A

DISSERTATION

ON

"RESERVOIR INDUCED SEISMICITY DUE TO TEHRI DAM"

Submitted towards the partial fulfilment of the requirements for the award of the degree

of

Masters of Technology

Department of Earthquake Engineering

(With specialization in Structural Dynamics)

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INDIAN INSTITUTE OF TECHNOLOGY ROORKEE

DECLARATION

l, Ali Ahmad Khan, hereby declare that the work which is being presented in this report entitled, “RESERVOIR INDUCED SEISMICITY DUE TO TEHRI DAM” in the partial fulfilment for the award of the degree of MASTER OF TECHNOLOGY in EARTHQUAKE ENGINEERING, with specialization in STRUCTURAL DYNAMICS, submitted in the Department of Earthquake Engineering, Indian Institute of Technology, Roorkee, is an authentic record of my own work carried out for a period from June 2017 to May 2017 under the supervision of Dr. M.L SHARMA (Professor) and DR. S.C GUPTA (Associate Professor), Department of Earthquake Engineering, Indian Institute of Technology, Roorkee.

The matter embodied in this report has not been submitted by me for the award of any other degree or diploma of this Institute or any other University/Institute.

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CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

Reservoir Induced Seismicity (RIS) refers to earthquakes that are triggered or induced as a result of artificial filling of reservoirs. As of today over 100 cases of reservoir induced seismicity have been registered throughout the world, the most damaging and severe case having been occurred due to Koyna Dam on December 10, 1967 where a 6.3 magnitude earthquake was triggered by the reservoir. Investigation of RIS is important from several viewpoints: to check for safer sites where a dam can be constructed and mitigation of any hazard due to triggered earthquakes, to improve our understanding of the physics of earthquakes. Events of highly damaging RIS have occurred in the past at Hsinfengkiang (China), Kariba (Zambia), Kremsata (Greece), Koyna (India), Oroville (California) and Aswan (Egypt). In this project deep understanding of the phenomenon of reservoir induced seismicity and the parameters affecting RIS have been studied. Calculation of reservoir induced seismicity using probabilistic approach for Tehri dam has been carried out. Tehri is a rock and earth dam constructed over River Bhagirathi in the Indian state of Uttarakhand. With a height of 260.5m and volume of over 3000 million m^3 it is the highest dam in India. The dam is constructed for the purpose of irrigation and power generation. Previous research suggests that there lies an active fault beneath Tehri Dam at a distance of approximately 4.5 to 5km beneath the surface which makes this study a matter of concern and importance.

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CHAPTER 01

INTRODUCTION

1.1 GENERAL

When a dam is built in a region and the reservoir is impounded, the dynamics of the area surrounding the dam are affected due to a considerable amount of change in the forces and the stress patterns in the area to the extent that a combination of certain parameters form a mechanism and are sometimes strong enough for triggering an earthquake. This phenomenon where the construction of a dam results in the increase of seismicity of the region, thereby triggering an earthquake or high seismicity is called as Reservoir Induced Seismicity. Dams are usually constructed in valleys where the seismicity is naturally high due to active erosion; therefore many dams have an active fault dipping under or around them. The additional forces generated post construction and impoundment of dam in presence of active fault lead to the triggering of an earthquake or a series of earthquakes; therefore it is sometimes also referred to as reservoir triggered seismicity. The first case of RIS was registered at Lake Mead by Carder in 1945. Since then hundred such cases have occurred throughout the world. The geological conditions of each land area are different which makes it difficult to generalize or quantify the effect of a said parameter for induced seismicity. Different parameters have a different magnitude of effect on the seismicity of a region depending upon the geology and the fault activity of that area. It is due to this fact that dams as low as 22m (Carmo do Cajuru, Brazil) have shown the phenomenon of reservoir induced seismicity whereas dams as high as 226m (Bhakranangal, India) have led to a decrease in seismic activity in the region which makes it a really complex phenomenon to identify or predict. There are five major parameters associated with reservoir induced seismicity which are Depth of the reservoir (D), Volume of reservoir (V), Stress state (S), Presence of active faults (F), Geology (G). Strong cases of RIS are usually associated with large dams having a height of over 100 meters but as discussed above dams with less than half this height has shown the phenomenon of reservoir induced seismicity which makes the pattern of RIS unique for each site. The most severe and destructive case of RIS, occurred on 10th December 1967 at Koyna Dam having a magnitude of 6.3 on the Richter scale killing 200 people, injuring nearly 2000 people and rendering several thousand homeless. The tremors of this earthquake were felt as far as 230 km from its epicentre; Koyna dam has a height of 103m and a volume of 2780 million m3. Depth and Volume of the reservoir are associated with an increase of weight and of pore pressure which increases the elastic stress due to impoundment of water and water pressure created in the micro cracks and fissures in the ground under and near a reservoir. The water seeps into the micro cracks and fissures lubricating the fault surrounding the dam region causing the slip that leads to frequent seismicity in the area. Pore water plays multiple roles in this process, the first being a mechanical effect as pore pressure, and secondly, a chemical effect causing corrosion with the help of an applied stress. There is evidence to suggest that pore water or pore pressure diffuses along pre-existing fractures, bedding planes, etc. it is suggested that the mechanical effects of pore pressure control the spatial and temporal pattern of RIS, whereas the actual onset of seismicity may be influenced by the chemical effect of water in reducing the coefficient of friction in clays (filling pre-existing fractures).

1.2 OBJECTIVES

The main objective of the present work is as follows:

- To have a deep understanding of the phenomenon of reservoir induced seismicity.
- To study the parameters associated with RIS and calculate its implications and the probability of occurrence of RIS for Tehri Dam using probabilistic approach.

1.3 SCOPE OF STUDY

The present work includes an understanding of reservoir induced seismicity and its effects on Tehri Dam using probabilistic approach. The five major parameters associated with RIS namely depth of reservoir, volume, geology, stress and fault are studied. Since the phenomenon of RIS revolves around these major parameters of study. An understanding of the mechanism involved in this phenomenon is also studied with deterministic study on the effect due to vertical loading caused by the filling of reservoir and the pore pressure studies made by Chadha et. al. Verification of statistical model by G.B Reacher and Keenay (1982) is made using additional data to the pre-existing model of conditional probability.

CHAPTER 02

LITERATURE REVIEW

2.1 GENERAL

When a reservoir is impounded, the seismic changes in the area, if any are a result of several associated parameters. Several studies have been carried out ever since the first case of RIS was observed by Carder at Lake Mead, Hoover Dam in 1945. The parameters affecting RIS as observed by several researchers include Depth of reservoir (D), Stress Environment (S), Volume of reservoir (V), Karst development degree (K), Fault activity(F), Permeable height of reservoir water (H), Communication relationship with water of reservoir (C) and background earthquake activity (E). However five major parameters that have been identified by several geologists, seismologist, engineers and research scholars are the depth, volume, stress environment, fault activity and the geology of reservoir. Our study is based on these five major parameters associated with RIS. The phenomenon of RIS revolves around these major parameters associated with it.

2.2 REVIEW OF RESEARCH

Gupta H.K (2001) reviewed RIS with special emphasis on Koyna Dam. He studied the seismic activity in the Koyna region and carried out an experiment in which 21 bore wells were drilled each being 90 to 250m deep to figure out the effect of change of depth on the seismicity. Another important development made by Gupta was the effect caused due to pore fluid pressure in anisotropic rocks. Seismicity could be bifurcated into three categories namely rapid response, delayed response and continuous response seismicity. A reservoir could exhibit more than a single type of response. Koyna Dam built on the Koyna River is an example which shows all three types of response. So far Koyna dam has triggered over 150 earthquakes of Magnitude greater than 4. Two events having M > 5 and several thousand micro earthquakes. He further suggested that much more work needs to be carried out for a comprehensive understanding of this topic given the number of limitations and complexities that surround this phenomenon.

Gupta H.K, Rastogi and Narain (1972) studied the common features of reservoir related seismicity. At that time the Koyna earthquake had recently occurred. They studied dams such as Lake Mead, Monteynard, Grandval, Vajont, Mangla, Kariba, Kremasta, and Koyna among others and found out some common features associated with them such as the maximum height upto which the reservoir was loaded and the time duration of filling of reservoir. They emphasised on the vicinity of the epicentre, b-values and magnitude ratios associated with the seismicity. They found out that epicentres lied in close vicinity to the reservoir about 25km in most cases. High b-values and magnitude ratios for all the events were found to exist.

Gupta H.K and Kausala R. (1986) studied large reservoirs in the Himalayas and found out that of the 11 large reservoirs having a capacity of 1 km^3 and a height of over 100 meters only one of these reservoirs had adequate instrumentation for monitoring at that time. However as of present day most of the dams in the Himalayan belt are under surveillance with proper instrumentation and so far no case of reservoir induced earthquake has occurred whatsoever. In fact after impoundment of some of these dams the seismic activity has reduced in the region. The primary reason for this is because in spite of having a high seismic zone the Himalayas have thrust-fault environment which prevents triggering of seismicity due to the construction of dams.

Qiuliang W (2008) studied methods of RIS prediction for three gorges reservoir. Two methods of prediction of RIS were studied by Wang. The methods of prediction included (1) statistical predictive model by G.B Reacher (1982) which takes into account the five major parameters governing RIS namely the depth(D), Volume(V), Fault Activity(F), Geology(G) and Stress State(S). (2) Gray system model, this model is not known fully and includes dispersive factors including an influence by human beings. The magnitude of earthquake was classified based on past earthquake activity for high earthquake activity a magnitude of $M_o \sim 4.5\text{-}6.0$ was assigned and for moderate earthquake activity $M_1 \sim 3.0 – 4.5$ was assigned and for low earthquake activity $M_2 < 3.0$ i.e. micro earthquake activity was proposed as per Gray system.

Reacher G.B and Keenay R. (1982) proposed a statistical method for the calculation of reservoir induced seismicity. Data was collected from dams associated with reservoir induced seismicity and 29 such dams were found and 205 dams that do not exhibit this phenomenon were statistically analysed. This predictive model gives an approximate idea of the probability associated with a certain dam since there are multiple factors determining the triggering of such event which makes it a difficult task to find the probability with no error, professional judgements are therefore very necessary in determining the probability of occurrence with least error.

CHAPTER 03

WORLDWIDE DISTRIBUTION OF RIS AND CASE STUDIES

3.1 GENERAL

As of today more than 100 cases of reservoir induced seismicity have occurred throughout the world. The first ever case of RIS occurred in 1945 at Lake Mead at Hoover Dam. Since then four events of magnitude greater than 6.0, ten events of magnitude between 5.0 to 5.9, twenty eight cases of seismicity was between 4.0 to 4.9 and another sixty cases of magnitude less than 4.0 have been recorded. The most severe case occurred at Koyna Dam, India where a Magnitude 6.3 occurred on the night of December 10, 1967. On the other hand eight cases have been reported where the seismicity reduced after impounding the reservoir. There have been another sixteen cases of suspected RIS. Cases of magnitude less than 4.0 are innumerable.

3.1 Cases of RIS throughout the world

Table 1 - Reported cases of reservoir-associated changes in seismicity in rest of the world

Reservoir	Country	Height	Volume (10^6 m^3)	Year of Impounding	Year of Earthquake	Magnitude
Hsinfengkiang	China	105	13,896	1959	1962	**6.1**
Kariba Zambia–	Zimbabwe	128	175,000	1958	1963	**6.2**
Kremasta	Greece	160	4750	1965	1966	**6.2**
Aswan	Egypt	111	164,000	1964	1981	**5.6**
Marathon	Greece	63	41	1930	1938	**5.7**
Benmore New	Zealand	110	2040	1964	1966	**5.0**
Charvak	Uzbekistan	148	2000	1971	1977	**5.3**
Eucumbene	Australia	116	4761	1957	1959	**5.0**
Geheyan	China	151	3400	1993	1997	**5.0**
Hoover	USA	221	36,703	1935	1939	**5.0**
Oroville	USA	236	4400	1967	1975	**5.7**
Srinagarind	Thailand	140	11,750	1977	1983	**5.9**
Bajina Basta	Yugoslavia	90	340	1966	1967	**4.5– 5.0**
Canelles	Spain	150	678	1960	1962	**4.7**
Clark Hill	USA	60	3517	1952	1974	**4.3**
Dahua	China (PRC)	74.5	420	1982	1993	**4.5**
Danjiangkou	China	97	16,000	1967	1973	**4.7**

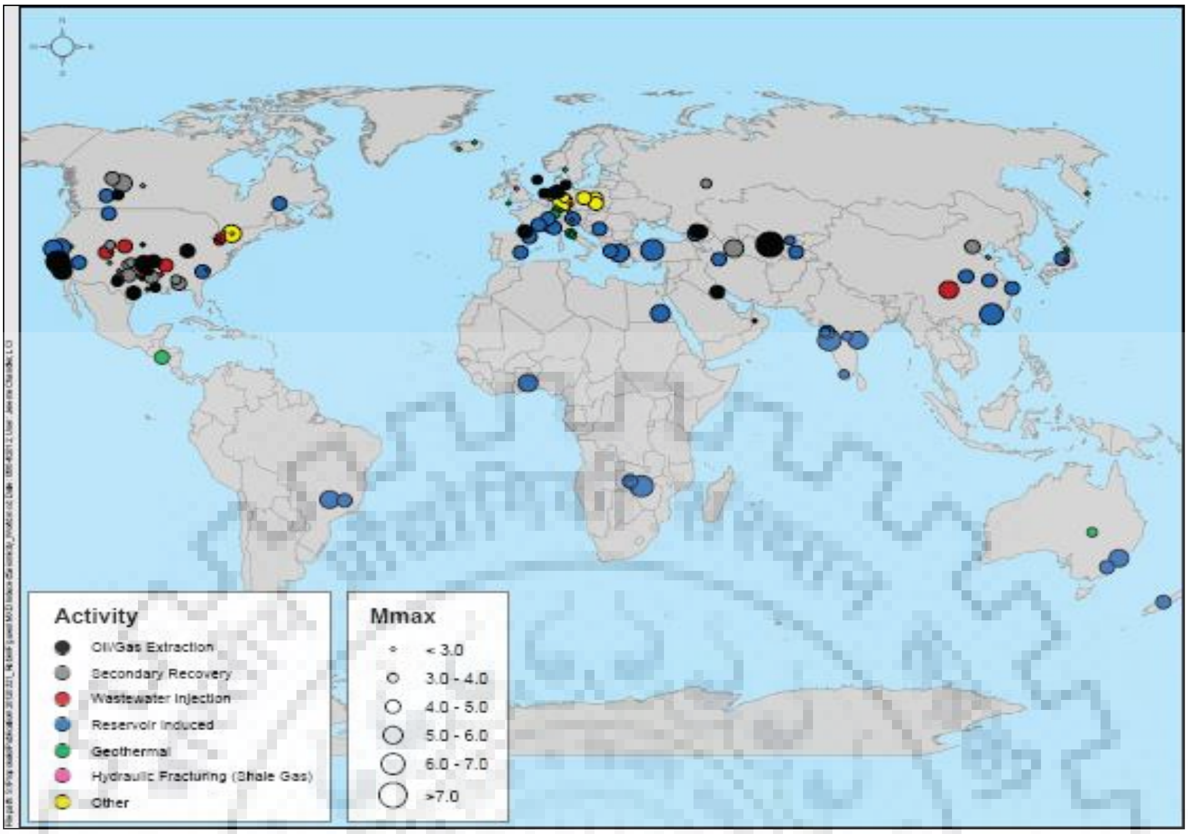
	(PRC)					
Foziling	China (PRC)	74	470	1954	1973	**4.5**
Hoa Binh	Vietnam	125	-	1988	1989	**4.9**
Kerr	USA	60	1505	1958	1971	**4.9**
Kurobe	Japan	186	149	1960	1961	**4.9**
Lake Pukaki	New Zealand	106	9000	1976	1978	**4.6**
Monteynard	France	155	275	1962	1963	**4.9**
Nurek	Tajikistan	317	1000	1972	1972	**4.6**
P. Colombia/V. Grande	Brazil	40/56	1500/2300	1973– 1974	1974	**4.2**
Piastra	Italy	93	13	1965	1966	**4.4**
Shenwo	China (PRC)	50	540	1972	1974	**4.8**
Vouglans	France	130	605	1968	1971	**4.4**

3.2 RIS observed in India

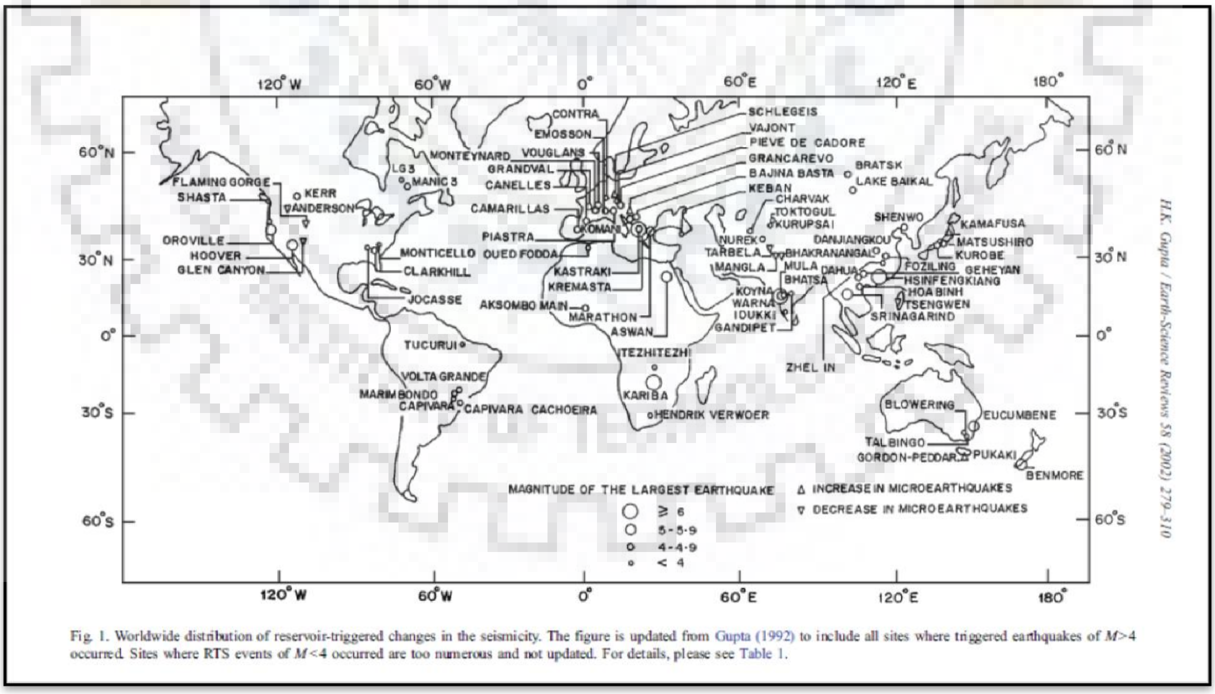
Table 2 - Reported cases of reservoir-associated changes in seismicity in India

Reservoir	**Height**	**Volume (10^6 m^3)**	**Year of Impounding**	**Year of Earthquake**	**Magnitude**
Koyna	103	2780	1962	1967	**6.3**
Warna	80	1260	1987	1993	**5.0**
Bhatsa	88	947	1981	1983	**4.9**
Dhamni	59	285	1983	1994	**3.8**
Gandipet	36	117	1920	1982	**3.5**
Idukki	169	1996	1975	1977	**3.5**
Mula	56	1017	1972	1972	**1.0**
Sriramsagar	43	32,000	1983	1984	**3.2**

Around 7 cases of RIS have taken place in India alone. The first case being the famous Koyna Earthquake in 1967 and other cases with magnitude ranging from 1.0 to 6.3



3.1 Cases of induced seismicity throughout the world



H.K. Gupta / Earth-Science Reviews 58 (2002) 279–310

Fig. 1. Worldwide distribution of reservoir-triggered changes in the seismicity. The figure is updated from Gupta (1992) to include all sites where triggered earthquakes of $M>4$ occurred. Sites where RTS events of $M<4$ occurred are too numerous and not updated. For details, please see Table 1.

Figure 3.2 – Worldwide distribution of reservoir Induced Seismicity

Koyna (M = 6.3), Kremasta (M = 6.2), Kariba (M = 6.2) and Hsinfengkiang (M = 6.1) happen to be the most severely affected cases of RIS where a maximum event of magnitude greater than 6 occurred within one to five years of filling of the reservoir. Koyna being the most prominent and unique site of RIS with multiple events of magnitude greater than 5.0 and thousands of events of micro seismicity. It is said to have claimed as much as 200 lives and injured over 2000 people. The earthquakes caused by Hsinfengkiang and Koyna dams is said to have caused considerable damage to the dam structure as well which tell us the intensity of these earthquakes.

3.3 CASE STUDIES OF SOME IMPOTANT OCCURENCES

Koyna Dam (December 10, 1967) - In the history of induced seismicity, Koyna Dam continues to be the most disastrous as well as a prominent site of induced seismicity where a magnitude of 6.3 which is the highest magnitude of RIS to occur anywhere in the world. Notably Koyna Dam has large height of 103m and a relatively large volume of 2780 million m^3. On December 10, 1967, 5 years after impounding the reservoir the earthquake of highest magnitude is known to have killed at least 200 people and injured over 2000 people while completely destroying the nearby areas in its vicinity. 12 cases having magnitude M > 4.0 occurred in a short span of 3 years between October 1973 to December 1976. Till now more than 10 cases of M > 5.0, over 160 earthquakes of M > 4.0 and more than 100,000 earthquakes cases of micro seismicity have taken place. The focal depth of the Koyna region is estimated to be 8-10 km.

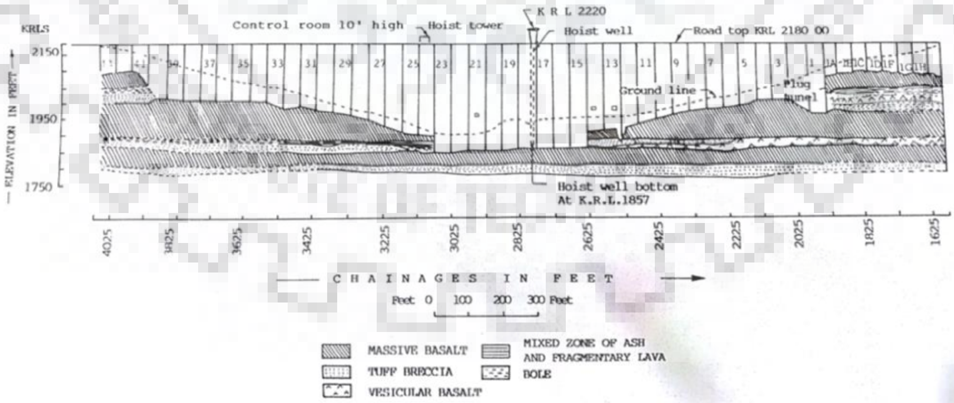
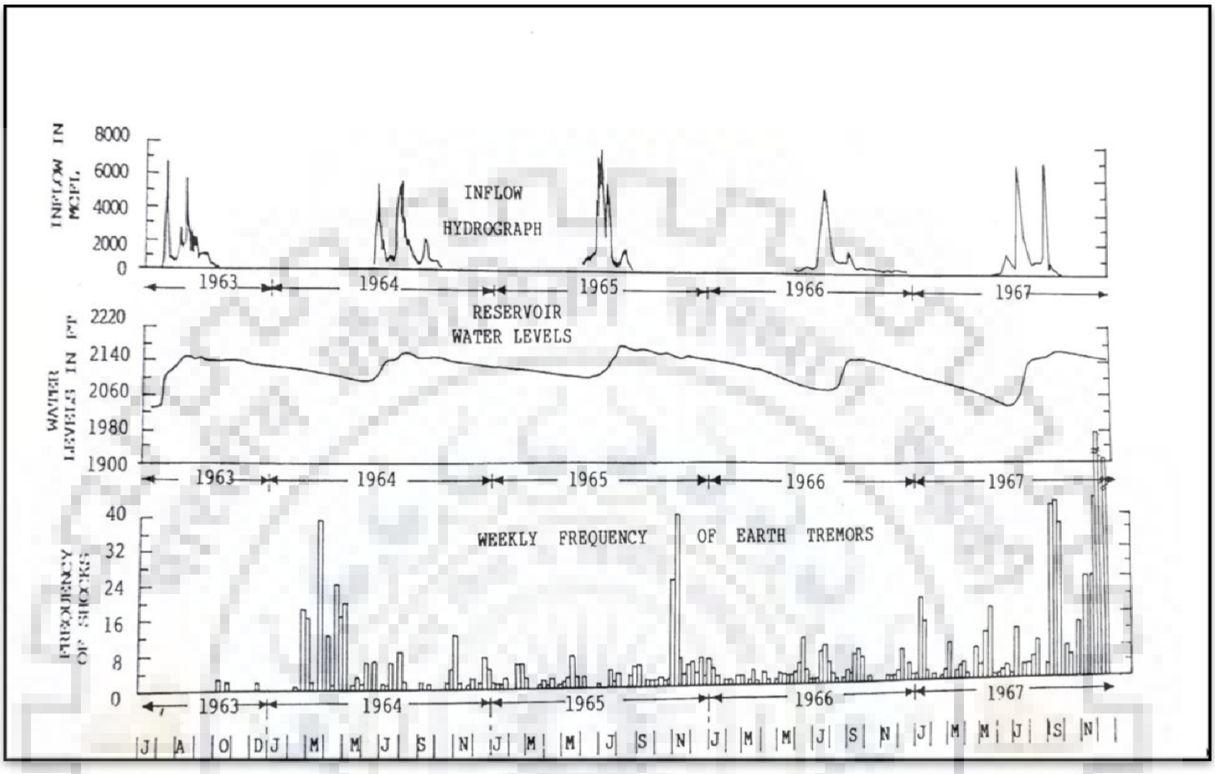


Fig. 4.21. Foundation geology of the Koyna Dam (modified from Committee of Experts, 1968).

3.3 Geology of Koyna Dam

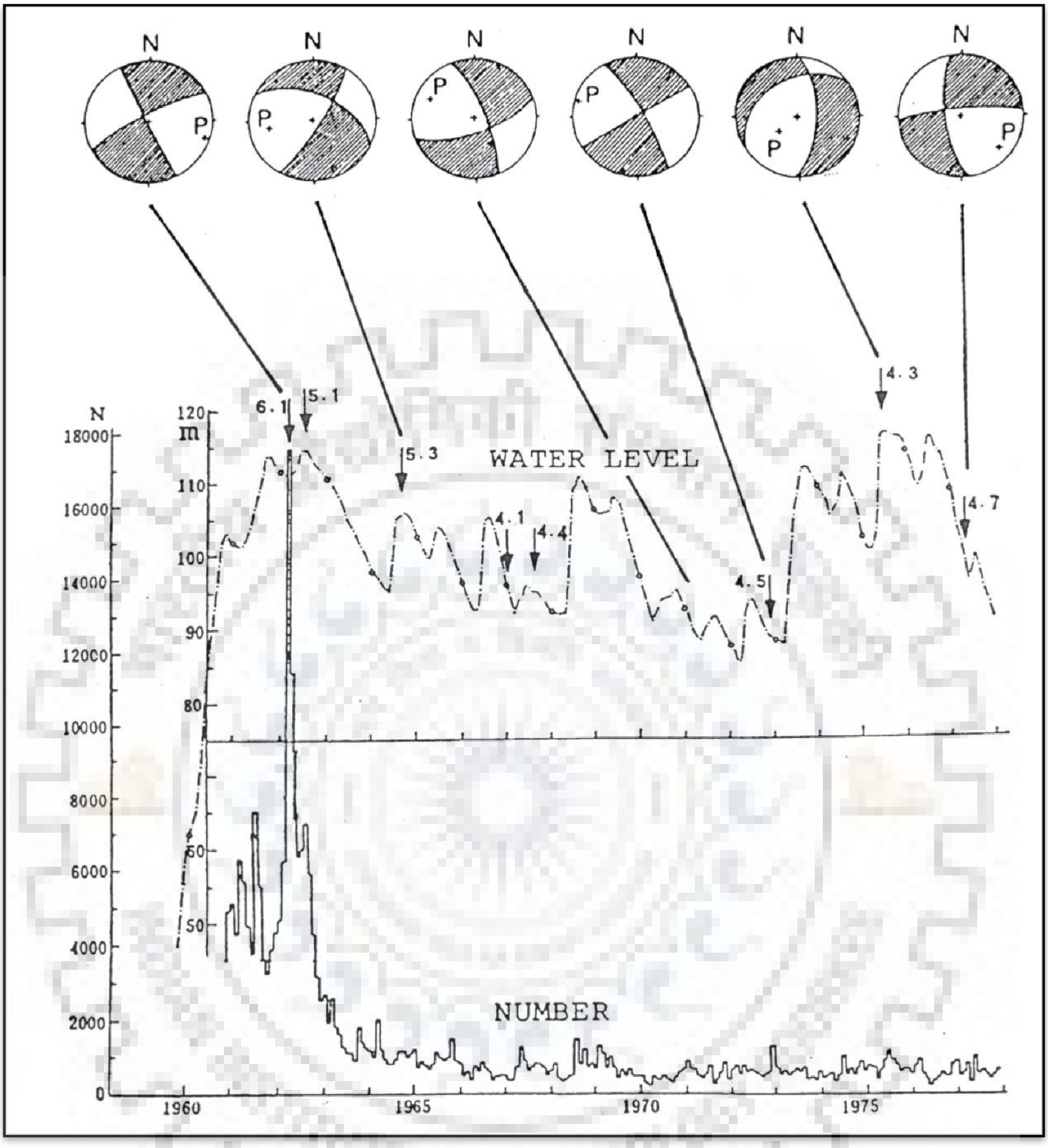
The geology of the Koyna Dam is shown in the above figure which shows massive basalt as the most part beneath the ground sandwiched between multiple layers of tuff breccia. Small regions also consist of Bole and vesicular basalt.



3.4 Seismicity in the Koyna region

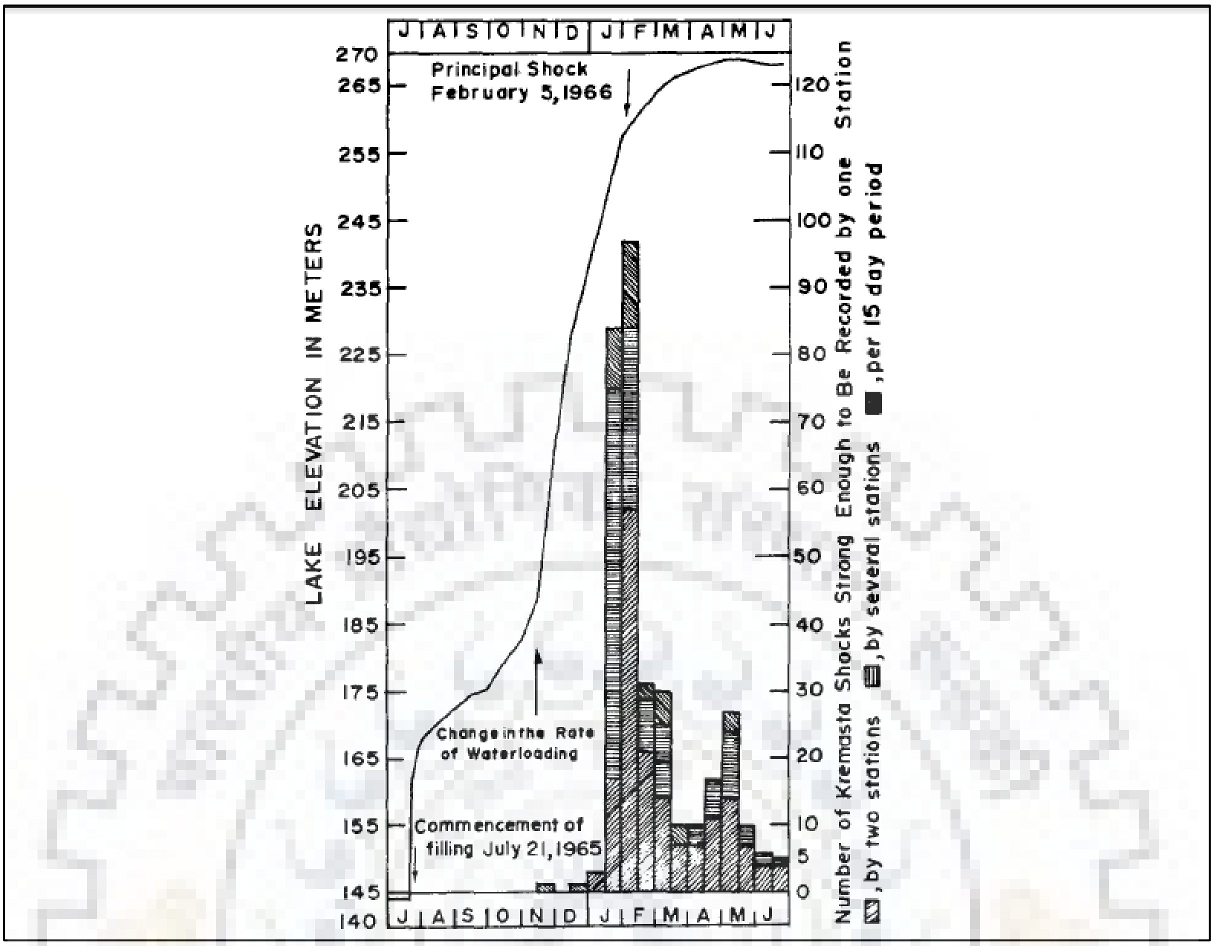
The above graph shows the change in water level to the seismicity of the Koyna region observed between the periods of 1963 to 1967. There is sharp spike is seismicity with water level changes.

Hsinfengkiang Dam (March 19, 1962) – Hsinfengkiang dam induced a maximum magnitude of 6.1 on the Richter scale on March 19. 1962, with a height of 105 m and a large volume of 13896 million m^3. It lies on East-West trending huge granite mass. It was recorded that the reservoir induced a staggering 258,267 shocks having $M > 0.2$, out of which 23,513 shocks had $M > 1.0$ by the end of the year 1972. The areas of highest seismicity were found to exist on the deeper sides of the reservoir where height of water column was found to be 80m. The focal depth of this region is very shallow and varies in between 1 to 11 km. 11 events of $M > 5$ occurred in February 1962itself and the b values of foreshocks and aftershocks was calculated as 1.12 and 1.04 respectively and the ratio of the largest aftershock to the main shock being 0.87



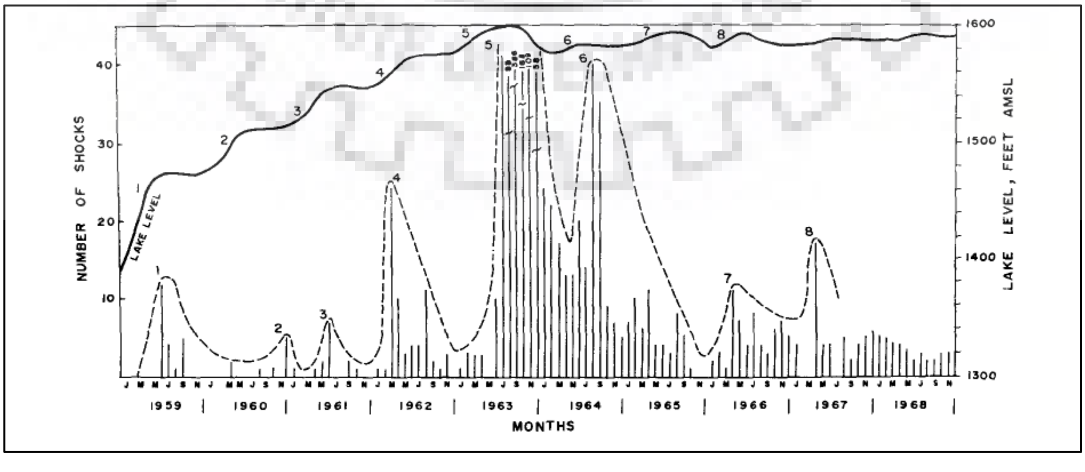
3.5 Water level and earthquake frequency in Hsinfengkiang Dam

Kremasta Dam (February 5, 1966) – No seismicity was observed 15 years prior to the construction of dam and no earthquake occurred within 50km of the dam site. The dam was impounded in July 1965 and first case of seismicity was observed in August of the same year. Seismicity was found to increase exponentially and the highest magnitude event of M 6.2 occurred in February next year i.e. 1966.



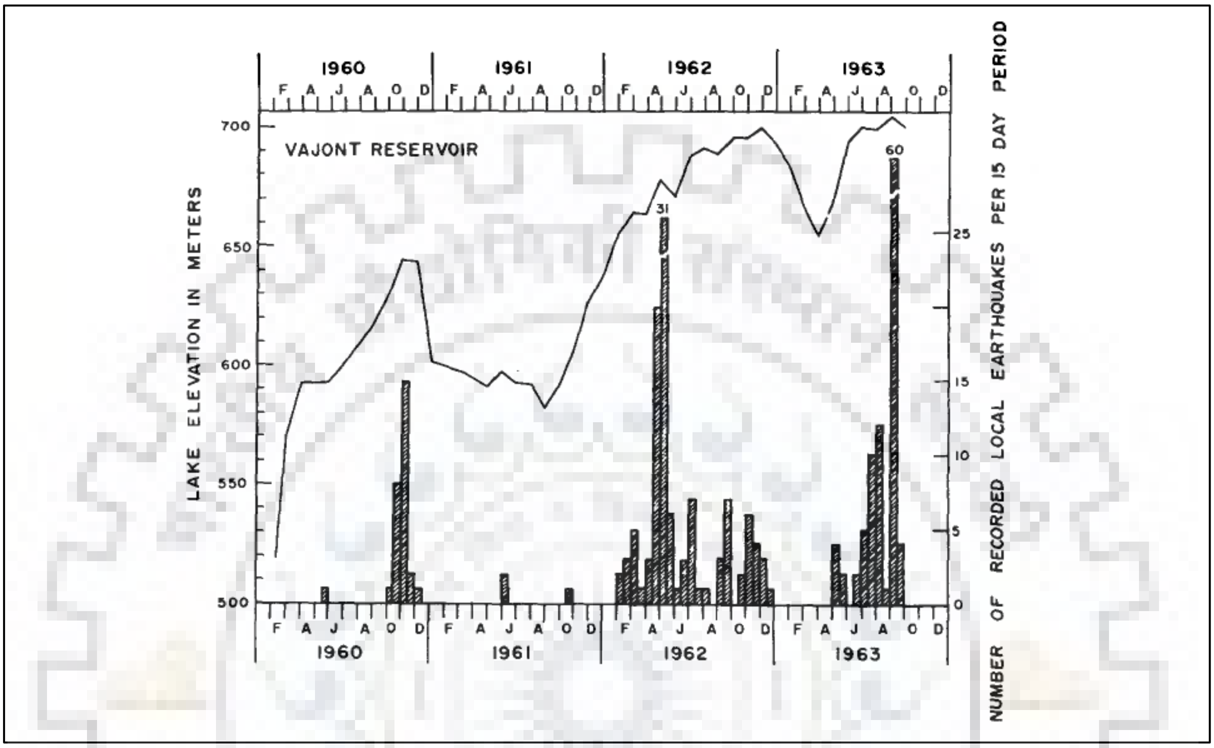
3.6 Kremasta Lake elevations and earthquake frequency

Kariba Dam – Previously considered to be seismically inactive area and no earthquakes were observed till 1963. Seismicity aroused in 1959 when the reservoir was filled. The dam has a height of 128m and large volume of 175,000 million m^3 making it a very large dam. The maximum magnitude of 6.2 occurred in 1963 five years after the initial seismicity was observed after the filling of reservoir. The region shows shallow focal depth of 8km.



3.7 Monthly tremor frequency and water levels of Lake Kariba

Vajont Dam – As soon as the filling of Vajont Dam took place in 1960 seismicity started to arise in the previously non seismic area and more than 250 cases of induced seismicity were observed in a span of 3 years from 1960 to 1963. The seismicity is linked to the filling of this reservoir.



3.8 Seasonal fluctuations of Vajont Reservoir levels and local Earthquakes

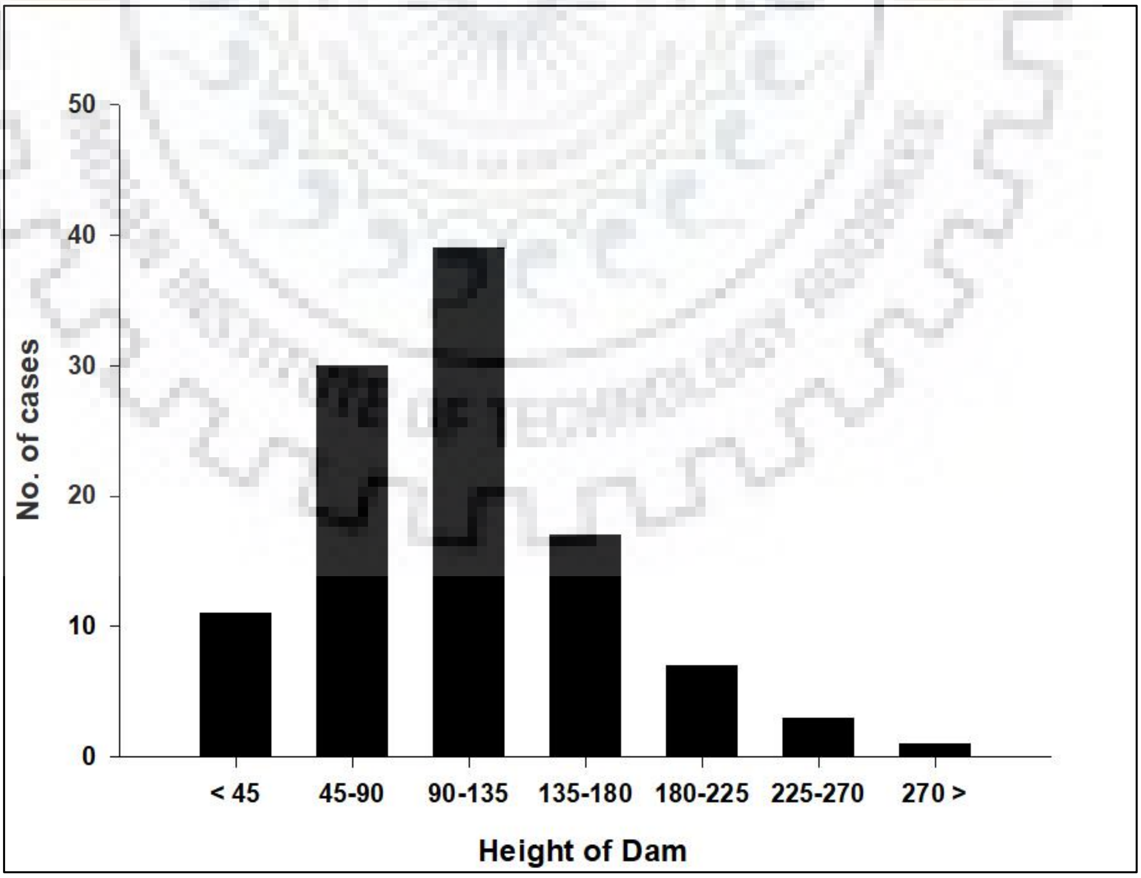
CHAPTER 04

RIS PARAMETERS

4.1 PARAMETERS ASSOCIATED WITH RIS

The five major parameters associated with RIS as discussed as below:

1) **Height and Volume of the Reservoir:** The most influencing factors for induced or triggered seismicity are the height and volume of the dam or basically the height upto which the reservoir is loaded since height and volume can also be treated as dependent factors. For the purpose of study the dams are categorized on their maximum depth and volume of water reached as it is directly proportional to the stress generated by the reservoir. The dams are categorized as shallow (less than 92m), deep (between 92 and 150m) and very deep (greater than 150m in depth). Dams having a height of over 100m are mostly associated with reservoir induced seismicity. In India Idukki and Koyna dam which have shown RIS fall into very deep and deep dams with a height of 169 and 103m respectively. Notably these dams also store large volumes of water 2000 and 2780 million m^3 respectively.

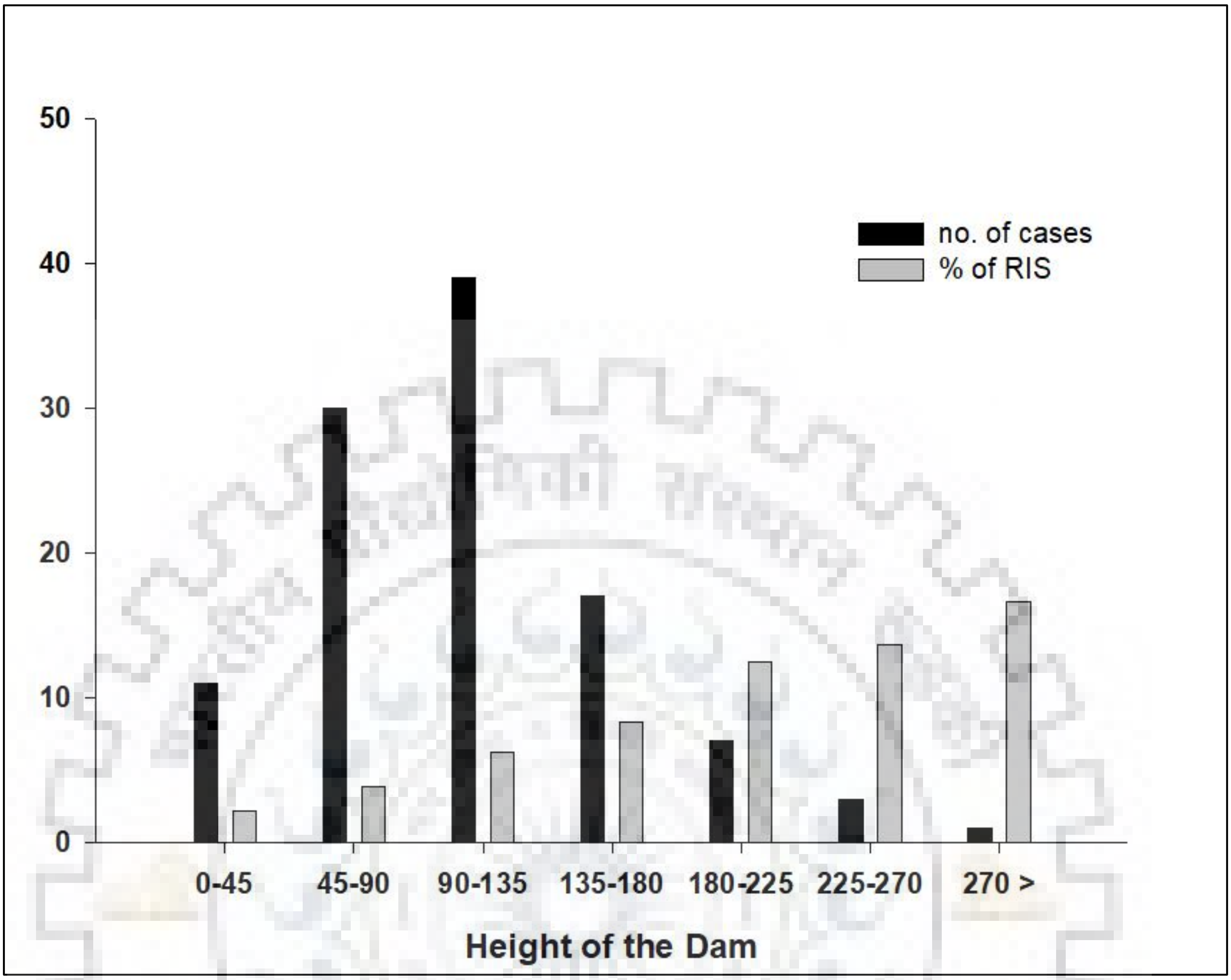


The above graph does not give an accurate relation between induced seismicity and height of the dam as it appears to increasing upto a height of 135m and then shows decrease in the number of cases upto 270m. This is because only a few dams are present in the world which possesses a height of 270m or more. Even dams in the range 225m to 270m are only 22 in number. To have an accurate measure of the relationship between height and RIS we plot the graph between percentages of dams causing RIS along with the number of cases to the height of dams.

Table 3 – Number of RIS cases and their distribution according to height

Height of Dam	**No. of Dams**	**No. of RIS cases**	**% of Dams causing RIS**
>45	500	11	2.20
45-90	779	30	3.85
90-135	450	39	6.22
135-180	204	17	8.33
180-225	56	7	12.50
225-270	22	3	13.63
270>	6	1	**16.67**

This gives us an accurate measure of increasing percentage of dams that have shown the phenomenon of RIS. Significant changes were observed in the Koyna and Warna reservoirs during 1993 preceding the enhanced seismic activity in the vicinity of Koyna–Warna Reservoirs. For a period of June 1993 to August 1993 an increment of 36m was made to the Koyna dam and an increase of 44m was made to the Warna reservoir in August 1993. This resulted in a spike in the seismicity of the Warna and Koyna region and two earthquakes having a magnitude M > 5 was observed due to this increase. This also points in the direction that there is a direct relationship between the height of water loaded in the dam and the seismicity of the region.



Volume	$>10^{10}$ m^3	$12\times10^8 - 10^{10}$ m^3	$<12\times10^8$ m^3
RIS Events	**15**	**17**	**35**

A plot of volume, height and largest magnitude RIS event was drawn by G.B Reacher and Keenay to find the relationship between depth, volume and RIS cases

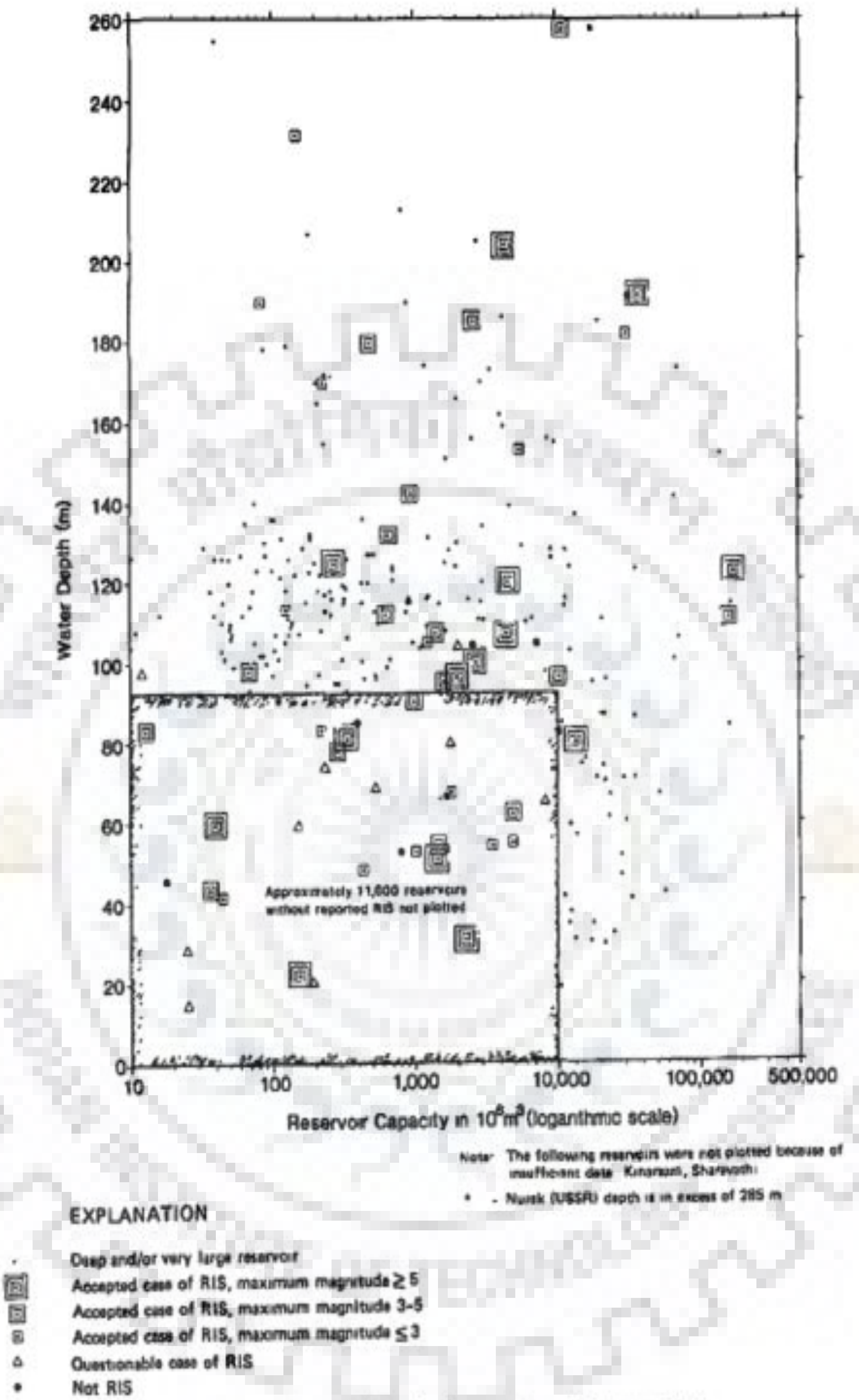
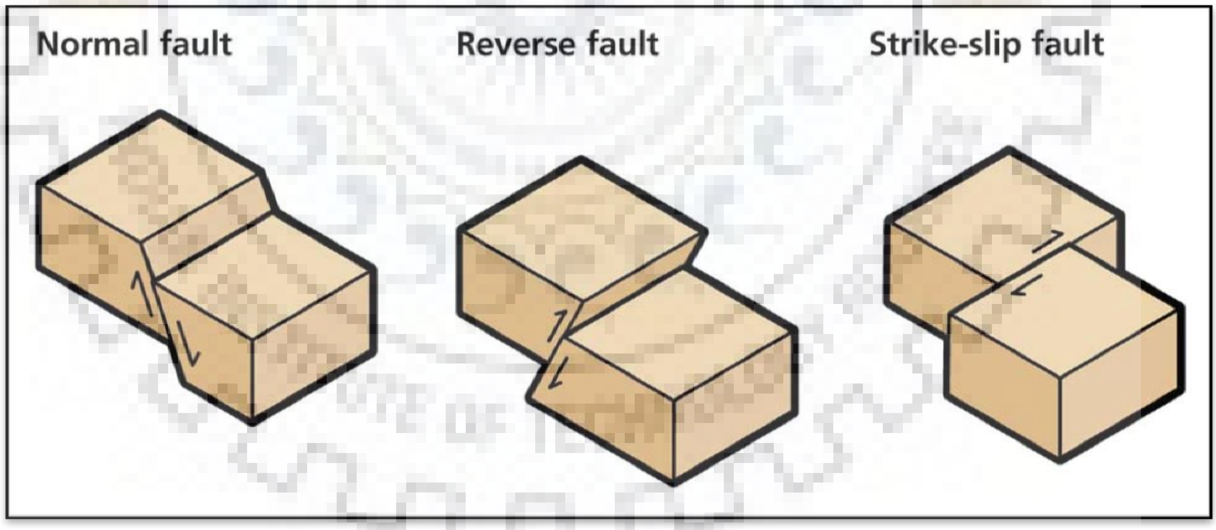


FIG. 1. Relationship of depth and volume and reported cases of RIS

4.1 Depth and Volume relationship of RIS

2) **Geology of the surrounding area:** The geological parameters refer to local geology of the area surrounding the reservoir, the tectonics and stress state. Based on the description provided by maps and soil type the area could be sedimentary, metamorphic or igneous. Each of them have different properties of permeability, maximum allowable stress, strength, hardness, shear modulus etc. Geology of a region is a not quantifiable and hence deep study is required to know the effect it has before and after the construction of reservoir mass.

3) **Faulting Parameters:** Faulting refers to the fact as to whether or not an active fault is present in the vicinity of the reservoir area. Various properties of faults such as its geometry, age of the fault, activity of the fault and its style are the determining factors for inducing an earthquake. It is assumed that many a times the water percolates deep into the fissures and cracks and lubricates the fault causing the slip which triggers an earthquake. There have been at least eight cases where the construction of dam has led to a decrease in the micro earthquake activity causing stability in the region, such as Bhakranangal dam (India), Ikawa (Japan), Mangla and Tarbela (Pakistan) etc. So the nature of fault is a determining factor as induced earthquake will depend on the nature of the fault type.



4.2 Types of Fault

4) **Stress State:** Three types of stress states occur in the reservoir region namely the extensional (or normal), shear (or strike slip) and compressional (or thrust). The construction of reservoir is related with additional vertical stresses added by the weight of water due to direct loading and by the pore pressure acting on the fault.

CHAPTER 5

MECHANISM AND CHARACTERSTICKS OF RESERVOIR INDUCED SEISMICITY

5.1 GENERAL

The basis of the comprehension of the occurrence of induced seismicity comes from the study of fluid injection induced seismicity in 1962 at the rocky mountain, Denver and the work by Hubbert in 1959 on the mechanism of induced seismicity by increase in the fluid pressure. The load of reservoir and the pore pressure were considered to be parameters of primary importance initially by many researchers including Bell and Nur (1978). H.K Gupta identified the seismic changes as a result of the rate as well as duration of loading of water in Koyna and Warna region.

Three main effects of reservoir loading were found to trigger earthquakes

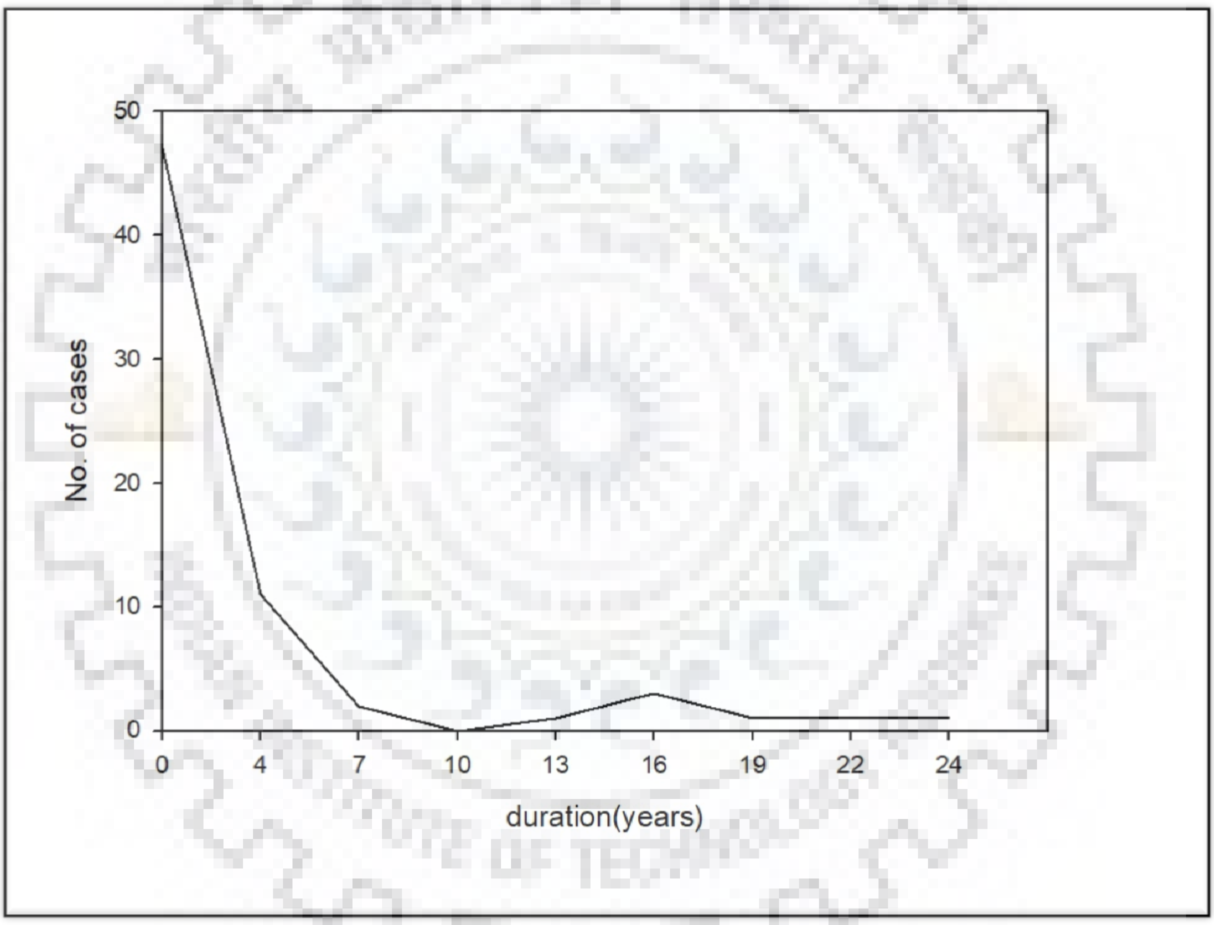
a) Increase in the elastic stress when the reservoir is impounded.
b) Pore pressure increase in saturated rocks as a result of decrease in pore volume that occurs by the effect of compaction, due to increase in the elastic stress.
c) Change in pore pressure due to fluid migration. In case the ground water table is low before the impounding of reservoir takes place water flows from the reservoir region to unsaturated soil which leads to increase in ground water table creating another factor of concern.

The essential mechanism can be caused due to coupling of any of the above factors individually or in combination. It is to be noted that for the occurrence of major earthquakes of M~5, pre-existing faults of adequate size must be present in the vicinity of the reservoir. The maximum size of RTS/RIS is dependant primarily on the state of stress around reservoir area. To find the effect of vertical stress due to direct loading of the reservoir calculations have been made to find its actual effect on the fault. Two types of responses are observed in reservoir induced earthquakes which are rapid and delayed response as mentioned below.

5.2 TYPES OF RESPONSE

Two types of responses are associated with reservoir induced seismicity:

a) **Rapid response:** As soon as the reservoir is loaded with water the seismicity in the vicinity of reservoir increases. It is denoted by low magnitude earthquakes, increased b-values, is confined to the immediate reservoir area the seismicity is directly related to changes in water level of the reservoir.
b) **Delayed response:** The seismicity is followed by a considerable delay after the reservoir is loaded. It is denoted by high magnitude earthquakes, no direct relationship between significant water level changes in the reservoir may extend significantly beyond the confines of the reservoir.



5.1 Types of Response

Out of the total cases of RIS recorded by H.K Gupta in his book “Developments in Geotechnical Engineering, 64 Reservoir Induced Earthquakes, Elsevier” the highest magnitude earthquakes are observed within the first three years of loading in 47 cases. This suggests rapid response is dominant in case of RIS and the possibility of occurrence is the highest within the first three years and decreases in the subsequent years. In more than 17 cases the seismicity of highest magnitude occurred within two years of loading of the reservoir.

5.3 MAGNITUDE RATIO OF THE LARGEST AFTERSHOCK TO THE MAIN SHOCK AND THE B-VALUES:

Gupta et al. (1969) studied the induced seismicity at Koyna after the disastrous Koyna earthquake and found a high b value and a high-magnitude ratio. This was presumed to be a typical characteristic of RIS. Similar observations are recorded at various other sites of reservoir associated earthquakes. The following table shows the ratio of the highest magnitude ($M_{0)}$ to the largest aftershock (M_1) and the b values of a number of dams. A high magnitude ratio (M_1/M_0) of approximately 0.9 was found for all the dams and the b-value exceeding 1 in most of the cases. This is postulated to be a general trend for RIS events. The highest b-value of 1.40 was observed for Lake Mead.

Table 4: Magnitude ratios and b values for various dams

Region	Main Shock M_o	Aftershock M_1	M_1/M_o	b Value
Lake Mead	5.0	4.4	0.88	1.40
Monteynard	4.9	4.5	0.92	0.72
Mangla	3.5	3.3	0.94	0.96
Kariba	6.1	6.0	0.98	1.03
Kremasta	6.2	5.5	0.89	1.12
Koyna	6.0	5.2	0.83	1.28
Hsinfengkiang	6.1	5.3	0.87	1.04

5.4 EFFECT OF DIRECT LOADING DUE TO VERTICAL STRESS

Direct loading refers to vertical stress caused by the added weight of water on the fault lying below the dam. In a large number of cases, change in seismicity is correlated to the filling of reservoir. Since a reservoir carries large mass of water it is bound to cause stress changes in the region in and around the reservoir due to direct vertical stress and the pore pressure due to water. To find the contribution of added pressure due to direct vertical stress on the fault in triggering induced seismicity following calculations have been made. Assuming the dam to be resting on rock mass with bulk density Υ_{rock} 27 KN/m^3 and specific weight of water to be Υ_{water} 9.81 KN/m^3. In most cases, a fault lies beneath or near the reservoir region. Assuming that an additional load is acting on the fault due to the weight of water column whereas the load due to rock mass was already acting on the fault we can calculate the additional load created and compare whether it is large enough to trigger an earthquake or cause a slip. For comparison let us consider a reservoir having an active fault beneath it at a distance of 1km, assuming the dam height to be 200m. The stresses acting on the fault will be:

1) Stress due to weight of water on the fault, defined as the product of height of reservoir and the specific weight of water defined by the mathematical relation
   $\boldsymbol{\sigma_w = \Upsilon_w}$ **x height of reservoir**
2) Stress due to rock mass on the fault, defined by the product of height upto which rocks are present and the bulk density of rocks, mathematically defined as
   $\boldsymbol{\sigma_v = \Upsilon_{rock}}$ **x height**

$$\sigma_w = \Upsilon_w \text{ x height of reservoir}$$

$$\sigma_w = 9.81 \text{ kN/m}^3 \text{ x } 200 \text{ m} = 1962 \text{ kN/m}^2$$

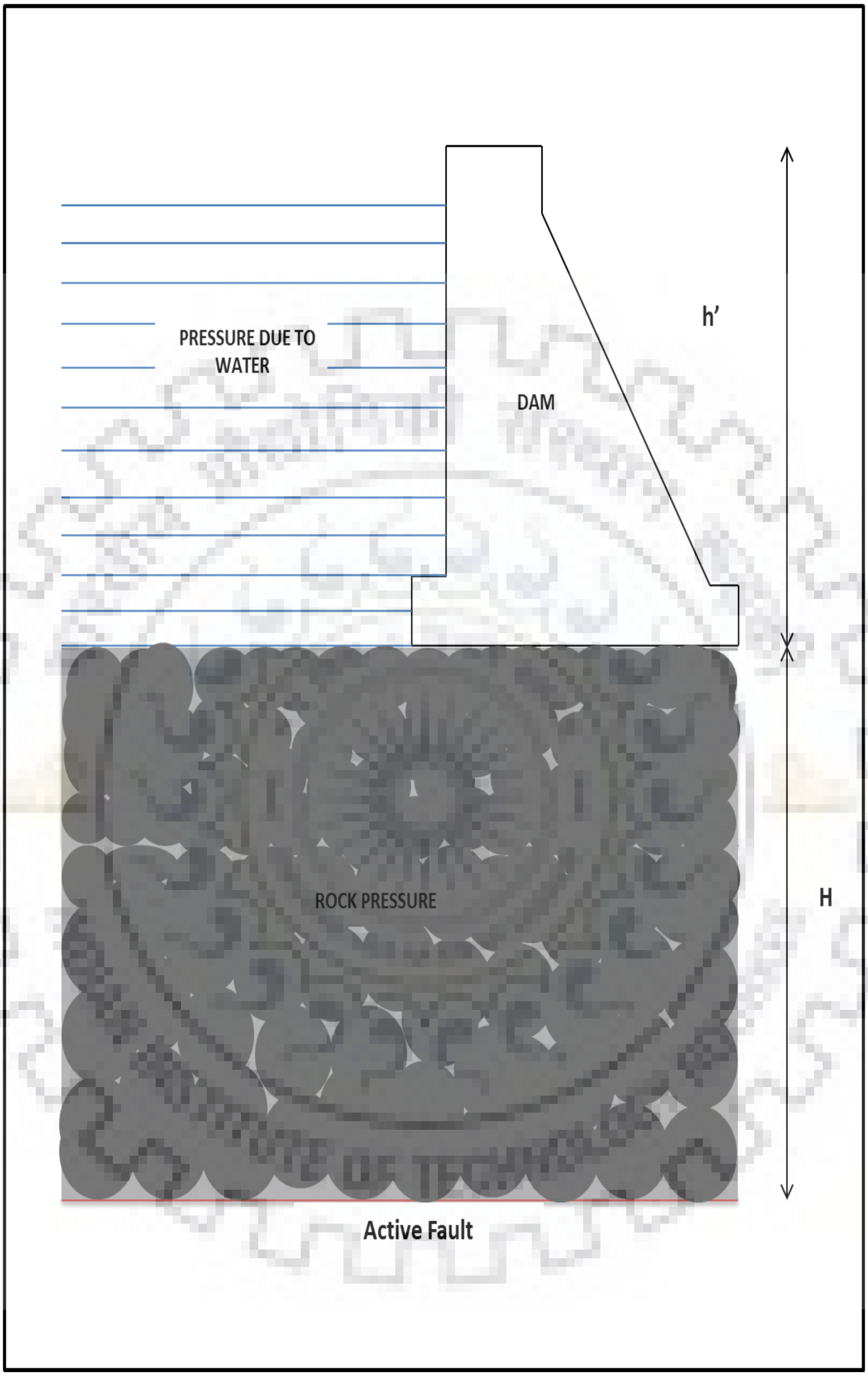
$$\sigma_v = \Upsilon_{rock} \text{ x height}$$

$$\sigma_v = 27 \text{ kN/m}^3 \text{ x } 1000 = 27000 \text{ kN/m}^2$$

$$\boldsymbol{\sigma_{total} = \sigma_v + \sigma_w = 28962 \text{ kN/m}^2}$$

Percentage increase in stress due to the weight of water = $(\sigma_{total} - \sigma_v) \text{ x } 100/ \sigma_v$ = **7.2%**

Similarly for a dam having focal depth of 10km the additional increase in stress due to weight of water shall be lowered down to 0.72% which is too less to trigger an earthquake. Thus we can say that the stress added due to direct vertical load in the form of water is very less and therefore not sufficient to cause or trigger reservoir induced seismicity.



5.4 Cross sectional view of a fault lying under a dam and the vertical stress acting on it.

Gupta S, et. al. has provided seismological evidence in their research paper that an active fault lies beneath the Tehri dam region at a focal depth of 5 km. Considering Tehri Dam to be resting on rock mass with bulk density of rocks to be 27 kN/m^3 and specific weight of water to be 9.81 kN/m^3 following calculations have been made to find the amount of direct vertical stress due to a water column of 260.5m on the fault lying beneath the dam.

1) Stress due to weight of water on the fault, defined as the product of height of reservoir and the specific weight of water defined by the mathematical relation
   $\sigma_w = \Upsilon_w$ x height of reservoir
2) Stress due to rock mass on the fault, defined by the product of height upto which rocks are present and the bulk density of rocks, mathematically defined as
   $\sigma_v = \Upsilon_{rock}$ x height

$$\sigma_w = \Upsilon_w \times \text{height of reservoir}$$
$$\sigma_w = 9.81\ \text{kN/m}^3 \times 260\ \text{m} = 2550.6\ \text{kN/m}^2$$
$$\sigma_v = \Upsilon_{rock} \times \text{height}$$
$$\sigma_v = 27\ \text{kN/m}^3 \times 5000 = 135000\ \text{kN/m}^2$$
$$\boldsymbol{\sigma_{total} = \sigma_v + \sigma_w = 137550.6\ \text{kN/m}^2}$$

Percentage increase in stress due to the weight of water = $(\sigma_{total} - \sigma_v) \times 100/\ \sigma_v$ = **1.88%**

Let us assume that in future if the height of dam is increased to a staggering 350m and the fault distance be reduced to 3km then the increase in percentage will be as below:

1) Stress due to weight of water on the fault, defined as the product of height of reservoir and the specific weight of water defined by the mathematical relation
   $\sigma_w = \Upsilon_w$ x height of reservoir
2) Stress due to rock mass on the fault, defined by the product of height upto which rocks are present and the bulk density of rocks, mathematically defined as
   $\sigma_v = \Upsilon_{rock}$ x height

$$\sigma_w = \Upsilon_w \times \text{height of reservoir}$$
$$\sigma_w = 9.81\ \text{kN/m}^3 \times 260\ \text{m} = 3433.5\ \text{kN/m}^2$$
$$\sigma_v = \Upsilon_{rock} \times \text{height}$$
$$\sigma_v = 27\ \text{kN/m}^3 \times 3000 = 81000\ \text{kN/m}^2$$

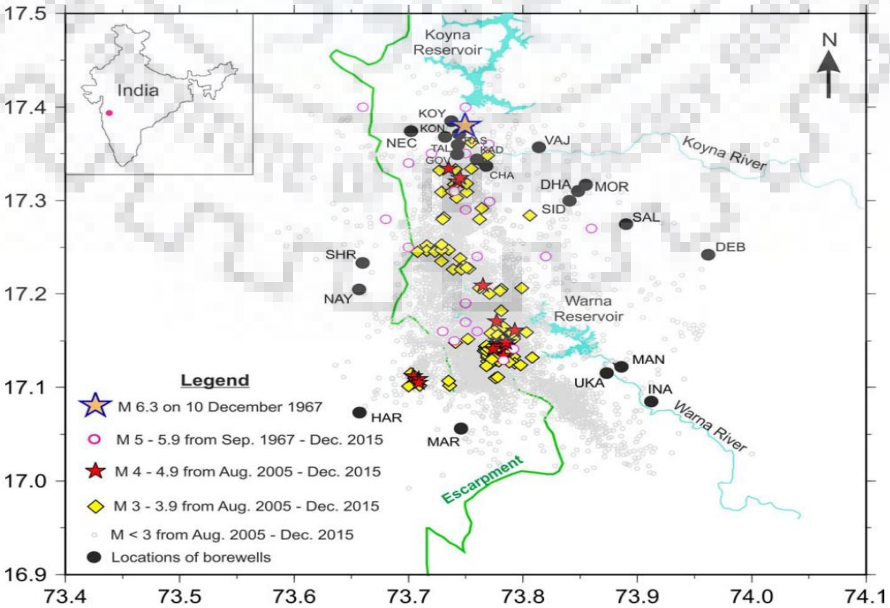
$$\boldsymbol{\sigma_{total} = \sigma_v + \sigma_w = 84433.5\ \mathrm{kN/m^2}}$$

Percentage increase in stress due to the weight of water = $(\sigma_{total} - \sigma_v) \times 100/\ \sigma_v$ = **4.23%**

This will cause an increment of only 4.23% which does not seem to be enough to cause an earthquake. This result suggests that the weight added by water does not play any significant role in the triggering the earthquake as the additional stress accounts for less than 2% of the existing stress that the fault. Taking account of this we can conclude that the effect caused due to pore water pressure and its chemical effects on the fault and the fissures are to be treated as major causes of concern rather than the vertical load caused by water.

5.5 EFFECT OF PORE PRESSURE

In his paper "In-situ Pore pressure variations in Koyna-Warna for triggered earthquakes" R.K Chadha et. al. discusses the effect of pore pressure variations and their effect on rock strength and failure of rocks results in the triggering of earthquake. For that purpose 21 pressure transducers were installed in and around the Koyna-Warna regions of high strain sensitivity from 1995 to 1998 to calculate the hydraulic pressure created. They concluded that the monitoring in Koyna and Warna region shows discrete co seismic step like changes to be related to earthquakes of magnitude 4.0 < M < 5.3 in the region. Various observations suggested that seismicity is correlated with water level drop.



5.5 Pressure Transducers in Koyna Warna Region

CHAPTER 6

RIS IN HIMALAYAS WITH SPECIAL REFERENCE TO TEHRI DAM

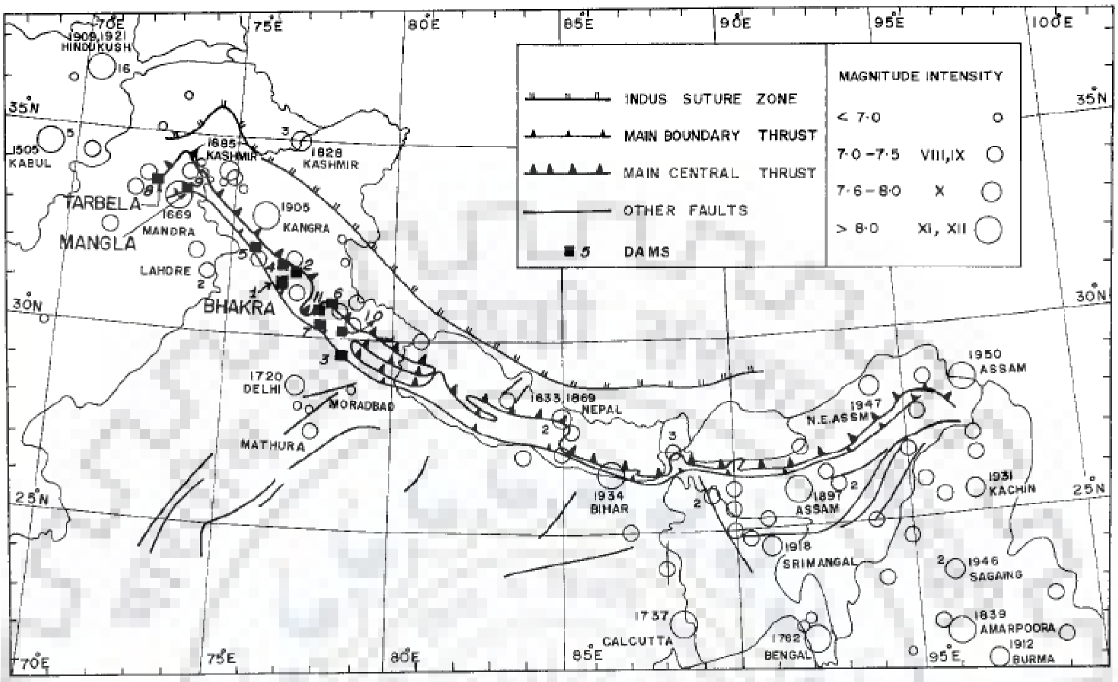
6.1 GENERAL

In the last 30 years, a large number of dams have been constructed, proposed and a dozen of dams including Duhangam, Rampur, Loharinag, and Subhansiri are presently under construction. Eleven of these dams mentioned below have large reservoir volumes of above 1000 million m3 and depths exceeding 100m. All these dams are located in the naturally high seismicity of the Himalayan range and therefore the risk associated with them is a cause of concern for the safety of people and the dam itself. So far, no incident of seismicity associated with reservoir impoundment has taken place in case of Himalayan dams. Thrust faults are by far the most common in the Himalayas. The fault plane solutions of most tectonic earthquakes in the Himalayas show evidence of thrust faulting. It is therefore concluded that this type of fault is known to have existed in the Himalayas in the past and continues to be present even today. A lot of civil engineers, earth scientists, and geologists use this fact to claim that the phenomenon of reservoir induced seismicity is unlikely in the Himalayas.

Table 5: Dams on the Himalayan Rivers with heights exceeding 100m

S. No.	Dam	River	Height (m)	Reservoir Volume (10^6 m^3)
1	Bhakra	Sutlej	226	9868
2	Pondoh	Beas	116	8141
3	Kalagarh	Ramganga	126	2369
4	Pong	Beas	133	8570
5	Thein	Ravi	147	3300
6	Kothar	Kosi	155	4080
7	Kishau	Tons	253	2400
8	Tarbela	Sindhu	143	1367
9	Mangla	Jhelum	118	7250
10	**Tehri**	**Bhagirathi**	**261**	**3539**
11	Lakhwar (under construction)	Yamuna	192	580

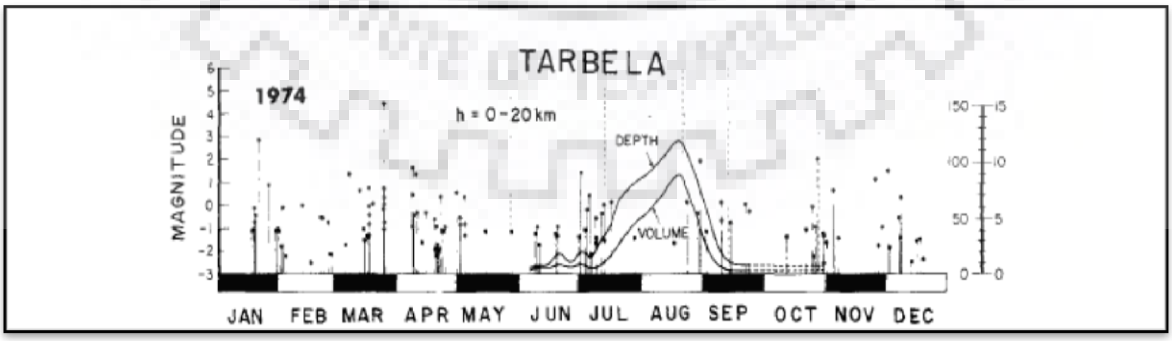
Himalayas falls into the seismically most active zones of the earth and devastating cases of earthquakes have taken place in the Himalayas of Magnitude as great as 8.4 on the Richter scale. A number of large reservoirs having height over 100m are under construction in the Himalayan belt from Pakistan to the North-East states of India covering Nepal and Bhutan in between. The figure below shows the large dams of height greater than 100m and earthquakes of high magnitude recorded. The event of reservoir induced earthquakes has not yet been recorded in the Himalayas and so it is not to be confused with the figure that the earthquakes are a result of construction of dams in the Himalayan region.



6.1 Major Dams and Earthquakes in the Himalayan belt

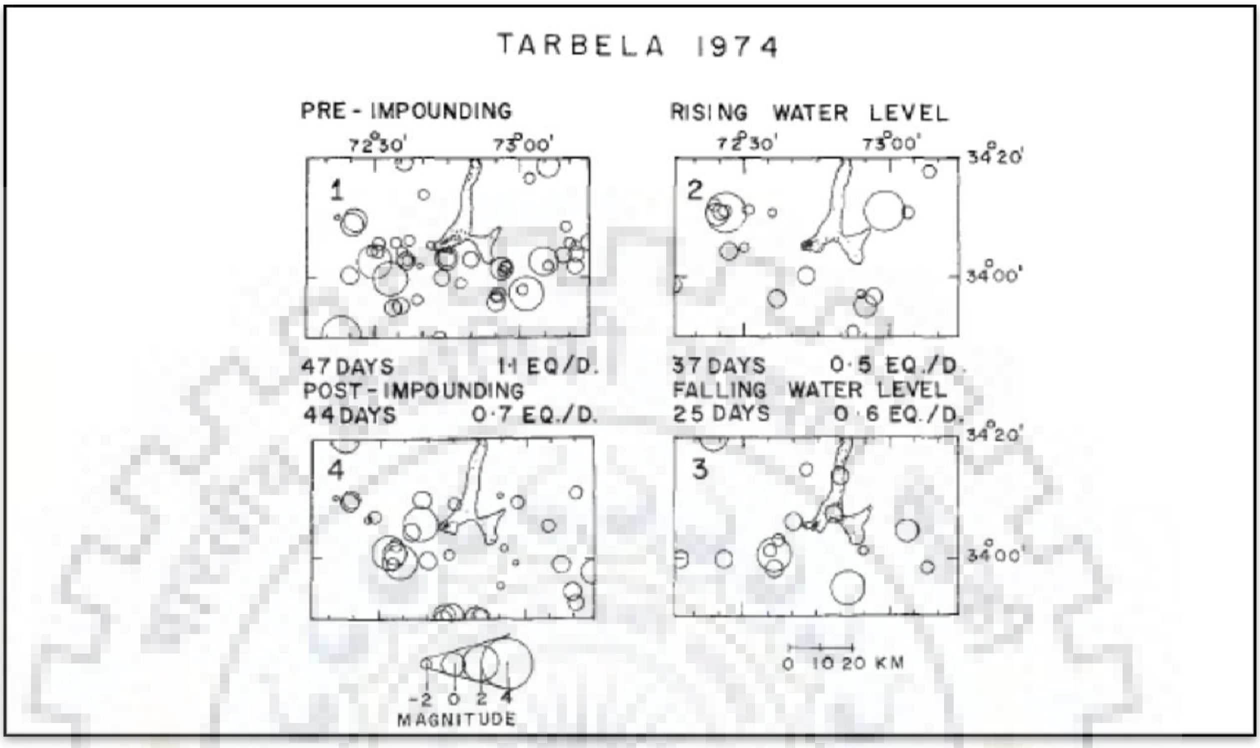
Tarbela Dam

Tarbela dam is one of the largest dams in the Himalayan belt with a volume of 1367 million meter^3 and a height of 143meter on the Sindhu River on the foothills of Himalaya in Northern region of Pakistan. This region has a history of seismicity with earthquakes of magnitude 7.0 or more occurring in the past. The dam was loaded in 1975 and astonishingly decrease in seismicity was observed post impoundment



6.2 Seismicity in Tarbela Dam (1974)

This graph shows the seismicity in the region in 1974 from January to December a peak magnitude of less than 3 was observed even on the maximum loading of 143m.



6.3 Seismicity of Tarbela Dam 1974

Mangla Dam

Mangla dam is located on the Jhelum River and with a volume of 7250 million m^3 and a height of 118 meters it constitutes to be a very large dam globally. This region has a history of catastrophic earthquakes like the Mandra earthquake that occurred on 4 June, 1669. Micro seismicity was observed in the region before and after filling of the reservoir but after five years of filling the reservoir decrease in micro seismicity was observed at the Mirpur station which is present there since 1965.

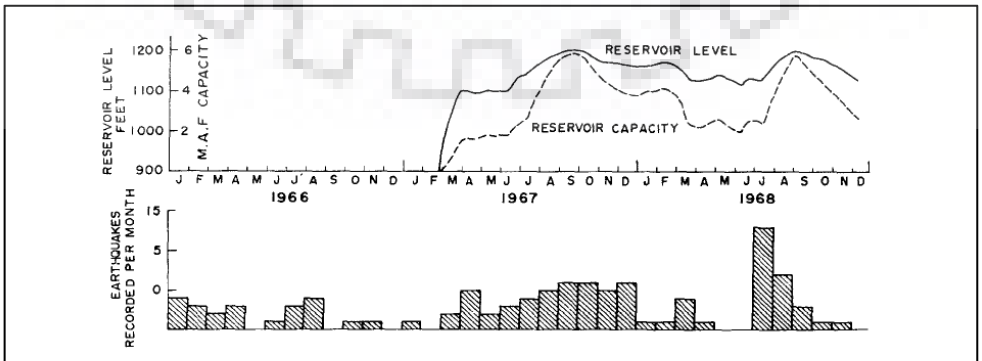
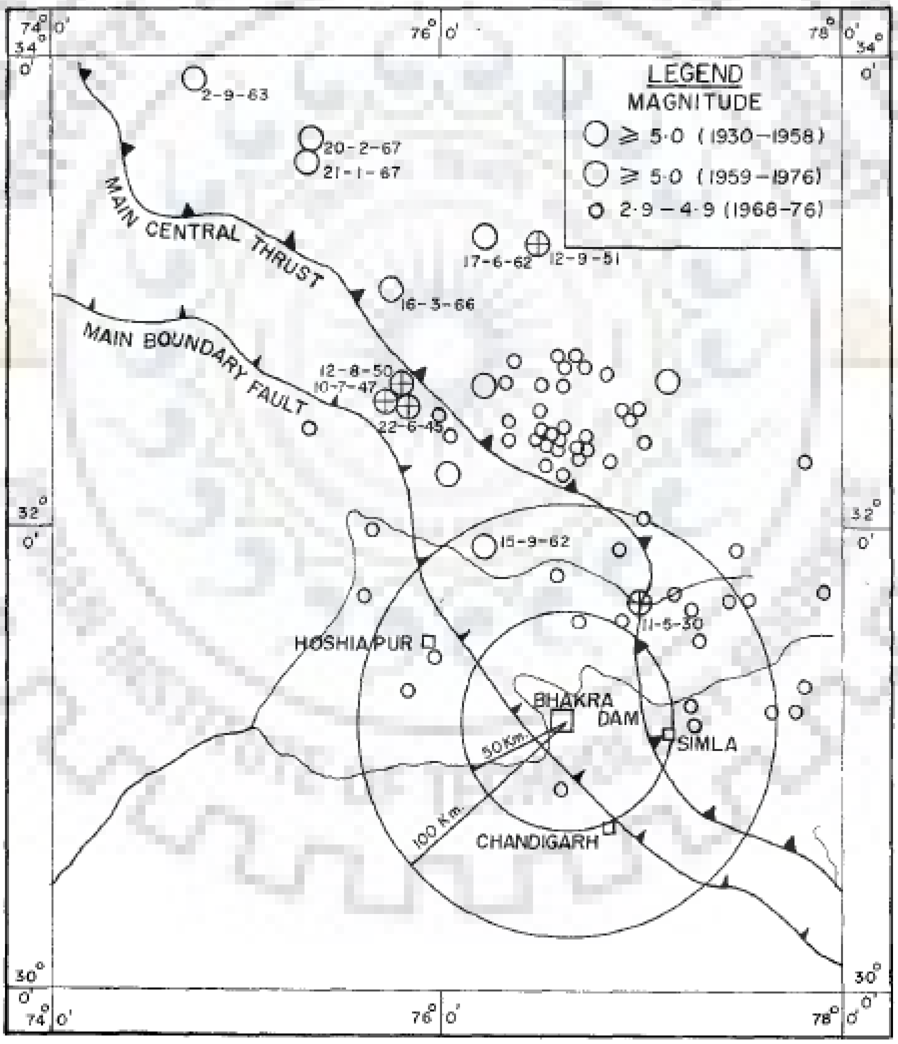


FIG. 3. Mangla Reservoir water-level variation and monthly frequency of the earthquakes recorded near it (Adams, 1969).

Bhakra Dam – The dam is constructed on the Sutlej having a volume of 9900million m^3 and a height of 226m it is one of the largest dams in the world. Earthquakes of high magnitude causing much destruction have occurred in the past as can be seen in the figure below magnitudes of $M > 5$ have occurred multiple times. The reservoir was filled in 1958 and a height of 155m was reached in 1963. No earthquake activity was observed anywhere in the range of 50km from the dam. An earthquake of magnitude 5 occurred within 100km of dam region but is not associated to RIS as most cases of RIS occur within 25km of the dam region.

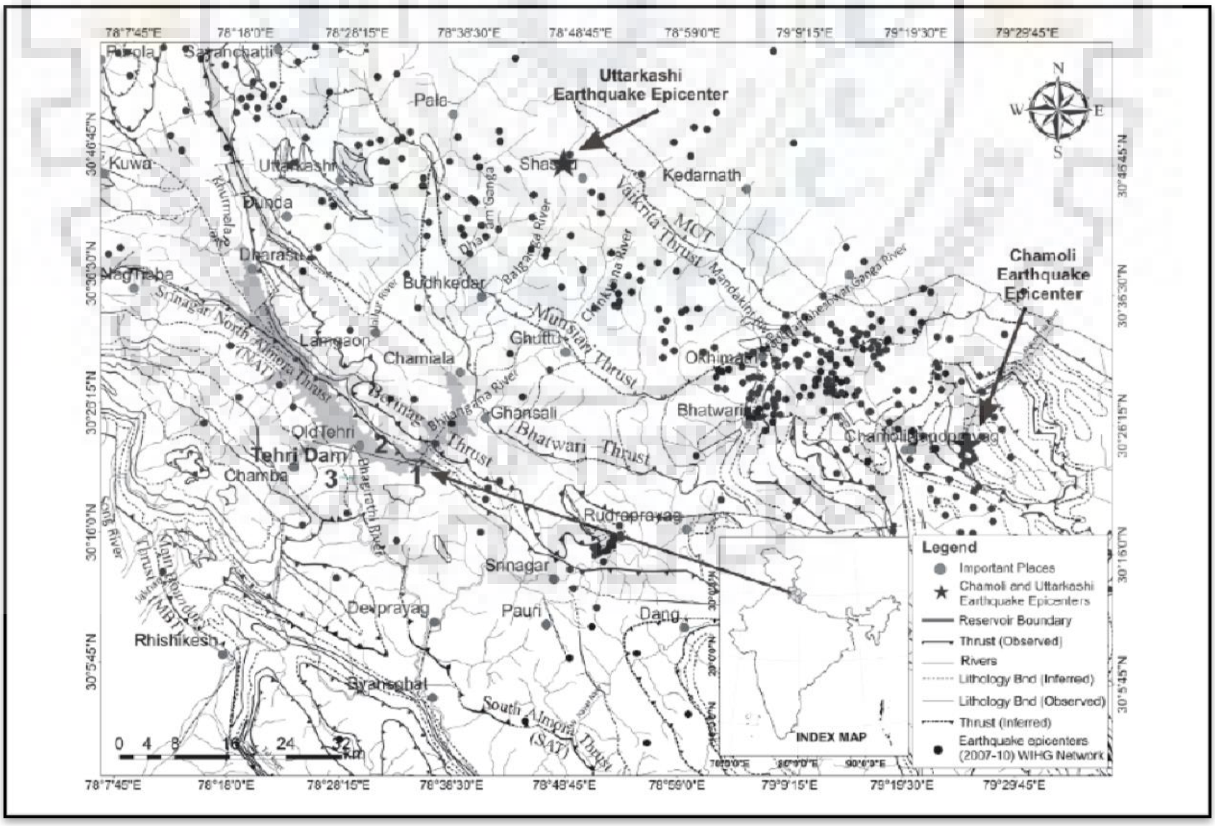


6.5 Earthquakes and Faults in Bhakra region

Also the seismicity observed by various seismographs at Kalagarh Dam, Pondoh and Pong Dam suggest that the seismicity in the area has not increased after impoundment of the dam even after reaching maximum heights and fluctuating level of water height but in most cases as seen above the seismicity has decreased after the construction of dam and it can be assumed that this is a general feature of this area and the filling of reservoir has had a stabilizing effect on this region in terms of seismicity.

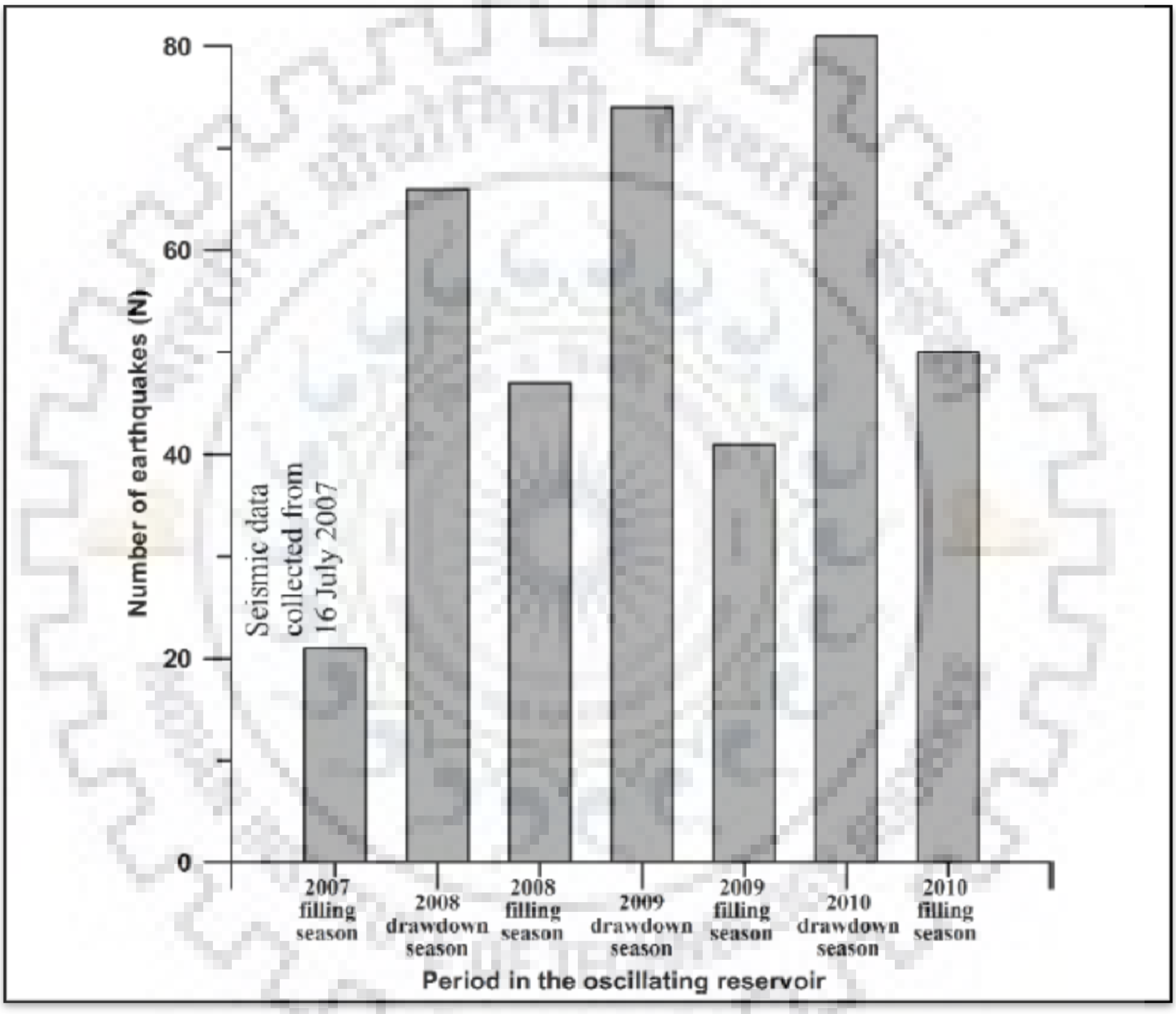
6.2 TEHRI DAM

With a height of 260.5 m and volume of 3539 million m^3 Tehri Dam is the highest dam in India and one of the highest dams in the world. Situated on the Bhagirathi River at the foothills of the Himalayas it is situated in one of the most seismically active regions of the world. Tehri dam is an irrigation and power generation project this means that due to the purpose of irrigation the dam undergoes drawdown and filling cycles. The filling of Tehri dam took place in 2005 right after the construction was completed. Tehri lies in zone V where Chamoli M~6.6 and Uttarkashi M~6.8 earthquakes took place in 1999 and 1991 respectively.



6.6 Major Earthquakes and epicentres in Uttarakhand

Presently holding a volume of 2620 million m^3, Tehri dam is a rock and earth dam. This type of dams exhibit high damping, inertia and a good amount of flexibility which prevents them against cracking. A study by Chaudhary et. al. using GPS shows that filling of the reservoir brings about a stabilizing effect in the region as higher micro seismicity is observed during drawdown of reservoir and low seismicity was observed when the dam was loaded.



6.7 Seismic changes in Tehri Dam during filling and drawdown cycles

CHAPTER 7

METHODOLOGY AND QUANTIFICATION OF RIS

7.1 GENERAL

The phenomenon of RIS has been observed in more than 100 reservoirs till now and the associated parameters as discussed previously; the height, volume, active fault, stress state and geology have been studied for various dams. For the available data probabilistic model is created and the probability of occurrence of RIS and its probable magnitude have been studied. Since volume and height of the dam are the only quantifiable parameters of study the probabilistic approach is best suited approach to calculate this hazard. Using the basics of conditional probability for the five parameters, likelihood ratios are obtained through which the final probability is calculated for RIS in case of Tehri Dam.

7.2 STATISTICAL PREDICTIVE MODEL

In 1982 G.B Reacher and Keenay gave a model to statistically determine the probability of RIS based on the study of 234 dams out of which 29 dams had shown the phenomenon of RIS and for 204 other cases of non RIS. Based on the method of conditional probability the likelihood ratios were obtained as explained below.

The five parameters are named as D, V, F, S, and G for depth (height), volume, fault activity, stress state and geology respectively. The depth is bifurcated into 3 categories: very deep (d_1), deep (d_2) and shallow (d_3) similarly the volume is categorized into very large (v_1), large (v_2) and small (v_3) and so on.

Table 6 – Attribute categorization and denotations

Attribute	1	2	3
Depth	d_1 = very deep	d_2 = deep	d_3 = shallow
Volume	v_1 = very large	v_2 = large	v_3 = small
Stress State	s_1 = extensional	s_2 = compressional	s_3 = shear
Fault Activity	f_1 = active fault	f_2 = no active fault	Not known
Geology	g_1 = sedimentary	g_2 = metamorphic	g_3 = igneous

Number in parenthesis refers to the number of events in that category. For example out of the 29 reservoirs of accepted RIS 10 reservoirs are categorized in very large dams so the probability of very deep having accepted case of RIS is 10/29 = 0.34. In data set D, frequency or prior odds of occurrence is defined by the number of dams showing RIS (29) divided by the total number of dams (234) = 29/234 = 0.12. Similarly the probability of non-occurrence of RIS will be 204/234 = 0.88

Table 7 - Accepted Cases of RIS

Attribute	Number of Reservoirs	1	2	3
Depth	29	10(0.34)	18(0.62)	1(0.03)
Volume	29	7(0.24)	11(0.38)	11(0.38)
Stress State	29	4(0.14)	18(0.62)	7(0.24)
Fault Activity	7	7(1.00)	0	-
Geology	28	13(0.46)	8(0.29)	7(0.25)

Table 8 - Non-accepted Cases of RIS

Attribute	Number of Reservoirs	1	2	3
Depth	204	27(0.13)	144(0.71)	33(0.16)
Volume	205	52(0.25)	36(0.18)	117(0.57)
Stress State	203	34(0.17)	138(0.68)	31(0.15)
Fault Activity	6	4(0.67)	2(0.33)	-
Geology	165	57(0.35)	64(0.39)	44(0.26)

Calculation of Variance

$$\mathbf{V (p) = p (1-p)/n}$$

$$= (0.34) (0.66) / 29 = 0.0077$$

Standard deviation is the square root of variance = $\sqrt{V}$ (p) = $(0.0077)^{0.5}$ = 0.088

Single Attribute analysis

For each attribute, applying Bayes' theorem

$P(RIS|x_1) = P(RIS)\,P(x_1|RIS) / [P(RIS)\,P(x_1|RIS) + P(nRIS)\,P(x_1|nRIS)]$

x_1	is the attribute (depth, volume, geology, fault activity, stress state)
P (RIS)	prior odds of accepted RIS
P (nRIS)	conditional probability of non-accepted RIS
$P(d_1|nRIS)$	conditional probability of depth d_1 for accepted RIS
$P(d_1|RIS)$	conditional probability of d_1 for non-accepted RIS

For depth:

$P(RIS|d_1) = P(RIS)\,P(d_1|RIS) / [P(RIS)\,P(d_1|RIS) + P(nRIS)\,P(d_1|nRIS)]$

$P(RIS|d_1) = (0.12)(0.34) / [(0.12)(0.34) + (0.88)(0.13)]$

$P(RIS|d_1) =$ **0.26**

For very deep reservoirs the conditional probability is 0.26

Similarly the conditional probability of RIS for single attribute will be

Table 9 – Conditional Probability of Single Attributes

Attribute	1	2	3
Depth	0.27(0.24)	0.11(0.10)	0.03(0)
Volume	0.12(0.22)	0.23(0.21)	0.09(0.07)
Stress State	0.10(0.11)	0.12(0.14)	0.18(0.17)
Fault Activity	0.18(0.20)	0.00	Not known
Geology	0.16(0.20)	0.10(0.10)	0.12(0.12)

In 1982 when G.B Reacher proposed this method of calculation details of only 29 dams were known for the purpose of calculation. As of today details of height and volume of around 67 dams are made available to us in the book written by H.K Gupta, using the data from the book let us find out the conditional probability for height and volume using the same attribute model.

Table 10 – Conditional Probability for updated data

Accepted RIS	No. of reservoirs	Very deep	Deep	shallow
Depth	67	16 (0.23)	26 (0.38)	25 (0.37)
Volume	67	15 (0.22)	17 (0.25)	35 (0.52)

From table 3 taking the conditional odds to be 16.67% applying Bayes' Theorem for calculating conditional probability for height

P (RIS|d_1) = P (RIS) P (d_1|RIS) / [P (RIS) P (d_1|RIS) + P (nRIS) P (d_1|nRIS)]

P (RIS|d_1) = (0.167) (0.23) / [(0.167) (0.23) + (0.833) (0.13)]

P (RIS|d_1) = **0.261**

The conditional odds for height are very much in line with the results of G.B Reacher and Keenay statistical model.

Similarly for volume P (RIS|v_1) = 0.13 which is comparable to the result obtained in statistical model.

From table 3 conditional odds of 13% are applicable for the values d_2 and v_2

P (RIS|d_2) = P (RIS) P (d_2|RIS) / [P (RIS) P (d_2|RIS) + P (nRIS) P (d_2|nRIS)]

P (RIS|d_2) = **0.117**

Similarly for v_2 P (RIS|v_2) = **0.231**

Multi Attribute Analysis

Multi attribute model takes into account all the attributes at the same time

P (RIS| d,v,s,f,g) = P (RIS) P(d,v,s,f,g| RIS) / [P(RIS) P(d,v,s,f,g|RIS) + P (nRIS) P (d,v,s,f,g | nRIS)

$$= \frac{\boldsymbol{P(RIS)LR(dvsfg)}}{\mathbf{P(nRIS)}}$$

This verifies that the model of Baecher and Keenay (1982) still holds good for single attribute model for the available data and can be used for further calculation of probability in case of Tehri Dam. Tehri Dam having a height of 260.5 m falls in d_1 category of height and with a volume of 3539 million m^3 v_1 category will be applicable. The fault near Tehri region is active and the stress state is compressional for sedimentary geology. Since multi attribute model is derived from single attribute model therefore it can be said that it is safe to use the values used by Baecher and Keenay for Independ parameters, where all the parameters are treated as independent of each other and dependent parameters where depth and volume are treated as dependent on each other and a single attribute is given to depth and volume of the reservoir. The attributes for the dependent and independent parameters are given in the following tables shown as follows:

a) Independent

Table 11: Attribute ratios for parameters (independent case)

Attributes	1	2	3
Depth	2.62	0.87	0.21
Volume	0.95	2.15	0.56
Stress	0.82	0.91	1.58
Fault Activity	1.50	0.0	-
Geology	1.34	0.74	0.94

b) Dependent discrete case – depth and volume

Table 12: Attribute ratios for parameters (dependent case)

Attributes	1	2	3
Depth	2.56	1.92	4.32
Volume	-	-	-
Stress	0.82	0.91	1.58
Fault Activity	1.50	0.0	-
Geology	1.34	0.74	0.94

Table 13 - Probability of RIS for Tehri Dam:

Attribute	Independent	Dependent discrete
Depth	2.62	2.56
Volume	0.95	-
Stress	0.91	0.91
Fault Activity	1.50	1.50

Geology	1.34	1.34
∏	**4.55**	**4.68**

Conditional odds ratio

Prior odds ratio = 0.16
Independent case: 0.16 x 4.55 = 0.728
Dependent case: 0.16 x 4.68 = 0.74
Possibility of RIS (Independent) = n / (1+n) = 0.728/1.728 = **0.421**
Possibility of RIS (Dependent) = n / (1+n) = 0.74/1.74 = **0.425**

CHAPTER 08

CONCLUSIONS

8.1 CONCLUSION

Several parameters associated with RIS and their effects were studied. Each site of RIS is unique in itself because of different fault pattern, stress states, and geology. Based on the available data it is observed that on an average 9.05% of the total dams in the world exhibit RIS and 16.67% of dams above 260m show this phenomenon of RIS. A direct relationship between the height of reservoir and Reservoir induced seismicity was observed. The most widely accepted mechanism of RIS is the direct stress due to the weight of reservoir and pore water pressure, however the effect of stress due to the weight of water was found to be 2550.6 KN/m3, which adds to only 1.88% of additional weight on the fault which is not enough to induce an earthquake and it can be inferred that effect of direct loading is negligible compared to the pre-existing stresses. Pore water plays a two-fold role in the earthquake process, the first, a mechanical effect as pore pressure, and second, a chemical effect as stress-aided corrosion. There is evidence to suggest that pore water or pore pressure diffuses along pre-existing fractures, bedding planes, etc. or it can be associated with new crack propagation through stress corrosion. It is suggested that the actual onset of seismicity may be influenced by the chemical effect of water in reducing the coefficient of friction in clays. It is as cumbersome to predict an event of RIS as it is to predict a tectonic earthquake. Even though no case of RIS has been observed in the Himalayan region where the seismicity is naturally high, the study of Mangla, Tarbela, Bhakra, Pong, Pondoh, Kalagarh and Tehri dam suggests that the filling of reservoirs has had a stabilizing effect on the seismicity of this region and due to thrust fault the possibility of RIS is negligible for the Himalayas. For Tehri dam, the possibility of RIS was calculated based on the method developed by Baecher and Keenay (1982) and it was calculated to be 0.421 in the case where the height and volume are treated as independent parameters and 0.425 in the case where height and volume are treated as dependent parameters. Gray suggested that based on previous earthquake activity of a region a magnitude ranging from 4.5 to 6.0 is assigned to regions having high earthquake activity.

8.2 SCOPE OF FUTURE WORK

- A deeper understanding of rock mechanics and pore pressure holds the key to better understand and predict an event of RIS
- More study is required for the study of pre-existing and young faults as they are the causative factors for both tectonic and reservoir induced earthquakes.

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