximum Design Earthquake (MDE), is classified in a DSHA as the extreme level of judging that can be experienced at the site. In a PSHA, the MDE is defined as an incident with a minor possibility of excessiveness during the life of the facility e.g. 3 to 5% [7].

3.3.2 Operating Design Earthquake

The Operating Design Earthquake (ODE) is an earthquake occurrence that can be rationally anticipated to happen at least once through the design life of the facility. In an ODE investigation, the seismic design shocking is subject to the structural presentation necessities of the structural affiliates. Since the ODE design objective is that the general system shall continue functioning during and after an ODE and experience petite or no impairment, inelastic distortions must keep to a minimum. The reaction of the underground facility should, consequently, persist within the elastic range.

3.3.3 Ground motion parameters

Once an MDE or ODE is demarcated, sets of ground motion structures are obligatory to illustrate the design proceedings. The selection of these limitations is associated to the type of investigation technique used in design. At a specific point in the ground or on a structure, ground motions can be pronounced by three translational components and three rotational components, although revolving components characteristically overlooked. A ground motion component is branded by a time history of hastening, rapidity or dislocation with three substantial parameters: amplitude; frequency content; and period of strong ground motion.

Table 1 - Ratios of peak ground velocity to peak ground acceleration at surface in rock and soil

Moment magnitude (M_w)	Ratio of peak ground velocity (cm/s) to peak ground acceleration (g)		
	Source-to-site distance (km)		
	0-20	**20-50**	**50-100**
Rock [a]			
6.5	66	76	86
7.5	97	109	97
8.5	127	140	152
Stiff soil [a]			
6.5	94	102	109
7.5	140	127	155
8.5	180	188	193
Soft soil [a]			
6.5	140	132	142
7.5	208	165	201
8.5	269	244	251

[a]In this table, the sediment types represent the following shear wave velocity range: rock ≥750 m/s; the stiff soil is 200-750 m/s; and soft soil <200 m/s. The relationship between peak ground velocity and peak ground acceleration is of less certain in soft soils.

Table 2 - Ratios of peak ground displacement to peak ground acceleration at surface in rock and soil after

Moment magnitude (M_w)	Ratio of peak ground displacement (cm) to peak ground acceleration (g)		
	Source-to-site distance (km)		
	0-20	**20-50**	**50-100**
Rock [a]			
6.5	18	23	30
7.5	43	56	69
8.5	81	99	119
Stiff soil [a]			
6.5	35	41	48
7.5	89	99	112
8.5	165	178	191
Soft soil [a]			
6.5	71	74	76
7.5	178	178	178
8.5	330	320	305

[a]In this table, the sediment types represent the following shear wave velocity range: rock ≥750 m/s; the stiff soil is 200-750 m/s; and soft soil <200 m/s. The relationship between peak ground velocity and peak ground acceleration is of less certain in soft soils.

Table 3 - Ratios of ground motion at depth at the ground surface

Tunnel depth (m)	Ratio of ground motion at tunnel depth to motion at ground surface
≤6	1.0
6-15	0.9
15-30	0.8
>30	0.7

3.4 Evaluation of ground response to shaking

The evaluation of ground response to shaking could be separated into two groups: 1. ground failure; and 2. ground trembling and distortion. This report concentrates on ground shaking and distortion, which postulates that the ground does not experience huge perpetual dislodgments. A brief summary of issues associated to the ground failure is also presented.

3.4.1 Ground failure

Ground failure as a consequence of seismic shaking includes liquefaction, slope variability, and fault disarticulation. Ground failure is predominantly dominant at tunnel portals and in superficial tunnels. Distinct design deliberations are obligatory for cases where ground failure is involved. While taking the ground failure into consideration, it is required to look for 1. Liquefaction 2. Slope characteristics prone to failures 3. Fault dislocation etc.

3.4.2 Ground shaking and deformation

In the nonappearance of ground failure that results in enormous permanent distortion, the design emphasis shifts to the fleeting ground deformation caused by seismic wave propagation. The deformation can be rather multifaceted due to the combination of seismic waves with soft surficial deposits and the development of surface waves. Underground structures can be presumed to experience three principal modes of distortion during seismic shaking: 1. compression expansion; 2. longitudinal meandering; and 3. Oval racking [7].

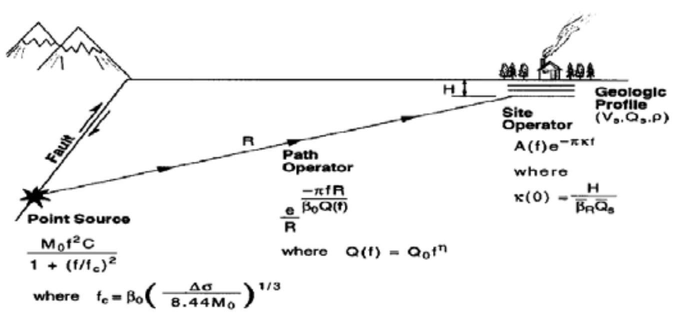

Fig. 4 - The schematic of the point source ground motion

Source: Adopted from Wong *et al*. [8]

The strictures Q and K can be considered as indeterminate variables in the seismic threat model and therefore, weakening relationships are established for a given site for the alternative Q° and K values. Because a solitary value of Q° should be fitting for approximating ground motions in the region, the choice of Q° is taken unambiguously in the hazard model logic tree (see subsequent discussions). Likewise, it understood that a single value of K is applicable for a given site. Vagueness in 'K' for a site can structured by considering a greatest approximation value and values that are ± a factor of two. Therefore, nine different stochastic associations can be industrialised for a given site [8].

$$In(Y) = C1 + C2(M-6) + C3(M- 6) + C4ln(R') + C6R \quad \text{for } R' <= 90 \text{ km}$$

$$In(Y) = C1 + C2 (M -6) + C3(M - 6)2 + C4In (90) + C5In (R' /90) + C6R \text{ for } R' > 90 \text{ km}$$

$$R' = R + \exp (C7\ C8M)$$

Diminution relationships for topmost ground hastening and peak spectral speeding up are attained by fitting the point source replications with the serviceable form [9]. Where Y is the peak ground motion stricture, M is moment magnitude (Mw), R is the shortest distance to the surface prognosis of breach and C, through cs are bounds fit to the data [8].

4. Design Criteria

4.1 Maximum Design Earthquake (MDE)

Given the performance goals of the MDE (i.e., public safety) Wang [10], the recommended seismic loading combinations using the load factor design method are as follows:

For Cut-and-Cover Tunnel Structures

$$U = D + L + E1 + E2 + EQ \tag{1}$$

Where, U = required structural strength capacity, D = effects due to dead loads of structural components, L = effects due to live loads, E1 = effects due to vertical loads of earth and water, E2 = effects due to horizontal loads of earth and water, EQ = effects due to design earthquake (MDE)

For Mined (Circular) Tunnel Lining

$$U = D + L + EX + H + EQ \tag{2}$$

Where U, D, L, and EQ as defined in Equation 2-1, EX = effects of static loads due to excavation [11], H = effects due to hydrostatic water pressure [7].

4.2 Operating Design Earthquake (ODE)

For the ODE, the seismic plan loading arrangement depends on the presentation necessities of the organisational members. Commonly speaking, if the members are meant to experience little to no injury during the lower level event (ODE), the inelastic distortions in the structure members should be kept short.

The following loading criteria, based on load factor design, are recommended:

For Cut-and-Cover Tunnel Structures

$$U = 1.05D + 1.3L + b1\ E1 + E2 + 1.3EQ \tag{3}$$

where D, L, E1, E2, EQ, and U are as defined in Equation 2-1, b1 = 1.05 if extreme loads assumed for E1 and E2 with alittle uncertainty. Otherwise, use b1 = 1.3.

For Mined (Circular) Tunnel Lining

$$U = 1.05D + 1.3L + b2\ EX + H + 1.3EQ \tag{4}$$

where D, L, EX, H, EQ, and U are as defined in Equation 2-2, b2 = 1.05 if extreme loads are assumed for E1 and E2 with little uncertainty. Otherwise, use b2 = 1.3 [7].

The load factors used in these two equations have been the subject of a lot of discussions. The final selection depends on the project-specific performance requirements [12].

5. Statistical Method Results

The statistical method is used to predict the seismic hazards, and data used in Design Earthquake methods and Statistical method analysis to find seismic shocks in a seismic zone especially, in the regions of Himalaya's.

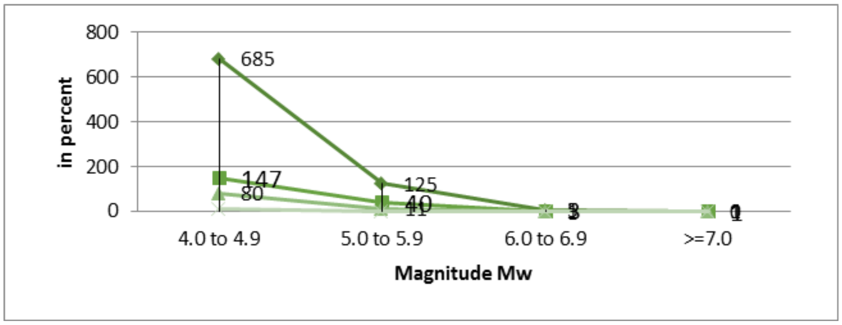

Fig. 5 - Illustrates the listing of an earthquake occurrence from the year 1500 to 2012

The occurrence of magnitude ranged from Mw 4.0 to 7.0. It found that highest frequency of events is on the non-cumulative curve with the magnitude of about 4.0 to 5.0 as high frequency as class based on the definition adopted from the magnitude completeness (Mc) this followed by 5.0 to 6.0 (5%). However, 6.0 to 7.0 (1%) has lowest frequency class.

Table 4 - Illustrates Frequency of earthquake with focal between years (1501 – 2012)

Depth (km)	**Frequency & Occurrence of Earthquake & Moment Magnitude (Mw)**			
	4.0 to 4.9	**5.0 to 5.9**	**6.0 to 6.9**	**>=7.0**
0 to 40	685	125	5	1
41 to 70	147	40	3	1
71 to 150	80	11	1	0
> 150	11	1	0	0

It observed that magnitude is of a large number of earthquake ranges between 4.0 to 4.9 at a depth of 0 to 40Km with a frequency of occurrence 685. The depth range from 41 to 70km had a frequency of occurrence 147, 71 to 150km depth range value had a frequency of occurrence 80 and greater than 150km with a frequency value of occurrence 11. However, the occurrence of Mw greater than 7.0 was observed to be the least which occurred during 1905 at a focal depth of 50km depth.

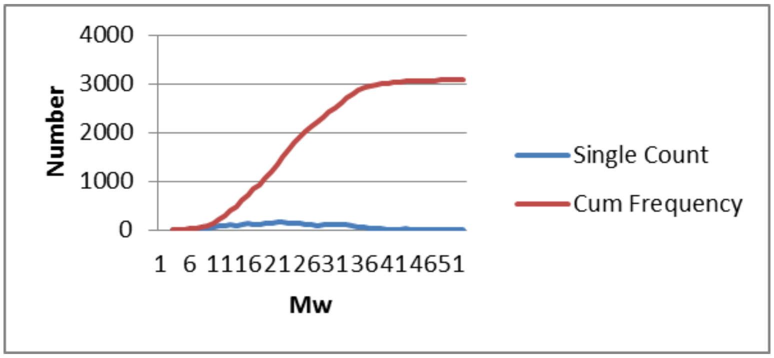

Fig. 6 - Illustrates the event occurrence from the year 1964-2012 with Mw 1.6-7.8

From this, it identified that there is an occurrence of about 1648 events with a magnitude of Mw 3.6 to 7.8 between the years 1964 to 2012. The b-value analysis was used to determine the crustal heterogeneity and precursory trend in the seismic zones. The b-value data segmented into four following time domains (1501 to 1963, 1964 to 1980, 1981 to 1992 and 1993 to 2012).

Table 5 - Temporal variation in b-value in the epicentral block

Year	**b-Value**
1501 to 1963	0.42
1964 to 1980	0.64
1981 to 1992	0.35
1993 to 2012	0.23

Table 2 illustrates the b-value sequence in the seismic zone, in which the highest peak value was identified between the intermediate-term recovery precursors from 1964 to 1980 with a b-value 0.64. This is followed by b-value 0.35 (1981 to 1992) and 0.42 (1501 to 1963).

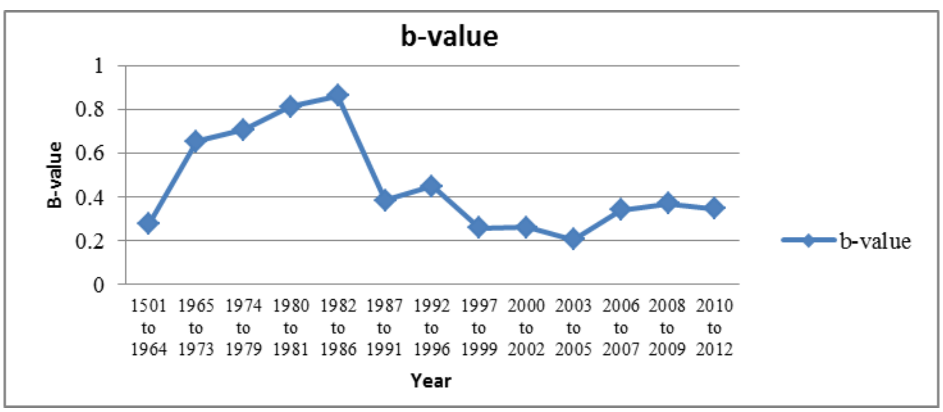

Fig. 7 - Temporal variation in b-value in the epicentral block

The least value is observed between the years 1993 to 2012 with a value of 0.23 and the same is shown in figure 7 when the average calculated, the uniform distribution was observed to be low b-value of 0.38 across the region. Higher b-value indicates intermediate-term recovery precursor while high b-value is often correlated with temporal quiescence (See Meredith et al. [13]. It observed, the higher value observed in 1982 to 1986 with b-value of 0.86, while lower at 0.21 during 1997 to 1999.

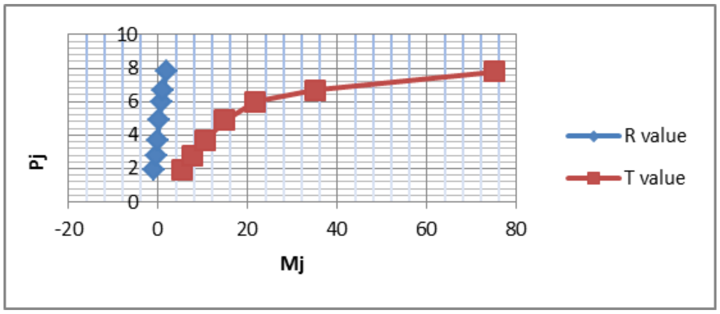

Fig. 8 - Forecast of maximum magnitude with return period

The above figure illustrates the forecasting from which it is clearly established the increase in time is directly proportional to the magnitude value (Mj) i.e. increase in time interval increases the Mj. The findings indicated that a probability event occurrence is about Mw>7.0 in the next 100 years.

Table 6 - Correlation between Year, Lat (Deg), Long (Deg), Depth (km) and MW

		Year	**Latitude(Deg #N)**	**Longitude(Deg#E)**	**Depth (km)**	**Mw**
Year	r-value	1	-.022	-0.59**	-.270**	-.425**
Latitude (Deg #N)	r-value	-.022	1	-.190**	.272**	.430**
Longitude(Deg #E)	r-value	-0.59**	-.190**	1	.032	-.129**
Depth (km)	r-value	-.270**	.272**	0.31	1	208*
Mw	r-value	-.425	.430**	-.127**	.208**	1

*p<0.05; **p<0.01, ***p<0.001

** Correlation is significant at the 0.01 level (2-tailed)

From the Table 6, it is evident that latitude is significantly related to depth (r = 0.272) and Mw (r=0.430). Additionally, the depth is also significant and positively associated with Mw (r = 0.208). However, in the correlation analysis, years are significant but negatively correlated with long (r= -0.059), depth (r = -0.270) and Mw (r = -0.428). The negative value indicates whenever, the year advances there is a remarkable decrease in the focal parameters (Lat, Long, Depth and Mw). Moreover, latitude is also found to have a negative correlation with the variables of longitude (r = -0.190). Finally, the longitude is significant but negatively associated with Mw (r = -0.129).

6. Discussion and Conclusion

The study analysed the seismic threat in the western Himalayan region where the extreme capable earthquake assessed during 1500 to 2012 which was done through a statistical prototype. The current work deals with extreme value statistics method to calculate the maximum magnitude (Mw) for next sequential 200 years of time intermission where earthquake statistics from the period ranging from 1500–2012is accounted. From the investigation, it is found that there is a probability of earthquake incidence with a Maximum Magnitude momentum more than 7.0 i.e. (Max Mw>7.0) in the next 100 years of the research location. With assumed magnitudes for next 100 years, it will be desirable to deliver seismic constant equivalent with maximum magnitude value of seven (Mw = 7). The outcomes displayed the upsurge in the incidence of earthquakes at a larger magnitude over the period of the years 1500 to 2012 in India. It also embarks that 7.0 Mw frequency would be the maximum value for underground passageways to survive a hazard over 100 years of the period.

7. Acknowledgement:

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