

Seismicity of region around dams in North West India

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(Received 21 May 2010, Modified 06 April 2011)

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सार – भूविज्ञानिक इतिहास में भारतीय और यूरोशियाई महाद्वीपों के टकराव के कारण दोनों महाद्वीपों के बहुत बड़े इलाके में बड़े पैमाने पर विरूपण और उच्च भूकंपनीयता के लक्षण बने। 1905 में कांगड़ा में आया भूकंप, 1991 में उत्तरकाशी में आया भूकंप और 1999 में चमोली में आए भूकंप के भ्रंश क्षेत्रों के अंतर्गत आने वाले हिमालय के उत्तरी-पश्चिमी भाग में 06 और उससे अधिक के परिमाण वाले अनेक भूकंप आए। विभिन्न वैज्ञानिकों द्वारा हिमालय के उद्गम से अब तक 30.0° – 35.0° उत्तर तथा 73.0° – 79.0° पूर्व के बीच उत्तर पश्चिम भारत के क्षेत्र में गहन जाँच की जा रही है। भारत मौसम विज्ञान विभाग ने साठ के दशक के आरम्भिक वर्षों में बाँध प्राधिकारियों की विशिष्ट माँग पर पंजाब/हिमाचल प्रदेश में भाखड़ा, पाँग, पंडोह बाँध तथा जम्मू एवं कश्मीर में सलाल बाँध में 13 भूकंपीय वेधशालाएँ खोली। इन वेधशालाओं ने इस क्षेत्र में 2 परिमाण से कम के भूकंपों का रिकॉर्ड किया है। हिमाचल में भूकंपनीयता और विवर्तनी की जाँच करने के उद्देश्य से वैज्ञानिकों के लिए पिछले दो दशकों के आँकड़ें अत्यंत उपयोगी हैं। इस अध्ययन से भूकंपनीयता के लिहाज से अत्यधिक सक्रिय और भूकंपीय अंतर के क्षेत्रों का भी पता लगाने में मदद मिलेगी। इस प्रकार इस अध्ययन से इस क्षेत्र में भूकंपीय गतिविधि के मेन बांडूज़ी थ्रस्ट (एम. बी. टी.) और मेन सेंट्रल थ्रस्ट (एम. सी. टी.) नामक दो मुख्य भ्रंश प्रणालियों के साथ संबंध की पुष्टि होती है। प्रत्येक बाँध से 100 कि. मी. के भीतर तुलनात्मक भूकंपीय गतिविधि से पता चला है कि पाँग के आस-पास का क्षेत्र अत्यधिक सक्रिय रहा और उसके बाद पंडोह, भाखड़ा और सलाल बाँध रहे। संपूर्ण अवधि के लिए b-मानों की कालिक विविधता से भी पता चला है कि लो b-मान विसंगतियाँ सामान्यतः $M > 5.5$ के बड़े भूकंपों के बाद होती हैं। बाँध के स्थानों के आस-पास प्रेक्षित भूकंपीय गतिविधि के साथ जलाशयों में जल के स्तर में उतार-चढ़ाव के मध्य किसी निश्चित परिणाम का पता नहीं चला है।

ABSTRACT. The collision of Indian and Eurasian continents caused large scale deformation and high seismicity of vast areas of both continents in the geological history. The North-West portion of the Himalayan arc which is lying under the rupture zones of Kangra earthquake of 1905, Uttarkashi earthquake of 1991 and Chamoli earthquake in 1999, has experienced many earthquakes of magnitude 6 and above. The region of North-West India between 30.0° - 35.0° North and 73.0° - 79.0° East is, therefore, under intense investigations by various scientists since the origin of the Himalayas. India Meteorological Department had opened thirteen seismic observatories in early sixties for monitoring of earthquake activities in and around Bhakra, Pong, Pandoh dams in Punjab / Himachal Pradesh and Salal dam in J&K on specific demand of the dam authorities. These observatories have recorded the earthquakes occurred in this region having magnitude even less than 2. The data collected for the last two decades is very useful for the scientists to investigate seismicity and tectonics of the Himalayas. The present study could locate the regions which are seismically most active and also the region of seismic gap. Thus present study confirms association of seismic activity in the region with two major fault systems called Main Boundary Thrust (MBT) and Main Central Thrust (MCT). Comparative seismic activity within 100 km from each dam, reveal that most active region was around Pong followed by Pandoh, Bhakra and Salal dams. The temporal variation of b-values for the whole period also shows that low b-value anomalies are usually followed by large earthquakes of $M > 5.5$. No definite conclusions could be drawn with regard to the relationship between the observed seismic activity around the dam sites with the corresponding water level fluctuations in the reservoirs.

Key words – Main boundary thrust (MBT), Main central thrust (MCT), Collision, Seismicity, Reservoir induced seismicity.

1. Introduction

The seismicity and tectonics of the Himalayas have been under intense investigation by the scientists in the

past due to the fact that Himalayas is believed to be result of ongoing collision of Indian and Eurasian continents (Umesh Chandra, 1992). It is a fact that occurrence of earthquakes causes damage, destruction and death. The

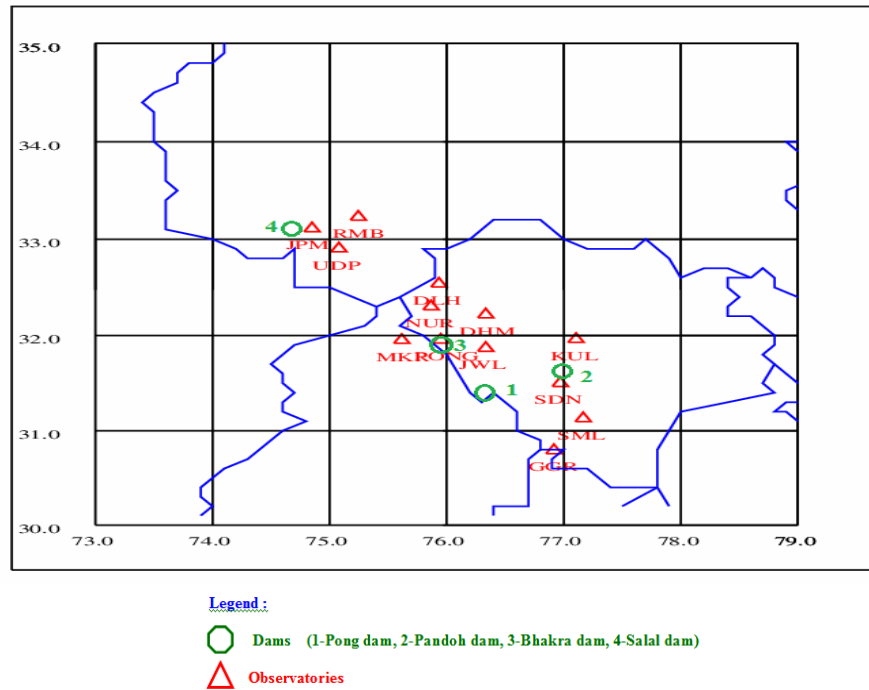


Fig. 1. Location map of dams and observatories

amount of destruction, however, depends on the location of the epicenter, time of occurrence and the magnitude of the earthquake. It may increase many fold if the earthquake occurs in or near the dam site. Not only it damages the solid concrete dam, an expensive structure, but also it directly affects the economy of the region affecting power generation, flood control and irrigation. Indeed, in various countries major dams are located in areas that in past have suffered from great earthquakes. In India also all the four dams, *i.e.*, Bhakra, Pong, Pandoh and Salal dams in North West Himalayan region are located very near to Main Boundary Thrust (MBT), Main Central Thrust (MCT) and some local faults of the region (Srivastava *et al.*, 2001). The likelihood of future damaging earthquakes in the study zone may not be over ruled as the region has experienced some large earthquakes in the past.

To ensure the continual safety of dams, the geological conditions near the site including landslides and faulting must carefully be taken into consideration. Evaluation of the induced seismicity around the dams is also taken in this study. Pong, Pandoh, and Bhakra dams of BEAS project in Himanchal Pradesh & Punjab and Salal dam of SALAL project in J & K are under study since 1963. IMD has set up a close network of 10 seismological observatories for monitoring Pong, Pandoh, and Bhakra dams and 3 observatories for Salal dam (Fig. 1).

The motive of the project is to study induced seismicity, monitoring and keeping watch on activities of existing faults in the region between Lat. 30.0° to 35.0° North and 73.0° to 79.0° East comprising of Pong, Pandoh, Bhakra and Salal dams and to assess the earthquake hazards. The Data for the period of 25 years from 1977 to 2002 recorded by the network of project observatories and observatories under National Seismological Network functioning in and around the study areas which are maintained by India Meteorological Department, has been used to study the seismicity and tectonics of the region. A similar study was carried out by Solarino *et al.*, 2002 by utilizing data of a network and evaluated seismicity of Garfagnana – Lunigianna (Tuscany, Itali).

2. Seismic background and tectonic features

The thrusts and faults in this region have been shown in Fig. 2. The intra plate tectonic theory is now well known and could explain the causes of major earthquakes. This region is seismically very active in the Alpidic belt. The collision of Indian and Eurasian plates resulted in the formation of Himalaya. The collision is continuous and north-eastward convergence of Indian plate with Eurasian plate produced crustal thickening along the entire length of Himalaya, giving rise to various thrusts, folds,

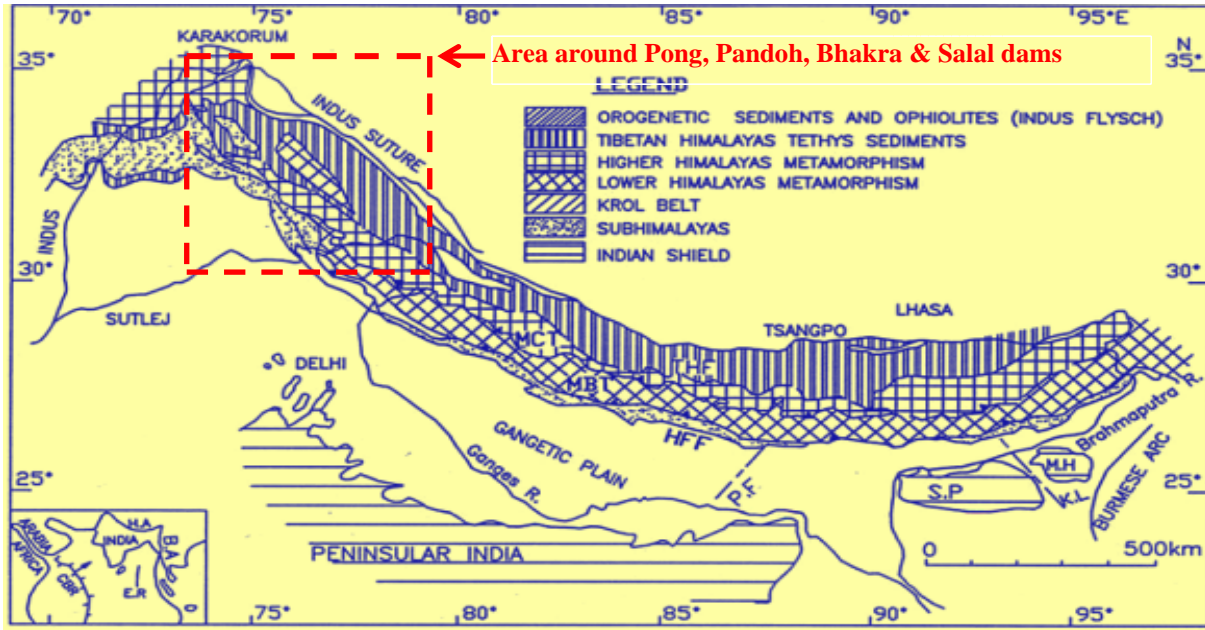


Fig. 2. Map showing major and other thrusts and faults in the Himalayan arc region

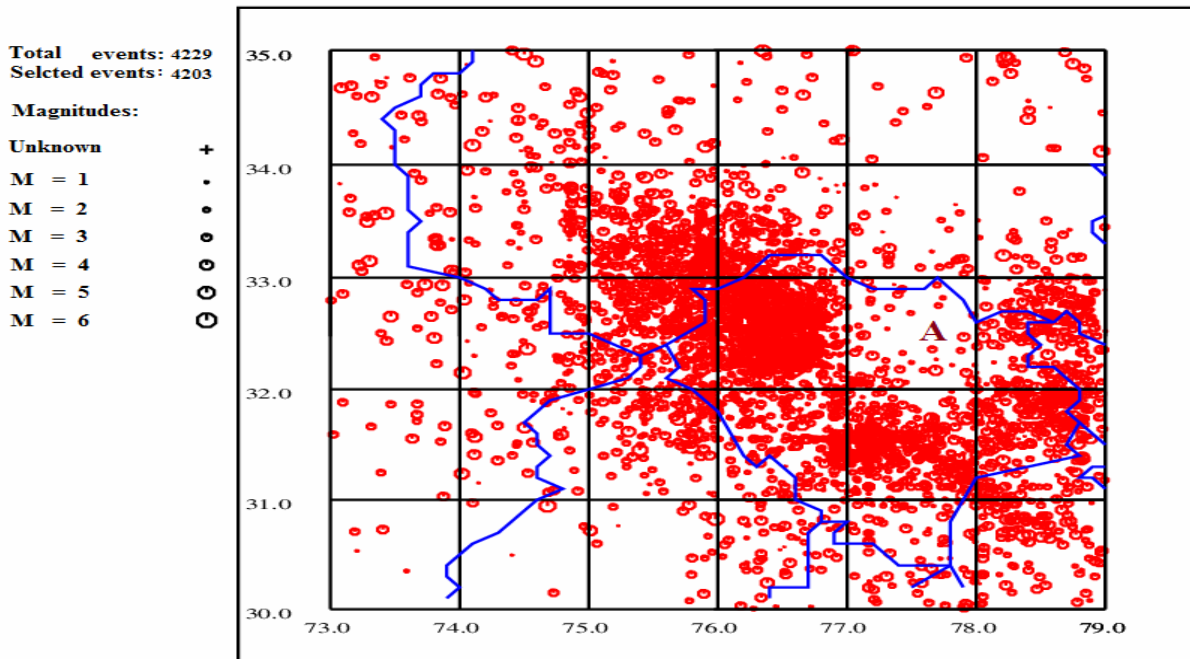


Fig. 3. Magnitude-wise distribution of epicenters of earthquakes occurred in Beas - Salal region (from October 1977 to September 2002)

repeated deformation and regional metamorphism (Srivastava *et al.*, 2000). There are two well-established major faults in the region under study and presently these are active. One of them is Main Boundary thrust (MBT) which passes through Ramban (RBN),

Dalhousie (DLH) and Sunder Nagar (SDN) in the project areas. The other one is Main Central Thrust (MCT), the track of which lies very close to MBT near Long. 76.0° East to the south of MBT in the Jammu area of Himalaya.

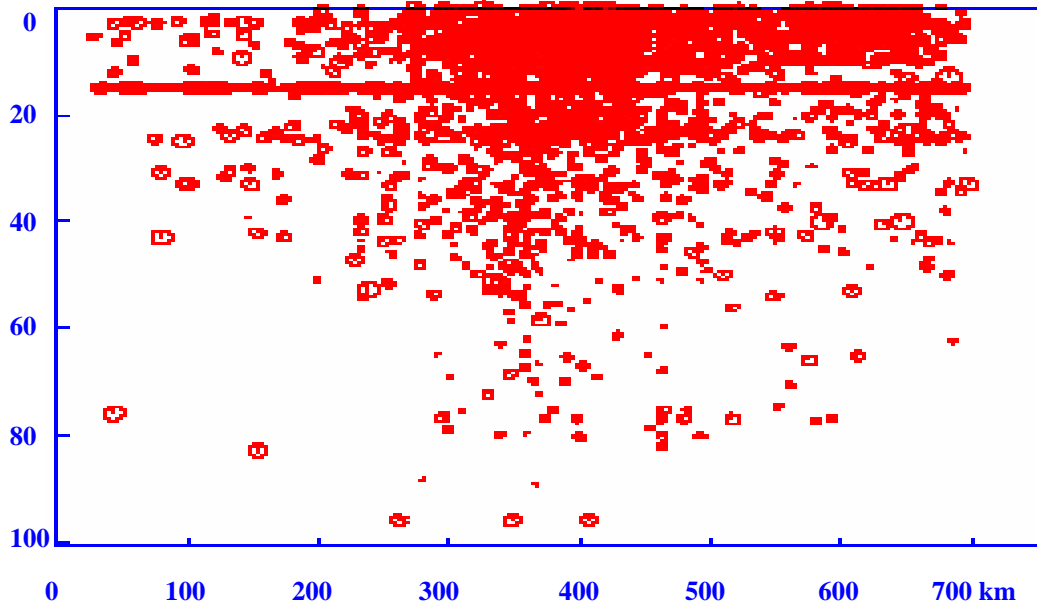


Fig. 4. Depth - wise profile of the earthquakes in the Beas-Salal region

In addition, there is a narrow zone of structure belt of the Himalayas between Punjab thrust and Muree thrust and is called Shali structure belt. Major earthquakes of Magnitude 8.0 and above occurred along the MBT. Kangra earthquake of 1905 ($M_b = 8.0$), Bihar-Nepal earthquake of 1934 ($M_b = 8.3$), and Assam earthquake of 1950 ($M_b = 8.5$) are some great earthquakes of India. Out of these, Kangra earthquake occurred in the close vicinity of the zone of consideration.

3. Data analysis and interpretation

All the located earthquakes during the period October 1977 to September 2002 were scrutinized and a plot of epicenters was prepared using SEISAN software. Fig. 3 shows the magnitude-wise location of epicenters of the earthquakes (Marcia *et al.*, 2001) while Fig. 4 depicts the depth section of the earthquakes in the region.

A very thick cluster of events is noticed from Fig. 3 which is to the north of Pong dam. Another cluster is seen south of Pandoh dam and east of Bhakra dam. Two more smaller clusters are also seen to the east of all the three dams, beyond 100 km. It is observed that most of the earthquakes in this region occurred along MBT and MCT.

It is also noticed from these maps that the area marked by 'A' between Lat. 32° North & 33° North and Long. 77° East & 78° East is devoid of any significant

seismic activity. In seismological parlance, it is called as a 'Seismic Gap'. This gap is continued as evident from epicentral map plotted during the period from 1965 to 1989 (Srivastava, 2004). The catalogue of earthquakes of 200 years for Indian region shows that no damaging earthquake has occurred in the gap 'A' (Srivastava *et al.*, 1979). The gap is nearest to Pandoh dam (about 60 km) in comparison to other dams.

A moderate earthquake of magnitude 6.6 occurred on 20th October 1991 in Uttarkashi area at a distance of about 205 km. from Pandoh dam; this was the largest magnitude event in the area during last 25 years. The shock was widely felt in the adjoining northern states of Punjab, Himachal Pradesh, Jammu & Kashmir, U. P. Haryana and the union territory of Delhi and caused widespread damage to the life and property in Uttarkashi, Nainital, Pauri Garhwal, Dehradun and also Sirmour district of Himachal Pradesh. Severe damage occurred in about 2100 sq. km area. A total of 760 people lost their lives due to this earthquake. Another earthquake of magnitude 6.8 occurred in Chamoli area (away from this study area) on 29 March 1999 which had also caused widespread damage to life & properties.

The yearly frequency of occurrence of earthquakes (Bhattacharya *et al.*, 1986) of magnitude range 2.0 to 6.6 located in the study area of 30° to 35° North and 73° to 79° East is shown in Fig. 5. It may be seen that the maximum number of earthquakes occurred during the period 1978 to 1984 and the

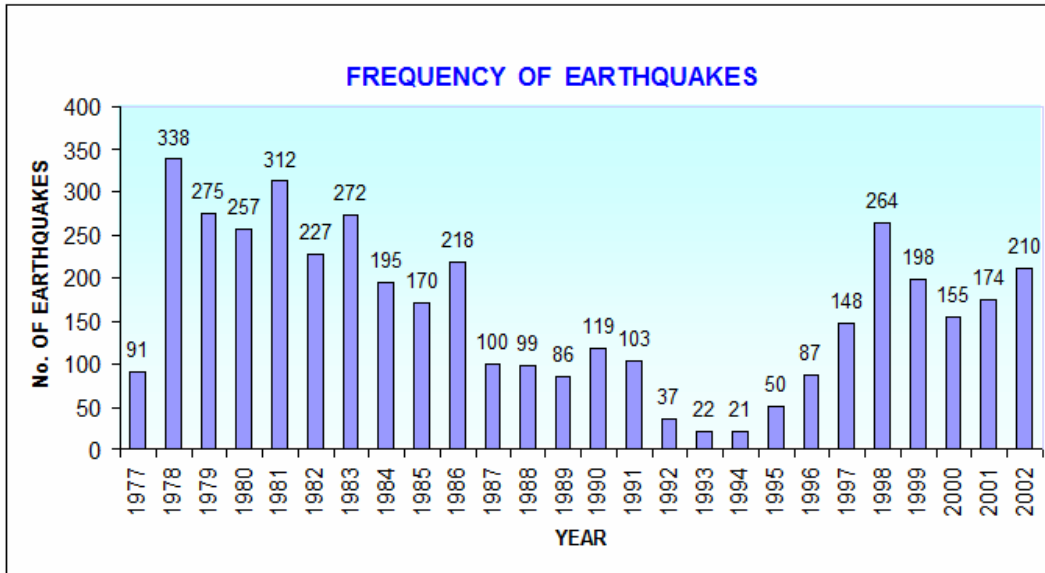


Fig. 5. Histogram showing annual frequency of earthquakes occurred during 1977-2002

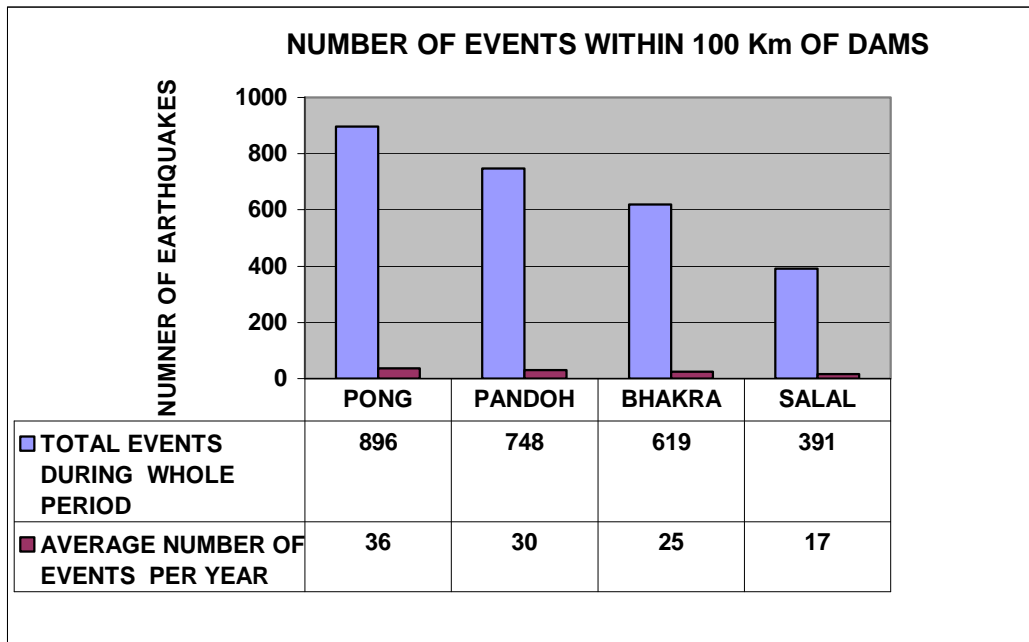


Fig. 6. Histogram showing number of events located within 100 km from dams during period from 1977 to 2002

minimum during the period 1992 to 1996. It is also seen that the maximum number of earthquakes occurred at a depth less than 25 km and a very few number of earthquakes occurred at a depth of 80 km or more (Fig. 4).

A comparison of seismic activity around 100 km of each dam under Beas-Salal projects during the entire period of 1977-2002 is shown in Fig. 6. It may be seen from Fig. 6 that the maximum seismic activity was around Pong dam and minimum seismic activity was

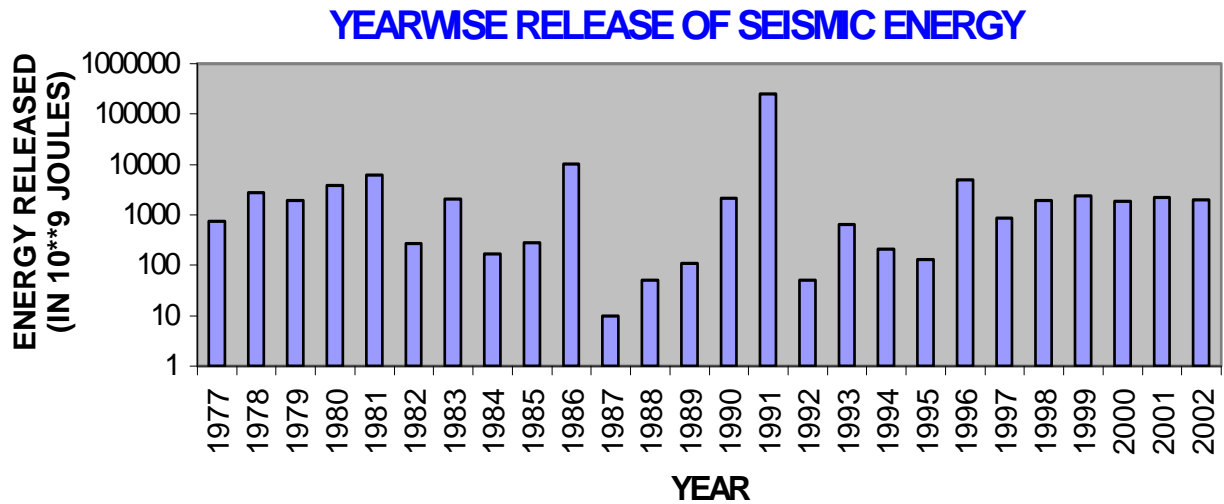


Fig. 7. Histogram showing year - wise release of seismic energy during period from 1977-2002

around Salal dam. The order of seismic activity dam- wise is Pong, Pandoh, Bhakra, Salal. Here, the statistical criteria, to distinguish reservoir-associated seismicity from normal tectonic earthquakes are discussed in comparison to other dams as published by Srivastava, *et al.*, 1991, 2004.

If 100 km area around the dams is considered, we find that the area around the Pong dam is seismically most active where 896 earthquakes occurred during the period 1977-2002 as compared to the region around Salal dam, which was found least active where only 391 earthquakes could be located.

3.1. Seismic Energy : Release

Both the magnitude and the seismic moment are related to the amount of energy that is radiated by an earthquake. Richter, working with Dr. Beno Gutenberg developed a relationship between magnitude and energy:

$$\text{Log}_{10} E = 9.9 + 1.9M_L - 0.024 M_L^2$$

This relationship enables estimation of the energy (E) in ergs from the magnitude M_L . Note that energy (E) is not the total "intrinsic" energy of the earthquake, but it is only the amount radiated from the earthquake as seismic waves, which ought to be a small fraction of the total energy transferred during the earthquake process.

The yearly release of seismic energy for the period 1977 to 2002 for the earthquakes of magnitude (M_L) 2.0

and above covering the study region Lat. 32° North & 33° North and Long. 77° East & 78° East, calculated on the basis of above formula and plotted in Fig. 7.

The annual release of seismic energy over the whole period does not deviate much from average value, except for a few peaks in 1981, 1986, 1991 and 1996 and a low in 1987. These peaks may be attributed to the occurrence of large magnitude events during the corresponding years.

It is also clear that when earthquakes of higher magnitude occurred, the release of seismic energy increases considerably. This is very clearly seen from the main peak in 1991 (due to Uttarkashi Earthquake) and other significant peaks in 1981, 1986 and 1996.

3.2. Frequency – Magnitude relationship of earthquakes

For the seismically active regions between 30° to 35° North and 73° - 79° East, a relationship between frequency and magnitude of earthquakes for the period 1977-2002 is given by the following empirical formula:

$$\text{Log}_{10} N = a - b * M$$

Where N is number of earthquakes with magnitudes $M \pm \Delta M$ and a, b are constants.

The slope of the regression line, represented by 'b'-value is a very significant parameter in understanding the regional seismicity. The relationship also suggests that

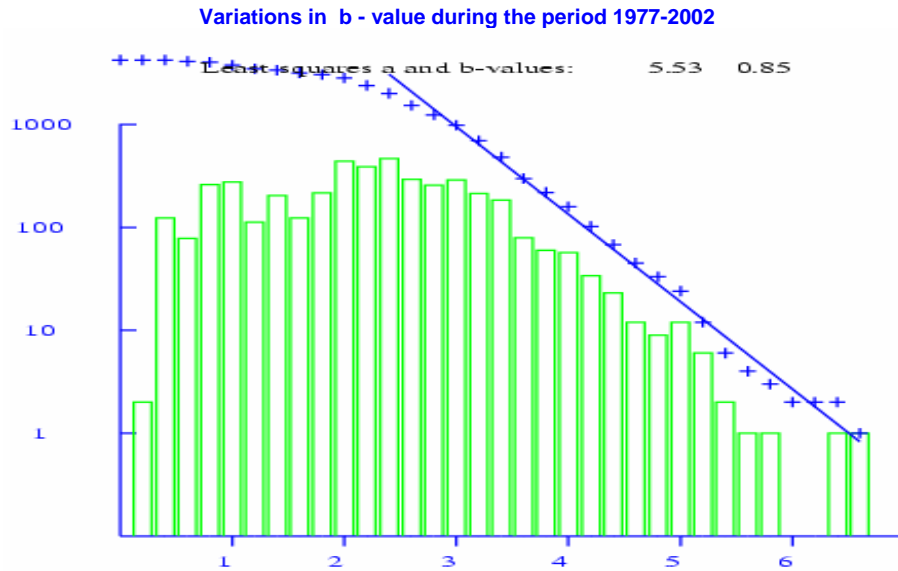


Fig. 8. Frequency magnitude relationship plot

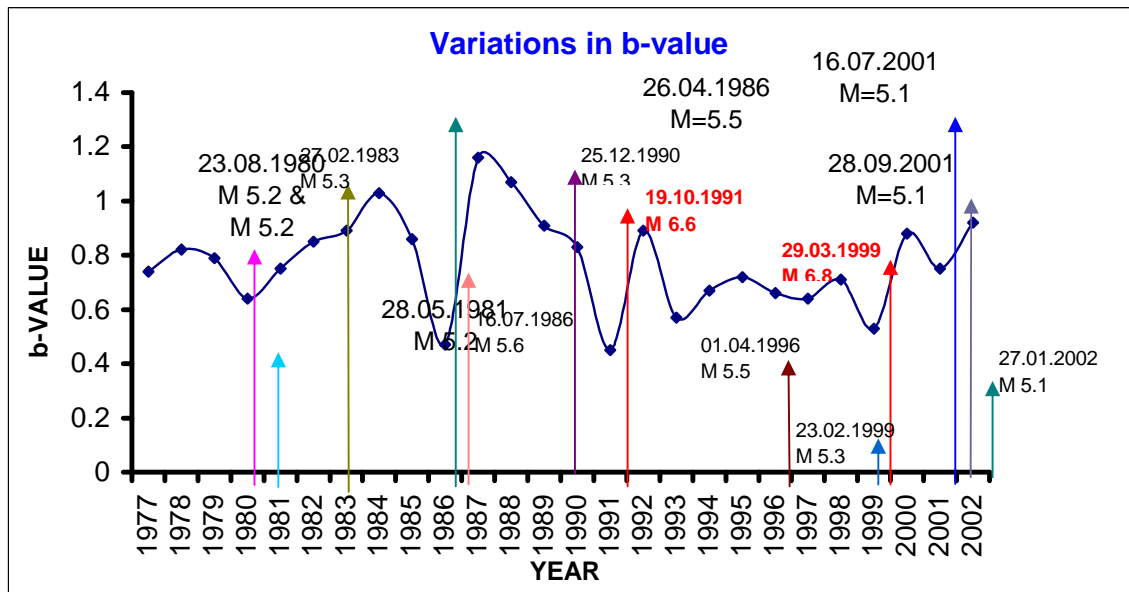


Fig. 9. Plot of temporal variations in b values for the region 30° to 35° N and 73° to 79° E during the period from 1977 to 2002

smaller magnitude earthquakes occur much more frequently than larger ones. The b-value is generally found to vary between 0.8 to 1.2 for a wide variety of regions with an average value of 1.0.

A plot of frequency magnitude relationship of all the located earthquakes for the entire region is shown in Fig. 8. The estimated variation of b-value for the whole period is 0.85, which is close to the normal value of 1.0. This implies that the area is under stress and generates

earthquakes of lower magnitude in time and space as expected in seismically active regions. However, stress released by occurrence of smaller earthquakes is insignificant in comparison to the accumulated stress due to plate movement. The stresses so accumulated are released only by intermittent medium/large earthquakes such as Uttarkashi earthquake of 1991.

It may also be seen from the b-value graph (Fig. 8) that the network of BBMB observatories equipped

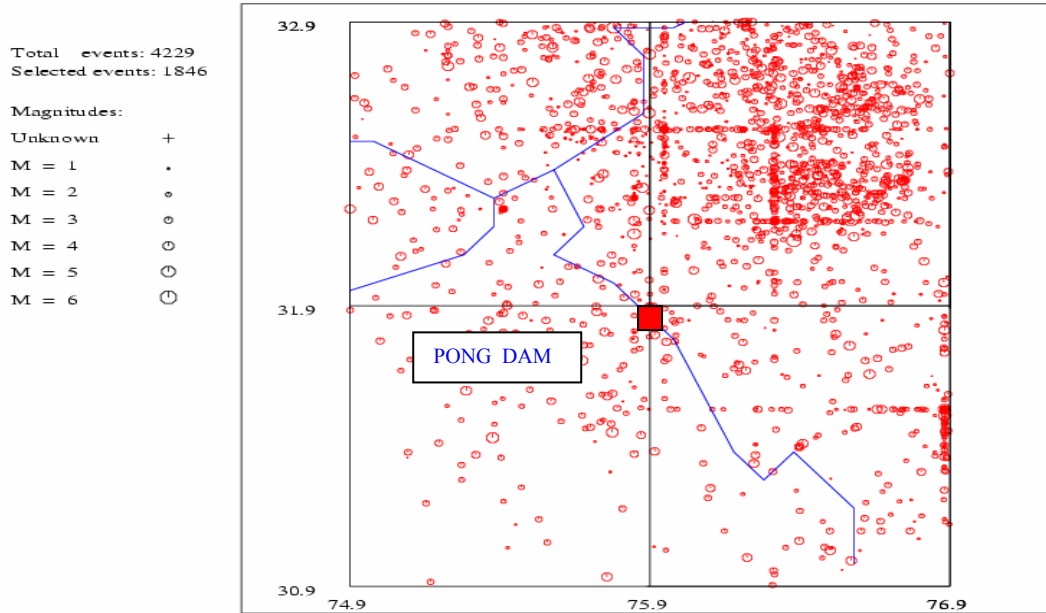


Fig. 10. Map showing epicenters around Pong dam during the period 1977-2002

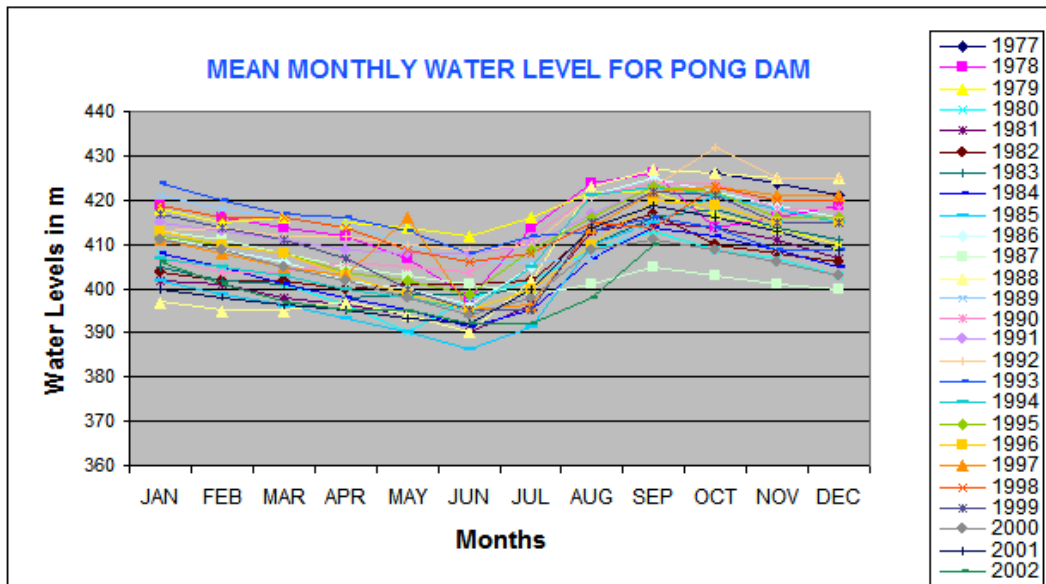


Fig. 11. Mean monthly reservoir water level at Pong dam

with analog seismographs is not capable of locating all the earthquakes of magnitude less than 2.5. The temporal variation of *b* - value (year wise) for the whole period is shown in Fig. 9. It is observed that whenever there is a sharp change in *b* values (descending), in most of the cases, it lead to the occurrence of earthquake of magnitude greater than 5.0. This complies with the results of studies published on changes in *b* - values and occurrence of earthquakes and similar to the study of Srivastava *et al.*,

1979. It is prominently evident for Uttarkashi (1991) and Chamoli (1999) earthquakes and even in the case of 1986 earthquake.

3.3. Seismic activity around Pong dam

All the epicenters of the earthquakes, which occurred during the period October 1977 to September 2002 around Pong dam are plotted in Fig. 10. This epicentral map

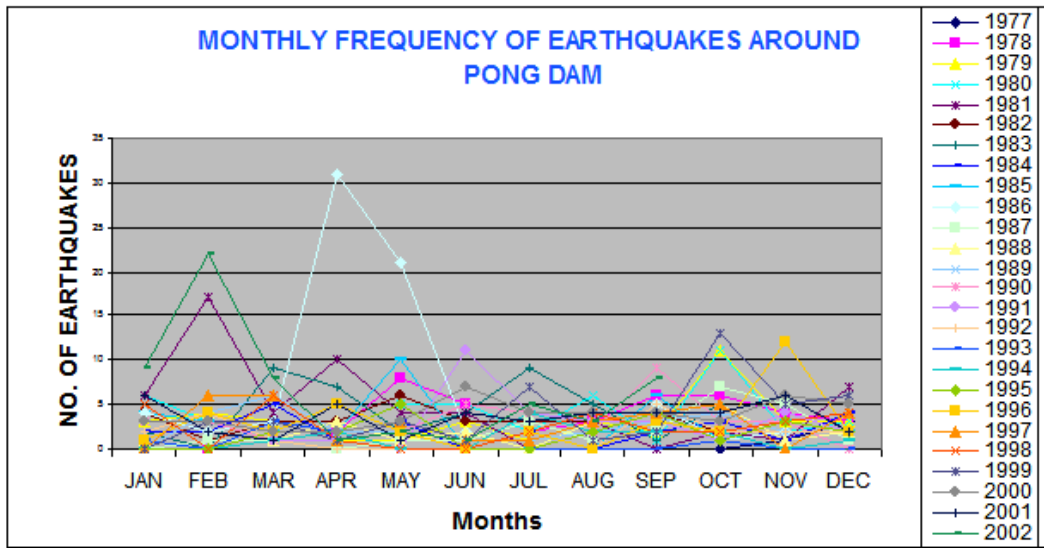


Fig. 12. Frequency of earthquakes around Pong dam

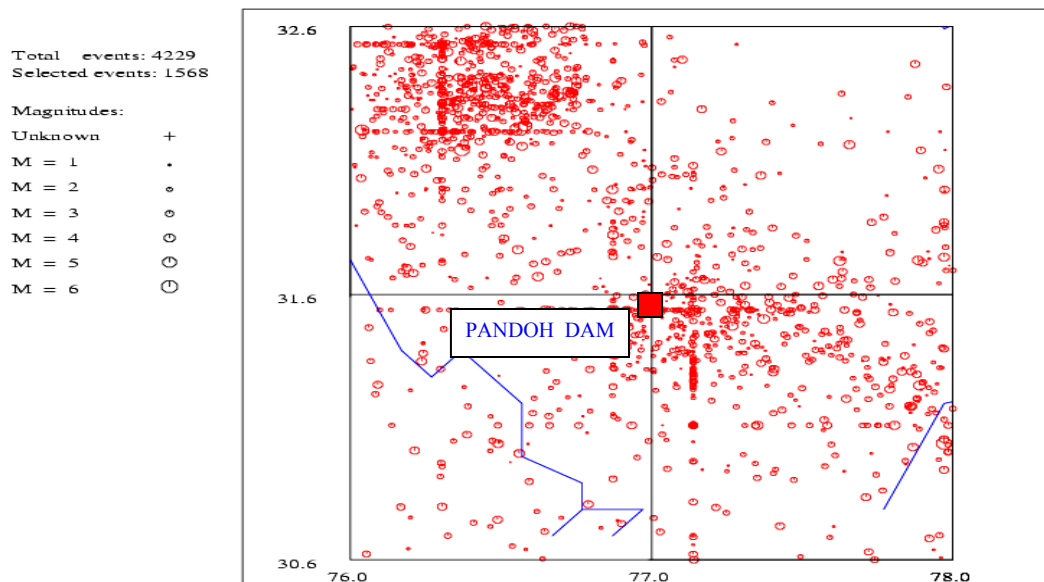


Fig. 13. Map showing epicenters around Pandoh dam during the period 1977-2002

shows that the area in the North and North East of Pong dam is very active.

Considering the area within 100 km of the vicinity of the dam, it may be seen that a thick cluster of earthquakes is present on the northeastward of the dam site. The same was found in the study of Srivastava *et al.*, 1982 and 1990. A total of 894 earthquakes (≥ 2.0) have been recorded by the seismographs in this region including one having highest magnitude of 5.5 which occurred on 26th April 1986 at a distance of 53 km North-East ward of the Dam. Another earthquake with a

magnitude of 5.4 occurred on 14th June 1978 at a distance of 78 km from the dam.

There are eighteen earthquakes which occurred within 15 km. from the dam and the nearest one occurred on 15th February 1989 at a distance of 2 km from the dam with a magnitude of 2.8.

To examine the relationship between the seismicity and the reservoir loading (Hassoup, 2002), mean monthly water levels of Pong dam and monthly number of earthquakes around the Pong dam are plotted in Fig. 11

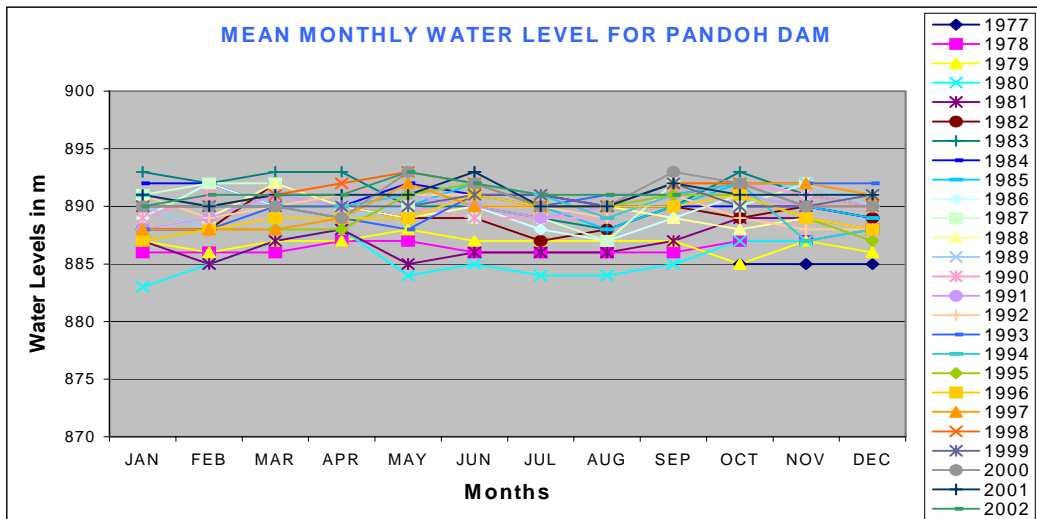


Fig. 14. Mean monthly reservoir water level of Pandoh dam

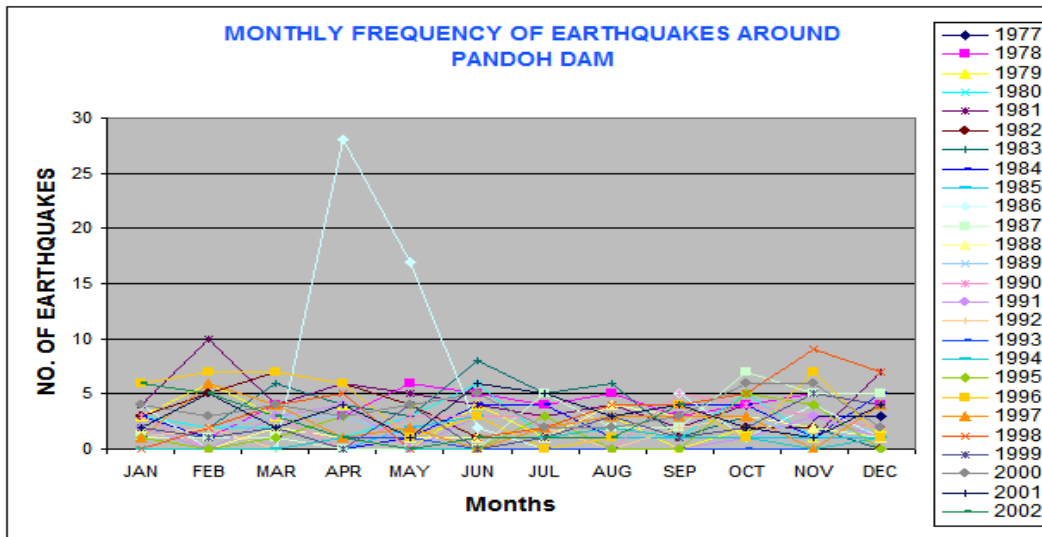


Fig. 15. Frequency of earthquakes around Pandoh dam

and Fig. 12 respectively for the whole period of 1977-2002. A prominent peak in the year 1986 and two smaller peaks in the years 1983 and 1981 are noticed in Fig. 12 which may be attributed to the increased earthquake activity of smaller magnitudes ranging between 2.0 to 3.5. However, no firm correlation between water level and occurrence of earthquakes around Pong dam could be established.

3.4. Seismic activity around Pandoh dam

All the epicenters of the earthquakes, which occurred during October 1977 to September 2002 around Pandoh

dam have been plotted in Fig. 13. This map shows that most of the activity is confined towards South, South East and North West of the dam site.

There are 747 earthquakes (≥ 2.0) within 100 km radius around Pandoh dam. There are two earthquakes having magnitude 5.0 or more which occurred on 14th June 1978 (M 5.4) at a distance of 80 km from the dam and another on 26th April 1986 with magnitude 5.5 at a distance of 83 km from the dam.

There are thirty seven earthquakes, which occurred within 15 km of the dam. The nearest earthquake with

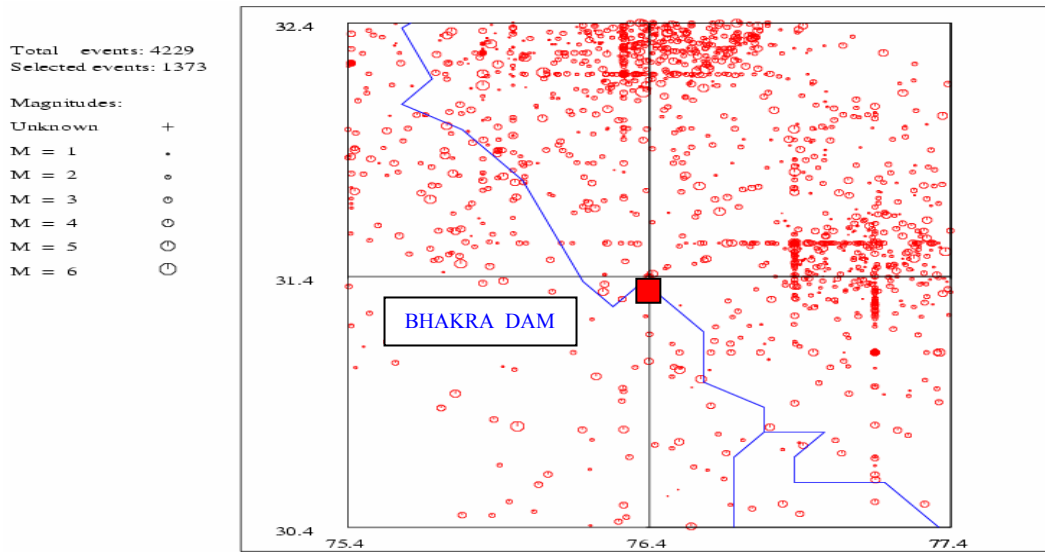


Fig. 16. Map showing epicenters around Bhakra dam during the period 1977-2002

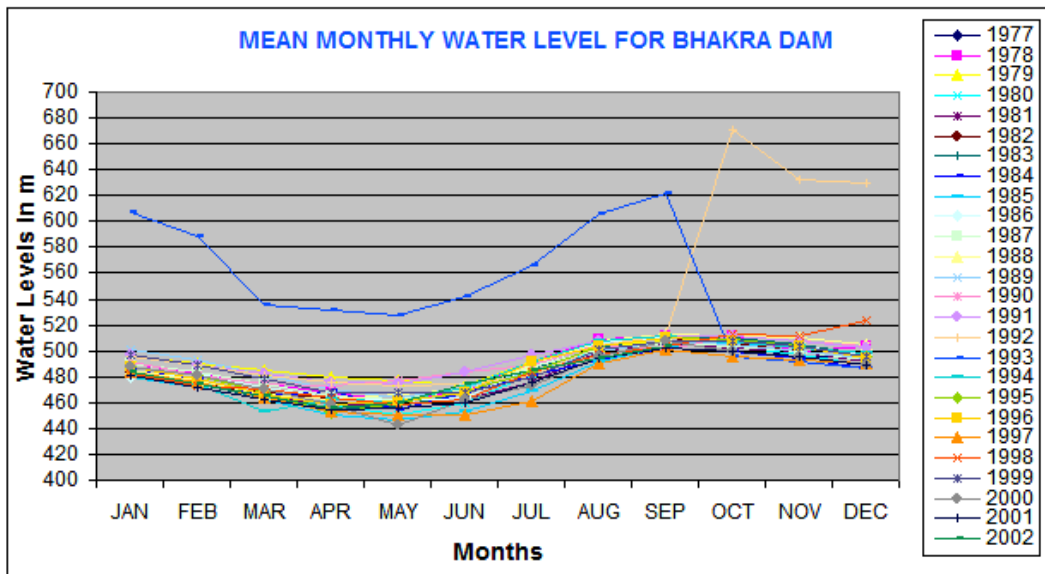


Fig. 17. Mean monthly reservoir water level of Bhakra dam

magnitude 3.0 occurred on 12th March 1990 at a distance of 3 km in the South East direction from the dam.

To examine the relationship between the seismicity and the reservoir loading (Hassoup, 2002), mean monthly water levels of Pandoh dam and monthly number of earthquakes around the Pandoh dam are plotted in Figs. 14 & 15 respectively for the whole period of 1977-2002. A prominent peak was noticed in the year 1986 in Fig. 15 which may be attributed to the increased earthquake activity of smaller magnitudes ranging between 2.0 to 3.5. However, no firm correlation between water level and occurrence of earthquakes around Pandoh dam could be established.

3.5. Seismic activity around Bhakra dam

All the epicenters of the earthquakes, which occurred during October 1977 to September 2002 have been plotted in Fig. 16. This epicentral map shows that the earthquake activity is mostly confined towards North and East side of the dam site.

There are 608 earthquakes of magnitude 2.0 and above within 100 km of the Bhakra dam recorded by seismographs in this region. It may be seen that majority of earthquakes have occurred away from the dam and associated with MBT. The same was found from the study

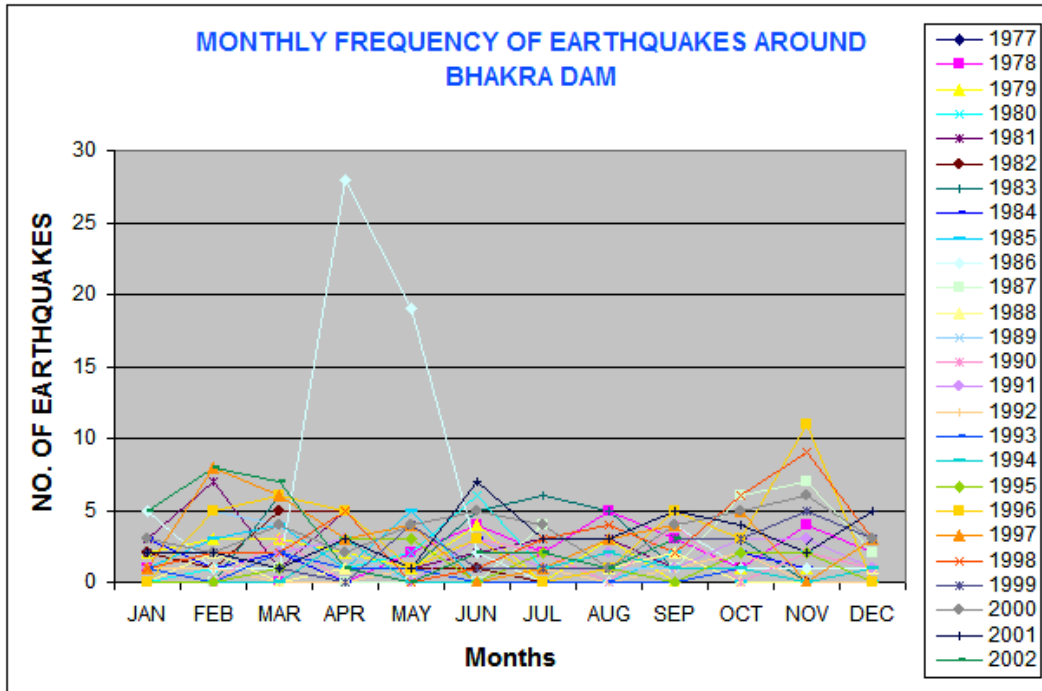


Fig. 18. Frequency of earthquakes around Bhakra dam

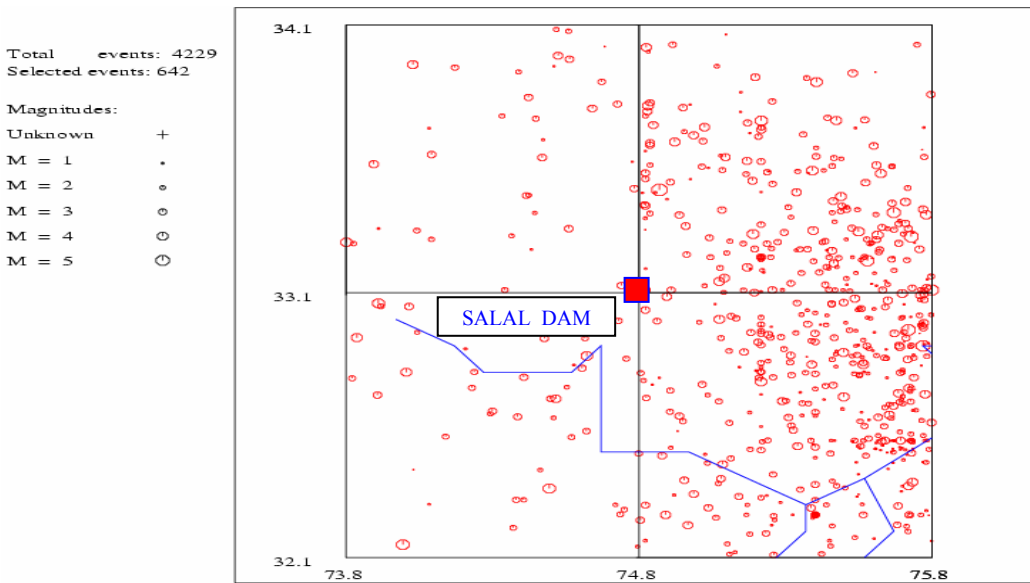


Fig. 19. Map showing epicenters around Salal dam during the period 1977-2002

of Chaudhury & Srivastava, 1978. During the period of 25 years, only two earthquakes of magnitude 5.0 and above have been located within 100 km of the Bhakra dam. One earthquake having magnitude 5.5 occurred on 26th April 1986 at a distance of 81 km from the dam in the northeast direction and another earthquake having magnitude 5.4 occurred on 14th June 1978

towards North at a distance of 90 km. from the Bhakra dam.

There are three earthquakes, which occurred within 15 km from the dam. The nearest earthquake occurred on 12th December 1979 with a magnitude of 2.9 at a distance of 10 km from the dam towards South-West side.

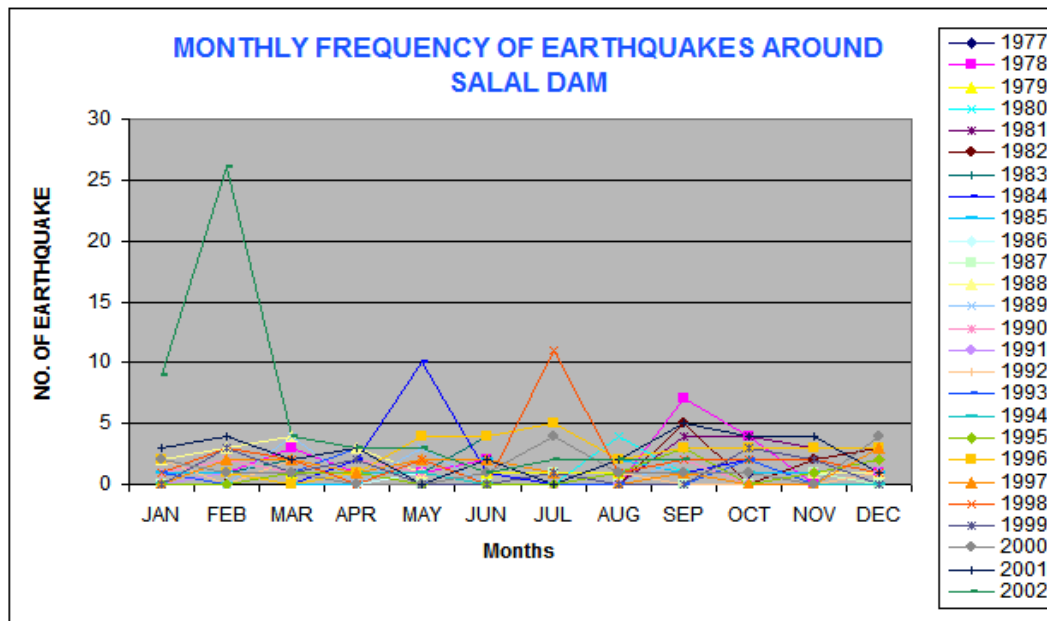


Fig. 20. Frequency of earthquakes around Salal dam

To examine the relationship between the seismicity and the reservoir loading (Hassoup, 2002), mean monthly water levels of Bhakra dam and monthly number of earthquakes around the Bhakra dam are plotted in Figs. 17 & 18 respectively for the whole period of 1977-2002. Two peaks are noticed in reservoir water loading in Fig. 17 in the year 1992 and 1993; however no increase in earthquake activity is noticed in the corresponding years. A prominent peak was noticed in the year 1986 in Fig. 18 which may be attributed to the increased earthquake activity of smaller magnitudes ranging between 2.0 to 3.5. However, no firm correlation between water level and occurrence of earthquakes around the Bhakra dam could be established.

3.6. Seismic activity around Salal dam

All the epicenters of the earthquakes which occurred during 25 years, *i.e.*, October 1977 to September 2002 around Salal dam have been plotted in Fig. 19. This map clearly shows that the earthquake activity is mostly confined to East and South East and North East of the Salal dam site. During the period October 1977 to September 2002, 389 earthquakes of magnitude 2.0 and above within 100 km of the Salal dam have been located. There are six earthquakes having magnitude 5.0 and more. Two of them occurred on 23rd August 1980, each with a magnitude of 5.2 at a distance of 90 km and 96 km respectively towards South East of the dam. The third of magnitude 5.3 occurred on 25th December 1990 at a distance of 92 km and fourth with a magnitude of 5.0

occurred on 15th September 1993 towards North East at a distance of 90 km from the dam. The fifth of magnitude 5.1 occurred on 28 September, 2001 at a distance of 76 km and sixth of magnitude 5.1 occurred on 27th January, 2002 at a distance of 96 km towards North East side of the dam.

There are eight earthquakes within 15 km of the vicinity of the dam. There were only two earthquakes which occurred very near to the dam, *i.e.*, at a distance of 6 km from the dam. These occurred on 28th April 1993 ($M = 3.2$) and on 13th September 1996 ($M = 2.9$).

The monthly frequency of earthquakes around Salal dam for the whole period of 1977-2002 is plotted in Fig. 20. A prominent peak was noticed in the year 2002 in Fig. 20 which may be attributed to the increased earthquake activity of smaller magnitudes ranging between 2.0 to 3.5. No correlation between water level and occurrence of earthquakes around the Salal dam could be evaluated due to non availability of data from Salal dam.

4. Conclusions

The conclusions arising out of the analysis of the seismic data collected over a period of 25 years (October, 1977 to September, 2002) through the network of analog seismological observatories operated by IMD around

Pong, Pandoh, Bhakra and Salal dam areas of the BEAS project are given below:

(i) The annual frequency of earthquakes in the region (30° - 35° North latitude and 73° - 79° East longitude) shows two periods of high activity during 1978 to 1986 and 1997 to 2002 with a low activity period during 1987 to 1996 (Fig. 5).

(ii) A comparison of the seismic activity within 100 km from each dam site over the 25 year period reveals that the number of earthquakes recorded around Pong dam (894) was maximum followed by Pandoh (747), Bhakra (608) and Salal (389) dams (Fig. 6). The same is evident from the work of Gautam *et al.*, 2002.

(iii) The annual seismic energy release over the whole period of 25 years does not deviate much from the average value, except for a few peaks in 1981, 1986, 1991 and 1996 and a few lows in 1987, 1988 and 1992 (Fig. 7). The peaks may be attributed to the occurrence of a few large magnitude events, during the corresponding years, such as Uttarkashi earthquake of 1991.

(iv) Using the Gutenberg-Richter frequency magnitude relationship for earthquakes recorded in the region for the whole period, a b-value of 0.85 is obtained, which is very close to the normal value of 1.0 expected for seismically active regions (Fig. 8). The temporal variation of b-values for the whole period also shows that low b-value anomalies are usually followed by large earthquakes of $M > 5.5$ (Fig. 9). Another interesting feature noted from the b - value analysis is that the magnitude threshold of detection and location of earthquakes in the region using BEAS network is about 2.5.

(v) No definite conclusions could be drawn with regard to the relationship between the observed seismic activity around the dam sites with the corresponding water level fluctuations in the reservoirs. The same conclusion was drawn from the study of Srivastava, 1990.

Acknowledgement

We thank to IMD and BBMB/SALAL dam authorities for utilizing data generated at their observatories.

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