RESERVOIR TRIGGERED SEISMICITY SCENARIO WITH SPECIAL EMPHASIS TO THE HIMALAYAS

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ABSTRACT

Himalayas are one of the mightiest mountain ranges in the world with immense, untapped hydropower potential (to the tune of 90,000MW in India; The Hindu; Business Line-2020) due to several mighty rivers originating from its glaciers. On the contrary because of its unique geotectonic setup, Himalayas also comprise the highest seismic zone of the country (Zone IV and V). Irrespective of this the large untapped hydro potential has attracted several developers to venture into construction of some big hydropower projects in the Himalayas. Himalayas are home to some largest hydropower projects in the country like Tehri, Bhakhra Nangal, Salal, Chamera-I etc. running successfully for past several decades.

In the recent years, however, the environmental hue and cry against development of these projects has started raising its head. One of the reasons cited is the occurrence of Reservoir Triggered Seismicity due to the pondage of large dams in the highly seismic Himalayas. Till date however there has been no example of significant RTS in the Himalayas. Still to satisfy the fear psyche of the common public a systematic and scientific approach is needed to be adopted by the hydro sector for seismic monitoring. Factors influencing RTS include Pore Pressure, volume of reservoir, duration of RTS, type of faulting and b value correlation. The historical details of RTS occurrences worldwide cited in this paper have been meticulously compiled from various technical sources. These include RTS instances from Europe, USA, Australia and Indian subcontinent. Seismicity due to Koyna Reservoir along with possibility of RTS in the Himalayas has also been delved with in detail. The theory of RTS and why its plausibility in the Himalayas can be negated have been discussed on scientific grounds.

Pre and Post construction seismic monitoring studies for dams of height greater than 100m and reservoir volume 500Mm^3 indicative of RTS have been discussed in a systematic manner.

Keywords*: Hydro projects, Dams, Himalayas, Reservoir Triggered Seismicity, Real Time Seismic Data Center.*

1.0 INTRODUCTION

"It is very common for people to start linking any natural hazards to manmade activities. However, we need to scientifically establish this link."

When it comes to water management on large scale agrarian country like India needs Dams for water storage. Building of dams will be a big step towards mitigating drought and flood control measures. The natural water resources and high gradient in the Himalayas make it an ideal source for tapping renewable, carbon free and sustainable hydropower.

The entire belt of the Himalayas bordering the northern limits of India falls in the seismic zone of the country namely Zone IV & V (BIS 1893: 2016- Part I). This has led in recent times to questions been raised on construction of dams in seismically active Himalayas. Another concern which has being raised time and again for hydro project development in the Himalayas is that of Reservoir Triggered seismicity (RTS). Although, till date there has not been any significant incidence of RTS reported for numerous hydroprojects running successfully in the Himalayas for the past several decades. To deal with the public fear scientifically, a planned seismic monitoring approach needs to be employed. NHPC has developed a centralized online seismic monitoring network with seismic instruments installed at all of its projects connected centrally for online monitoring on a continuous basis.

2.0 SEISMO TECTONIC SETUP OF THE HIMALAYAS

More than half of the area of India along the Himalayan Belt is susceptible to strong ground motion from earthquakes. Himalayan range of about 2400km length extending from Kashmir in the northwest to Arunachal Pradesh in the northeast, evolved as a consequence of the collision of the Eurasian and Indian continents some 50 million years ago.

Large earthquakes frequently occur at the margins of Eurasian & Indian continental plates due to sudden release of strain energy which has built up over a period of time. As the Indian landmass moved northwards, the sedimentary pile with its crystalline basement was complexly folded and repeatedly split by faulting and thrusting. These faults, from north to south, are: the Trans Himadri Fault (THF), the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Himalayan Frontal Thrust (HFT). The Indus Suture Thrust (IST) to the north represents the junction of the two colliding continents, and HFT is now the primary surface expression of shortening between the Himalaya and the Indian plate. Fig.1 is depicting the major features along the Himalyan belt.

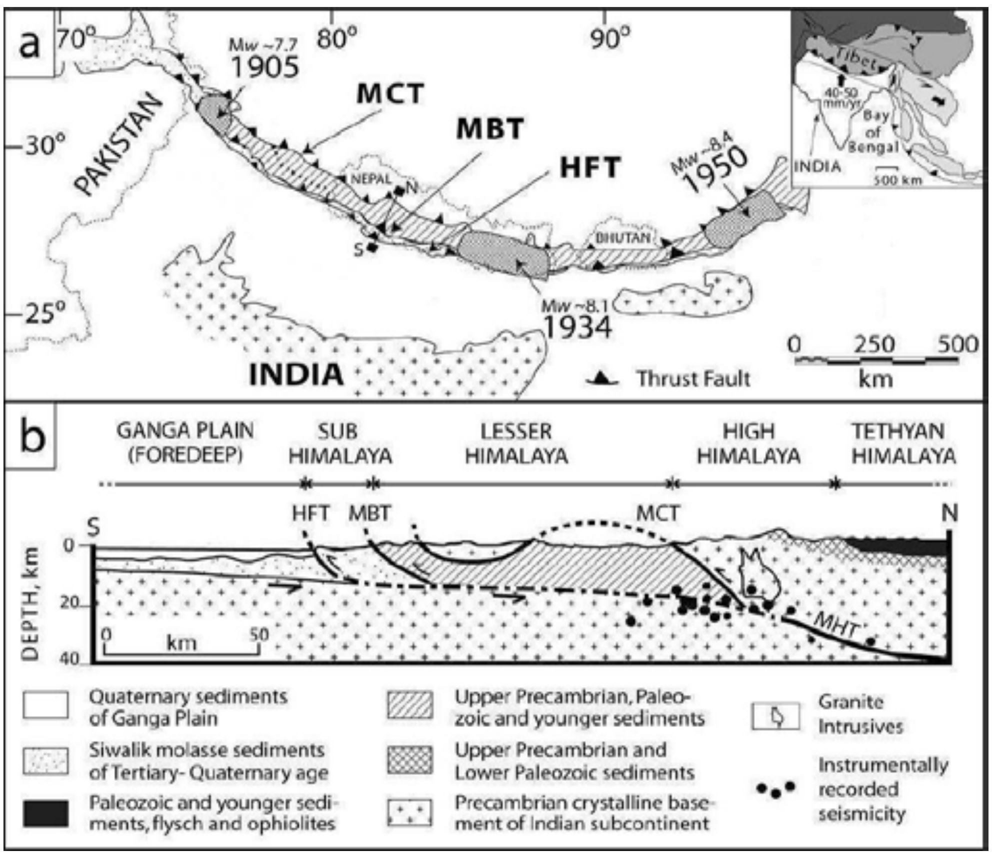

Fig. 1 : Major tectonic features of the Himalayas

2.1 Seismic Status of Himalayas and Great Earthquakes in India

Seismicity is mainly confined to the upper and middle crustal zones near the plate boundary and also near several active NE-SW lineaments. The continent-continent collision resulted in large fragmentation of the lithosphere in Himalaya, which in turn could result in rotary motion of some blocks and their displacement over a large distance. This is supported by the presence of long tear faults cutting across the Himalaya and supported by the occurrence of recent deeper strike-slip earthquakes, like the 1988 M6.8 Bihar-Nepal and the 2001 M6.9 Sikkim earthquakes. In the past century, three great earthquakes (M>8.0) have occurred in the Himalayan arc (1905 Kangra, 1934 Bihar and 1950 Assam); one in Shillong plateau shield (1897) and one in northwestern margin of peninsular shield (1819 Kutch) (Kayal, 2008)

3.0 RESERVOIR TRIGGERED SEISMICITY- BACKGROUND

Triggered seismicity refers to typically minor earthquakes and tremors that are caused by human activity that alters the stresses and strains on the Earth's crust. Mostly induced seismicity is of a low magnitude. For triggered earthquakes to occur, the area is required to be already under considerable tectonic stress. Since these earthquakes are triggered along pre-existing and pre-stressed tectonic faults, they show typical characteristics of double couple source mechanism (Kayal, 2008). The energy released in a reservoir triggered earthquake is normal tectonic strain energy that has been prematurely released because of the reservoir. The most widely accepted explanation of how dam causes earthquake is related to the extra water pressure created as the reservoir fills and another explanation is of failure caused by increasing the vertical principal stress as a result of the weight of impounded water.

3.1 Factors Related to Reservoir Triggered Seismicity

In general following factors have been observed to show some correlation with Reservoir Induced Seismicity:

(a) *Pore Pressure* : The column of water in a large and deep artificial lake (greater than 60m depth) alters in-situ stress along an existing fault or fracture. In these reservoirs, the weight of the water column can significantly change the stress on an underlying fault or fracture by increasing the total stress through direct loading, or decreasing the effective stress through the increased pore water pressure. This significant change in stress can lead to sudden movement along the fault or fracture, resulting in an earthquake

(b) *Duration of Reservoir Induced Seismicity* : When the reservoirs are filled or drained, triggered seismicity can occur immediately or with a small time lag. Once stress and pore pressure fields have stabilized at new values, reservoir Triggered seismicity will cease. Earthquake hazard will then revert to similar levels that would have existed if the reservoir had not been filled. In general, it is observed that Triggered seismicity phenomenon is observed maximum up to a period of few years after impoundment beyond which the stresses are stabilized in the area for any enhanced seismic activity. In the case of Koyna reservoir seismic activity was observed for a period of two years

(c) *Volume of the Reservoir and Reservoir Triggered Seismicity* : From experience it is possible to say that, if they trigger any earthquakes at all, most water reservoirs trigger only small earthquakes, a few have triggered magnitudes exceeding 5.0 and a couple of large reservoirs have triggered magnitudes larger than 6.0. Most reservoir triggered earthquakes are located under or near large reservoirs, with water depths exceeding 60 meters, and reservoir volumes exceeding 500Mm^3. (M. Weiland, ICOLD bulletin; 2016).

(d) *'b' value correlation* : The frequency-size distribution of triggered earthquakes has the general form of the Gutenberg-Richter relationship, that is, a power-law or log-linear relationship. Since Triggered events usually occur at shallow depths, they tend to have small magnitudes similar to those in normal shallow earthquake swarms. The relative number of small to large reservoir triggered earthquakes, the Gutenberg-Richter b-value, is often comparable with background seismicity in the region. In most cases the rate of reservoir-triggered activity reduces after about 20 years, and the probability of earthquake activity reverts to the levels that existed prior.

(e) *Type of fault* : The type of faulting (reverse, strike-slip, or normal) of triggered earthquake is not different from a normal earthquake at a location. As with normal tectonic earthquakes, the magnitude of the Triggered earthquake depends on the stress levels about the fault. If the stress is high over a long segment of the fault, the magnitude may be large.

3.2 Reservoir Triggered Earthquakes Worldwide

Worldwide, about 2% of large reservoirs are known to have triggered earthquakes, although many do not have local seismometer coverage and if events were of small magnitude such activity may not have been detected (Gupta & Rastogi, 1976; Simpson et.al., 1988).Table1 and Fig.2 depicts the world wide reported cases of RTS.

Magnitudes of this type of seismicity range from less than 1.0 to 6.3. Most of the examples of RTS have been observed from Europe and USA. Some examples of RTS worldwide due to filling of the reservoirs are from Vajont Dam, Italy, Oroville California and Nurek Dam Tajikistan. Recently, some studies on Rihand Dam in Narmada rift valley of Central India (K Gahalaut et.al) have found good correlation between earthquakes during 1984–2004 (for MN3 from ISC and IMD catalogues) and during 1997–99 (for Mb3 from DMG catalogue) with reservoir water level which possibly suggests that the reservoir triggered earthquakes occurred in this region after the impoundment and the reservoir continued to trigger earthquakes even after 40 years of impoundment. However, there is no knowledge about the earthquake occurrence immediately after the reservoir impoundment in 1962 and before 1984, when reliable earthquake catalogues were made available.

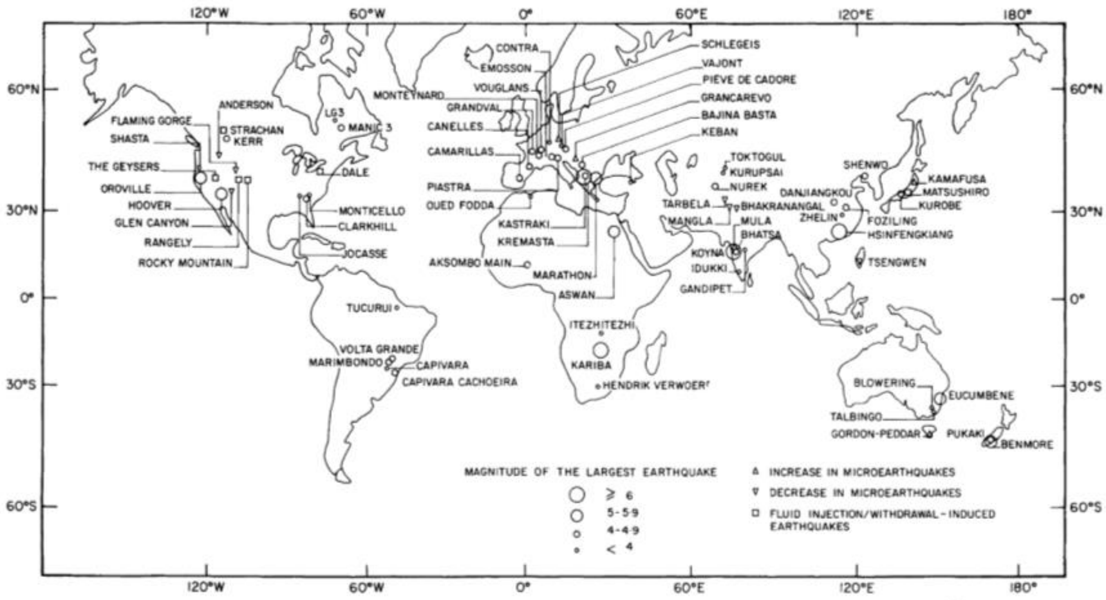

Fig. 2 : Worldwide distribution of RTS (Dr. Harsh K Gupta)

Table 1 : Compilation of major RTS cases in the world

Dam reservoir	**Country**	**Height (m)**	**Volume ($x10^6 m^3$)**	**Year of filing**	**Strongest Earthq.**	**M_{max}**
Vaoint	Italy	262	168.7	1960	1963	4.9
Koyna	India	103	2.780	1964	1967	6.3
Kremasta	Greece	165	4.750	1965	1969	4.4
Oroville	California	235	59.34	1967	1975	5.7
Xingfengjiang	PR China	105	10.500	1959	1962	6.1
Kariba	Zimbabue	128	160.368	1959	1963	6.2
Hoover	USA	221	36.703	1936	1939	5.0
Marathon	Greece	63	41	1930	1938	5.7
Aswan	Egypt	115	165.000	1978	1981	5.3
Benmore	New Zealand	118	2.100	1965	1966	4.5
Monteynard	France	155	240	1962	1963	4.9
Kurobe	Japan	186	199	1960	1961	4.9
Bajina-Bašta	Serbija	89	240	1965	1967	4.7-5.0
Nurek	Iran	317	10.400	1972	1972	4.6
Mangla	Pakistan	116	7.250	1967	1967	4.2
Grandval	France	88	292	1959	1963	4.7
Canalles	Spain	150	678	1960	1962	4.7

From above table it is clear that incidence of RTS have been observed from peninsular/central India. However, no such incidence has been reported from the Himalayas in past several decades. The first case of reservoir-Triggered seismicity occurred in 1932 in Algeria's Oued Fodda Dam. The largest confirmed 18 reservoir triggered earthquakes were of magnitude 6.3 near the Hsinfengkiang Dam, China in 1962 and the Koyna Dam, India in 1967.

The largest earthquake attributed to reservoir-Triggered seismicity occurred at Koyna Dam in Peninsular India. The 6.3 magnitude, 1967 Koynanagar earthquake occurred in Maharashtra, with its epicenter, fore- and aftershocks all located near or under the Koyna Dam reservoir. Decrease in seismic activity has also been reported at certain reservoir sites, as would be expected for compressive stress regimes including (counter to observations) Australia's. This problem is resolved by an alternative triggering mechanism where pore fluid pressure increases as a result of diffusion of water under a reservoir. Thomson and Warragamba Dams both experienced earthquakes exceeding magnitude 5.0 more than ten years from commencement of filling. The volume of upper crust where ground water pore pressure has been affected by a large reservoir is significant, perhaps 2,000 to 20,000 km^3 or more. In comparison, a magnitude 5.0 earthquake involves a source volume of something like 30 km^3, and a magnitude 6.0 about 1000 km^3.

3.3 Reservoir Triggered Seismicity in the Himalayas

In general it is observed that the Himalayas have a thrust environment and no incidence of RIS has been observed in the prevalent tectonic regime of the Himalayas. Till date no incidence of RIS has been reported from any hydro project developed in the Himalayas. Some major hydro projects running successfully in the Himalayas for the past several decades without any incidence of RIS are Bhakra project (Dam Height: 226m, Reservoir Capacity: 7.55 BCM), Chamera HEP-I (Dam Height: 140m, Reservoir Capacity: 391MCM) Salal HEP-I&II (Dam Height: 118m, Reservoir Capacity: 284MCM) and Teesta V (Dam Height 88.6m, Reservoir Capacity 13.25MCM) and Tehri project (Dam Height: 260.5m, Reservoir Capacity: 3.54 BCM).

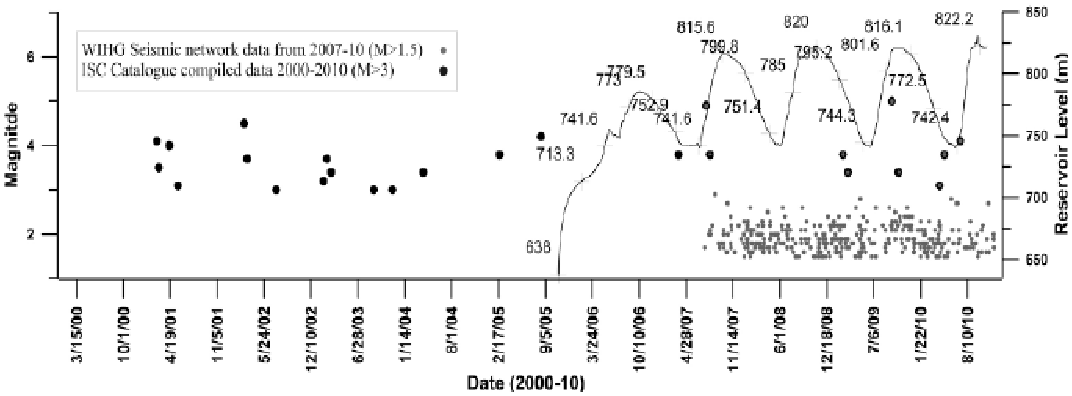

Fig. 3: Earthquake data along with water level history of the Tehri from Oct. 2005 (since filling) to 2010

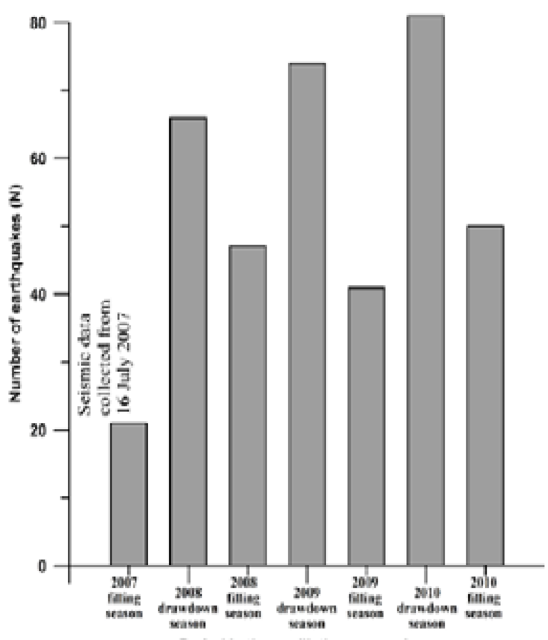

Fig. 4 : Number of earthquake events per filling period (filling and drawdown cycles) around the Tehri Reservoir, India. Seismicity appears to be more pronounced in the drawdown periods

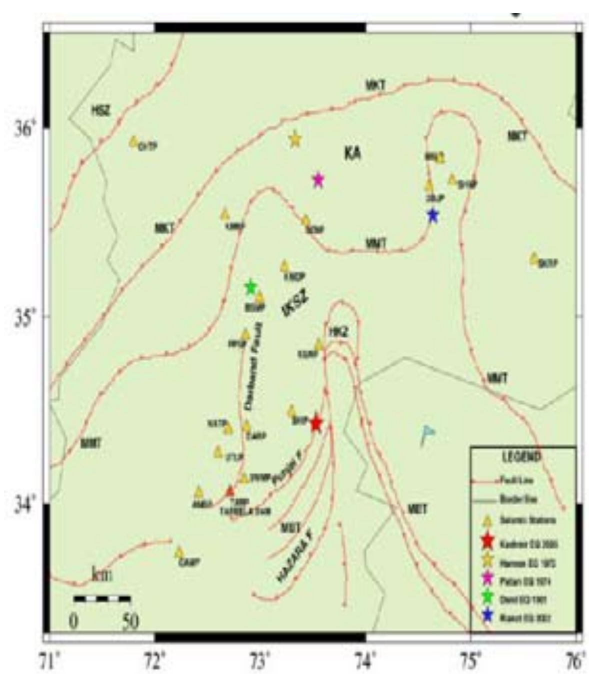

Fig. 5 : Micro seismic network around Tarbela Dam

The seismicity data for Tehri dam is being monitored for last several decades with the objective of RIS. Department of Earthquake Engineering, Indian Institute of Technology Roorkee has been monitoring the local seismicity in Tehri region employing a radio-linked local seismological network on behalf of the Tehri Hydro Development Corporation (THDC), India Ltd. for the last more than twenty five years and the studies have been indicating that there does not exist any RS activity till now. (Kumar et al, 2010, Sharma et al, 2014) It is to state that till date there has been no reported incidence of RTS in the Himalayas. With most of the large hydro projects running successfully in the Himalayas without any incidence of RTS till date, it is observed that the thrust environment of the Himalayas has a major role to play in abetting any RIS. Moreover, a prerequisite for reservoir-Triggered seismicity is availability of critically stressed rock strata within shallow (~10 km) depths, so that the pore fluid pressure increases and/or incremental stress due to reservoir loading could trigger failure. This is obviously not the case in the foothills of the Himalaya, where a thick strata of relatively mechanically incompetent sedimentary formations exist. In general, the earthquakes in these regions have focal depths in excess of 20 km. (Harsh K. Gupta and Kusala Rajendran 1986).

Out of the three identified cases of RIS in the Himalayan region two cases are of Mangla and Tarbela dams in Pakistan and Bhakra Nangal dam in India. There does not seem to be any relation between seismic activity and the Govind Sagar Reservoir created by the Bhakra Dam. On the contrary, in all these cases the effect of reservoir in the seismicity of the area is the reduction in the earthquake activity (Gupta H. K., 1992). Construction of these projects has resulted in mobilizing the stresses towards a stable environment. Almost all the reported cases of RIS in India are from peninsular India.

4.0 PRE- CONSTRUCTION SEISMIC STUDIES UNDERTAKEN AT NHPC PROJECTS

NHPC is committed towards seismic monitoring of its projects for the last more than two decades for assessment of Reservoir Triggered Seismicity around its projects. Specialized seismicity studies like Micro Earthquake (MEQ) Studies and Local Earthquake Tomography (LET) studies are carried out by installation of seismographs to record the seismic activity in the area within 50km radius of the dam site. The studies are planned as per the guidelines laid down by National Committee on Seismic Design Parameter Studies for river valley projects (NCSDP), CWC, GoI. These studies are carried out to assess the seismo-tectonic setup, status of various faults/ thrusts and identification of the location and geometry of the faults in the area, in a precise way. These studies are being carried out in association with premier institutes of the country like Department of Earthquake Engineering (DEQ), IIT-Roorkee, CWPRS-Pune, Institute of Seismological Research (ISR) Gandhinagar and Wadia Institute of Himalayan Geology (WIHG), Dehradun etc. The seismicity studies play a very important role in the determination of design earthquake parameters for hydroelectric projects as well for understanding the periodic seismogenic activities in and around the project site. These studies give finer, detailed picture of the present activity status of various thrusts/faults in and around the project area. Mapping of the activity levels of these faults/lineaments etc provide a background seismicity data for the area which is later compared with the post impoundment seismicity data to assess changes in the seismicity levels due to the project if any. The details of studies undertaken for some big NHPC projects (dam height >100m; reservoir volume >500m^3) are given in Table below:

S. No.	Name of Project	Project Highlights	Seismological studies undertaken by NHPC	Remarks
1	Bursar project, Jammu & Kashmir (800MW)	Seismic zone IV; 289m high concrete gravity dam	Micro Earthquake (MEQ) and Local Earthquake Tomography (LET) studies were carried out by Institute of Seismological Research (ISR), Gandhinagar, Gujarat; Nine months seismic data was collected.	This data will form the base data of pre impoundment seismicity. Further seismic monitoring can be carried out after reservoir filling and pre-impoundment seismicity can be compared with the post impoundment data to establish Reservoir Triggered Seismicity if any
2	Kwar Project, Kishtwar region of Jammu & Kashmir	Seismic zone IV; 109m high concrete gravity dam on river Chenab	MEQ studies were carried around the project site by Wadia Institute of Himalayan Geology Dehradun; six months seismic data was collected	
3	Dibang Multipurpose Project, Arunachal Pradesh (3000MW)	Seismic zone V; 279m high concrete gravity dam across the river Dibang.	MEQ studies along with LET were carried out by GSI; six months seismic data was collected	
4	Subansiri Lower Project, Assam/ Arunachal Pradesh (2000MW)	seismic zone V; 125m high concrete gravity dam across the river Subansiri.	a seismic network of six broadband seismographs and an accelerograph has been deployed permanently since May 2006	

5.0 POST CONSTRUCTION SEISMIC MONITORING OF DAMS BY NHPC

NHPC is actively involved in the seismic monitoring of its power stations for taking adequate safety measures. For this NHPC has installed accelerographs at all its power stations for seismic monitoring. In order to handle proper maintenance of installed accelerographs and earthquake data analysis in an organized and efficient way, Real Time Seismic Data Center has been developed at its Corporate Office, Faridabad and about 53 seismic monitoring instruments (accelerographs) installed at all of its power stations has been connected to the data center for continuous online monitoring. Fig.6 is depicting the schematic representation of the NHPC network and data collection Fig.7 marks the epicentral distance vs. magnitudes of natural earthquakes recorded by NHPC seismic network. In case of occurrence of an earthquake event at and around the project site the data is downloaded at the Real Time Data Center and a detailed report is prepared.

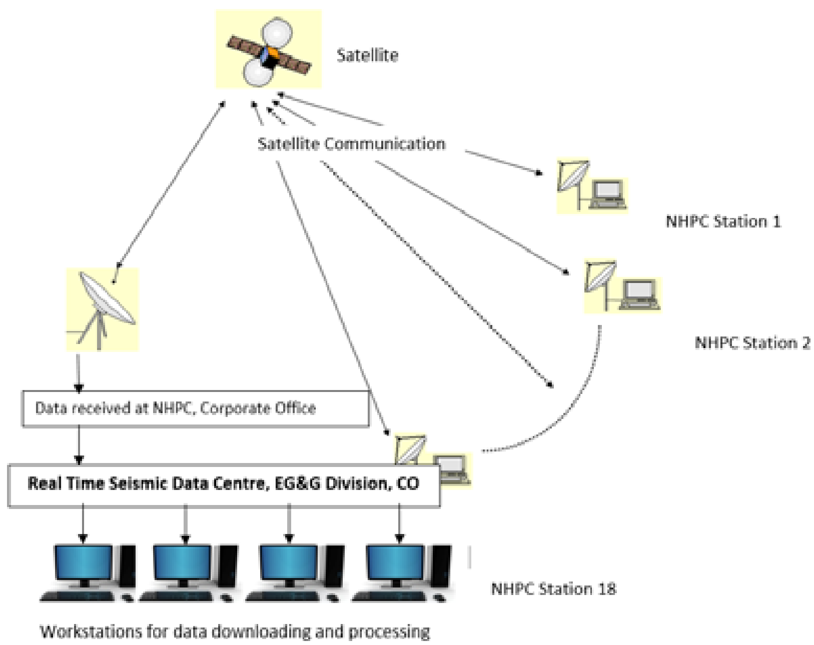

Fig. 6 : Schematic of data collection network at NHPC

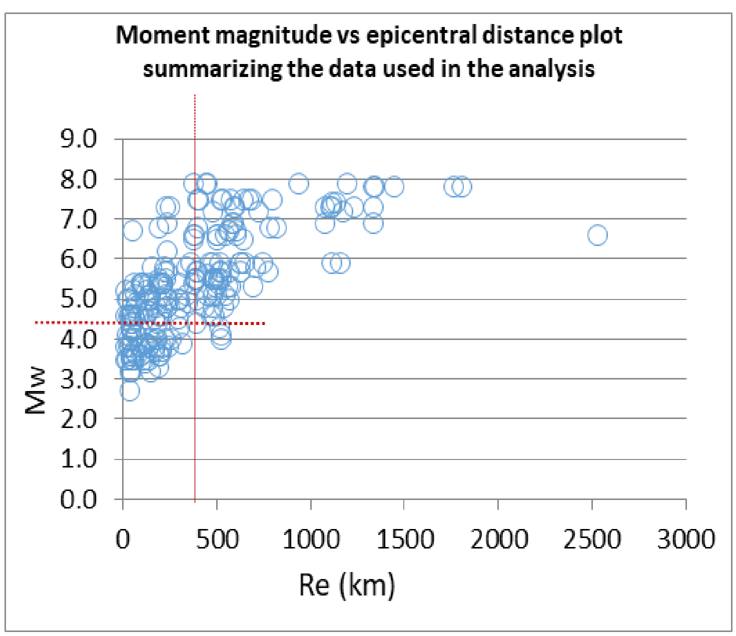

Fig. 7 : Epicentral distance vs. magnitude plot for events recorded by NHPC network

The recorded acceleration data is further compared with the design acceleration of the project to ensure adequate safety of its structures. One of the largest event of this decade in the Indian subcontinent recorded by NHPC data center was that of M=7.9, Gorkha Nepal earthquake. PGA value recorded at Rangit power station for this event was of the order of 0.0548g which is much less than the design value for the project. Other projects recorded even lower values.

Our projects are designed to withstand much higher PGA values and are completely safe in case of any RTS event.

6.0 CONCLUSIONS

Himalayas have high potential for development of hydropower which is essential to augment the power crisis in the country. Himalayan belt also lies in the highest seismic zone of the country i.e. Zone IV/V as per the seismic zoning map of India. In view of this whenever any large dam construction is undertaken lot of public speculations arise regarding the effect of such projects on the seismicity of the region. Considering this, NHPC has taken an initiative to assess the Reservoir Trigerred Seismicity factors in the Himalayas and propose a detailed plan to assess any indication of RTS post impoundment of the reservoir.

It is observed that incidences of RTS in the Himalayas is not common. Moreover, the few incidences of RTS in the Himalayan region have resulted in the decrease in the overall seismicity of the region. This is because of the prevalence of thrust environment which results in mobilization of stresses towards stability on reservoir impoundment which is evident from the cases of Bhakra, Mangla and Tarbela reservoirs in the Himalayas.

NHPC has established online Real Time Monitoring of its projects by setting up of a Real Time Seismic Data Center and connecting online all the accelerographs installed at its power stations.

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