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An Overview of Earthquakes and Dams in India

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ABSTRACT: Dams are one of the biggest structures built on the Earth. They are known as a life line structure, as they serve the purpose of irrigation, hydro-electric power generation, flood control, domestic and industrial water supply etc., which are important for the existence of humans. This makes a dam a reliable structure. For this reason, dams should always be designed for the highest safety, resisting worst forces of nature. India is a country with nearly 5,100 massive dams. India is also a seismically active country with over 1,040 active faults. Earthquake events like 1988 Bihar, 1991 Uttarkashi, 1993 Killari, 1997 Jabalpur, 1999 Chamoli, 2001 Bhuj, 2002 Andaman, 2004 Sumatra, 2005 Kashmir, and 2011 Sikkim have caused a huge loss of life and property in the country. Also events like 1992 Landers, 1994 Northridge, 1995 Hyogoken-Nanbu and few other events that took place around the world proved how devastating an earthquake could be, particularly if it is near-field.

KEYWORDS: Dam, earthquake, near-field earthquake, numerical modelling, discrete element modelling.

I. INTRODUCTION

Dams are an impressive construction in our world and it's a fascinating chapter of our history to investigate their origin. History tells, that these constructions are not the innovations of today, because the first predecessors existed even 6000 years before the modern times. Throughout the world, histories of dams have been successful in upholding and enhancing the quality of life. At present, the oldest dams are very few in number. A dam is a barrier or a structure which is usually built across a stream, river, or a waterway for the purpose of confining and controlling the flow of water. Depending upon the requirements, construction of a dam can vary in size, material from small earthen embankments to massive concrete structures. Primary purpose of dams include irrigation, hydro-electric power generation, and flood control, domestic and industrial water supply etc. All these features make these structures, one of the life line structures. As such, dams are cornerstones in the water resources development of river basins.

Dams are built to serve many purposes and are therefore known as multipurpose river valley projects. With rapid growth of population in India and the demands over water for various purposes, it has now become necessary not only to construct new dams with revised design procedures which can sustain worst forces of nature but also to rehabilitate and maintain the existing ones. However, due to lack of technology, people in the past have failed to retain and rehabilitate the dams. However, there is not even a single way to store huge amounts of water other than dams. That's why in the present world with new growing technologies; we see different shapes and sizes in dams. Some dams are tall and thin, while others are short and thick. Also dams are made from a variety of materials such as rock, earth, concrete etc. varying from small earthen embankments to massive concrete structures. Considering all these parameters, to reach the needs of humans and their activities, construction of dams has become the most important and necessary item which can't be ignored from very beginning of planning for a dam to selection of site, until its construction and maintenance.

Natural hazards like earthquake, landslide, cyclone, flood, drought, etc., are quite common in different parts of India. These can create catastrophe leading to the loss of life, property damage and socio-economic disturbances. Such losses have grown over the years due to increase in population and misuse of natural resources. Among all these natural hazards earthquakes are one of the worst and it is also known that it is impossible to prevent earthquakes from occurring. However, the disastrous effects of these can be greatly minimized. This can be achieved through scientific understanding of their nature, causes, and areas of influence. By identifying the areas, population and

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structures vulnerable to hazards, earthquake disaster mitigation and preparedness strategies to those would reduce miseries to mankind. The study of life line structure like dam is thus required to design resisting worst forces of nature. One such force of nature which could cause failure of dam is an earthquake.

II. CAUSES OF DAM FAILURES

Till the end of 20th century, there are over 45,000 large dams built in 150 countries (International Commission on Large Dams – ICOLD). No doubt, the dams provide mankind with sufficient benefits. However, if any dam breaks or breaches, the large volume of water stored in the reservoir gets suddenly released and flows in the downstream valley resulting in a catastrophe. Thus the analysis of "Dam Failure" has attained significance in concerns of Dam Safety. Every structure which is built will have a life time and so for dams. However, the failures can also occur before the structures life time with more than a few reasons.

Table 1: Causes of failures of dams around the world with percentage

Cause of failure	% Cause of failure
Foundation problems	40
Inadequate spillway	23
Poor Construction	12
Uneven Settlement	10
High pore pressure	5
Acts of war	3
Embankment slips	2
Defensive materials	2
Incorrect operations	2
Earthquakes	<1

Even though the failure of dams caused by earthquakes is < 1%, they still remain a serious threat as they are capable to completely break the dam with the energy released from the event.

III. PERFORMANCE OF CONCRETE GRAVITY DAMS SUBJECTED TO EARTHQUAKES

The first failure of a dam due to earthquake reported in the literature was Augusta Dam, Georgia, during the 1886 Charleston, South Carolina earthquake. However, the milestone in the seismic analysis of dams turned after the 1967

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Koyna earthquake in India where damage was caused to the upstream and downstream side of the concrete gravity dam and 1971 San Fernando earthquake in California where damage was caused to embankment dams (San Fernando dams) and also to an arch-gravity dam (Pacoima dam). Although such ground motions caused problems to dams, no serious damages were observed. However, during some earthquake events, concrete gravity dams were uprooted when blind faults which were lying below the dam body turned active. These events show that the earthquake hazard is still a serious threat to dams, as the failure of a full reservoir concrete gravity dam can cause a disaster on the downstream.

In the area of the epicentre of the earthquake, a number of concrete gravity dams have experienced ground shaking. However, only around 20 dams have been subjected to 0.3g PHGA or higher without apparent damage. Some of these concrete dams performance to earthquakes are tabulated below.

Table 2: Concrete dams subjected to significant shaking (PHGA > 0.3g) [Courtesy: USSD Proceedings 2012]

Dam (completed)	Country	Ht. (m)	Earthquake name and date	Dist. to fault (km)	Mag.	PHGA (g)	Remarks
Concrete Gravity Dams							
Lower Crystal Springs (1890)	USA	47	San Francisco Apr 18, 1906	0.4	8.3	0.52 to 0.68 (est.)	Not the slightest crack
Koyna (1963)	India	103	Koyna Dec 11, 1967	3.0	6.5	0.63 (cc)	Cracks on both faces
Williams (1895)	USA	21	Loma Prieta Oct 17, 1989	9.7	7.1	0.6 (est.)	No damage
Bear Valley (1912, 1988)	USA	28	Landers Jun 28, 1992	45.0	7.4	0.18	Multiple arch modified to gravity dam in 1988.
			Big Bear Jun 29, 1992	14.5	6.6	0.57	No damage, except slight displacement of crest bridge girders.
Gohonmatsu (1900)	Japan	33	Kobe Jan 17, 1995	1.0	7.2	0.83	No damage on this masonry dam
Shih-Kang (1977)	Taiwan	21.4	Chi Chi Sep 21, 1999	0.0	7.6	0.51 h 0.53 v	Vertical disp. of 9 m, Rupture of concrete.
Mingtán (1990)	Taiwan	82	Chi Chi Sep 21, 1999	12.0	7.6	0.4 to 0.5 (est.)	No damage
Kasho (1989)	Japan	46.4	Western Tottori Oct 6, 2000	3.0-8.0	7.3	0.54	Cracks in control building at crest

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Uh (_1990_)	Japan	14	Western Tottori Oct 6, 2000	1.0-3.0	7.3	1.16	Small crack at spillway base
Takou (2007)	Japan	77	Tohoku Mar 11, 2011	109.0	9.0	0.38	Cracking of gate-house walls at crest.
Miyatoko (1993)	Japan	48	Tohoku Mar 11, 2011	135.0	9.0	0.32	No damage
Concrete Arch Dams							
Gibraltar (1920, 1990)	USA	52	Santa Barbara Jun 29, 1925	?	6.3	> 0.3 (est.)	No damage. Modified in 1990 with RCC.

Notes: Legend: Ht. =height, est. =estimated, Dist.=distance, Mag.=magnitude (ML or MB for less than 6.5 and MS above 6.5), cc=cross canyon, h=horizontal, v=vertical. PHGA=Peak Horizontal Ground Acceleration, disp. = displacement.

Table 2 illustrates about the worldwide performance of concrete (Arch, Buttress & Gravity) dams subjected to ground motions > 0.3g. From the table it can be concluded that concrete dams have performed well when subjected to high intensity accelerations. There might be several reasons as to why concrete dams have performed well and consistently well than that predicted by design or analysis when shaken by an earthquake. However, the dams present in highly seismic zones are always under threat as some dams have performed less than what was expected. Several factors like magnitude, epicentral distance, PHGA, range of frequency can solely vary the performance of dams subjected to earthquakes. A thorough understanding on the ground motions should be studied for that respective area before the construction of dam.

IV. PREVALENT SEISMIC HAZARD IN INDIA

USGS estimates that around 5 lakh earthquakes hit the Earth every year, approximately 1 lakh can be felt and some of them very few cause damage. Moreover, in Indian-Subcontinent, especially the north-eastern and north-western regions are the most earthquakes-prone regions of the world. 1988 Bihar earthquake, 1991 Uttarkashi earthquake, 1993 Killari earthquake, 1997 Jabalpur earthquake, 1999 Chamoli earthquake, 2001 Bhuj earthquake, 2002 Andaman earthquake, 2004 Sumatra earthquake, 2005 Kashmir earthquake, 2011 Sikkim earthquake are some of the worst hit earthquakes, which cumulatively have caused over 1 lakh death toll.

The seismic zonation map given below clearly shows that India is highly vulnerable to earthquake hazard. During last 100 years, India has witnessed more than 650 earthquakes of magnitude ≥ 5.0 . In addition to the very active northern and north-eastern range, the recent events of 1993 Killari (Maharashtra) and Jabalpur (Madhya Pradesh) in the Peninsular India have started raising doubts as the disasters caused by these earthquakes are alarmingly increasing. Earthquake events reporting from the Himalayan mountain range, Andaman and Nicobar Islands, Indo-Gangetic plain as well as from peninsular region of India belongs to subduction category and a few events had also been under intra-plate category.

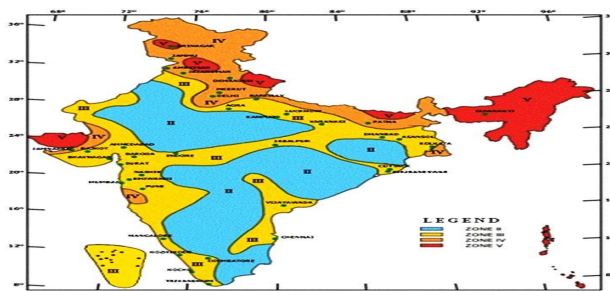


Figure 1: Seismic zonation map of India

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Himalayan Frontal Arc (HFA) ranging about 2,500 km extends from Kashmir in the west to Assam in the east. It undergoes subduction process, making it one of the most seismically active regions in the world. The Indo-Australian plate came into existence after initial drifting of the southern Gondwanaland in late Triassic period. Later the force from spreading of the Arabian Sea on either side of the Carlsberg ridge caused to continue drifting since mid-Jurassic to late Cretaceous time to finally collide with the Eurasian plate. This led to the formation of Himalayan mountain range and the present day seismicity in this region is due to the continuous collision between Indian and Eurasian plates. Some of the most important earthquakes that have occurred during the past century in Himalayan Frontal Arc are tabulated below in Table 3.

Table 3: Important earthquakes in Himalayan Frontal Arc (Kamalesh Kumar (2008), <http://gbpihed.nic.in>)

<i>Place</i>	<i>Year</i>	<i>Magnitude</i>	<i>Casualty</i>
Kangra Valley	April 4, 1905	8.6	>20,000
Bihar-Nepal border	January 1, 1934	8.4	>10,653
Quetta	May 30, 1935	7.6	about 30,000
North Bihar	1988	6.5	1000 approximately
Uttarkashi	October 20, 1991	6.6	>2,000
Chamoli	March 29, 1999	6.8	>150
Hindukush	November 11, 1999	6.2	no death reported

The peninsular part of India which was once considered to be a stable region has started to experience earthquakes in an increased number because of intra-plate mechanism. Even though the magnitudes of these earthquakes are less and occurrence intervals are larger than those of the HFA. It started to create panic among the inhabitants in this region. Some of the most important earthquakes that have occurred in Peninsular India in the past are tabulated below in Table 4.

Table 4: Important earthquakes in Peninsular India

<i>Place</i>	<i>Year</i>	<i>Magnitude</i>	<i>Casualty</i>
Kachchh	June 16, 1819	8.5	No record
Jabalpur	June 2, 1927	6.5	—
Indore	March 14, 1938	6.3	—
Bhadrachalam	April 14, 1969	6.0	—
Koyna	December 10, 1967	6.7	>200
Killari (Latur)	September 30, 1993	6.3	>10,000
Jabalpur	May 22, 1997	6.0	>55
Bhuj	January 26, 2001	7.6	>20,000

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North-eastern region of India which is one of the six most seismically active regions of the world lies at the junction of the Himalayan arc to the north and the Burmese arc to the east. Eighteen large earthquakes with magnitude ≥ 7.0 occurred in this region during the last hundred years (Kayal, 1998). High seismicity in the north-eastern region may be attributed to the collision tectonics in the north (Himalayan arc) and subduction tectonics in the east (Burmese arc). Some of the most important earthquakes that have occurred in this region of India in the past are tabulated below in Table 5.

Table 5: Important earthquakes in Northeastern region of India

<i>Place</i>	<i>Year</i>	<i>Magnitude</i>	<i>Remark</i>
Cachar	March 21, 1869	7.8	Numerous earth fissures and sand craters
Shillong Plateau	June 12, 1897	8.7	About 1542 people died
Sibsagar	August 31, 1906	7.0	Property damage
Myanmar	December 12, 1908	7.5	Property damage
Srimangal	July 8, 1918	7.6	4500 sq km area suffered damage
S-W Assam	September 9, 1923	7.1	Property damage
Dhubri	July 2, 1930	7.1	Railway lines, culverts and bridges cracked
Assam	January 27, 1931	7.6	Destruction of Property
N-E Assam	October 23, 1943	7.2	Destruction of Property
Upper Assam	July 29, 1949	7.6	Severe damage
Upper Assam	August 15, 1950	8.7	About 1520 people died. One of the largest known earthquake in the history
Indo-Myanmar border	August 6, 1988	7.5	No casualty reported.

Seismologists seem not to believe that the frequency in the occurrence of earthquakes has increased. Unfortunately, earthquakes of higher magnitudes which use to occur in uninhabited areas or virtually uninhabited areas have hit some thickly populated areas. Consequently, they have killed thousands of people. Increase in the loss of life and property damage is due to increasing vulnerability of human civilization to these hazards. This can be understood by the fact that Kangra event of 1905 ($M_w=8.6$) and Bihar-Nepal of 1934 ($M_w=8.4$) killed about 20,000 and 10,653 people respectively. On the other hand 1897 and 1950 events of the northeast ($M_w=8.7$ each) caused death to about 1542 and 1520 people. This is because Kangra and Bihar-Nepal events struck in densely populated areas of Indo-Gangetic plain. On the other hand, the north-eastern region was thinly populated in 1897 and 1950 [Kamalesh Kumar, 2008]. The concentration of population has become denser since the time when such major earthquake occurred in these regions, creating more alarming situation and the devastation it would become if such event occurs now. There are several examples, where high number of casualties and deaths occurred when the event occurred during early morning hours and quite opposite when they occurred during the day time even when the epicenter is too near to the inhabited areas. These examples clearly tell that the time of occurrence of the event and the epicenter also matters, to quantify loss of life and damage to property.

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V. LARGE DAMS IN INDIA

Around the time India got independence in 1947, there were nearly 300 large dams in India. Currently this number has grown to about 5,100 [National Register of Large Dams – 2009], with 181 dams of national importance. Among 5100 dams, more than half of them were built between 1971 and 1989. Today India’s rank is fourth in the world in dam building, after USA, Russia and China. While some of these dams were built primarily for flood control, water supply, and hydro-electric power generation, the primary purpose of most large dams (96%) remains irrigation in India. The bar chart of Figure 2 gives the state-wise distribution of large dams in India. Figure 3 – figure 4 describes the decade wise distribution of large dams in India, state-wise completed dams and state-wise under construction dams in India.

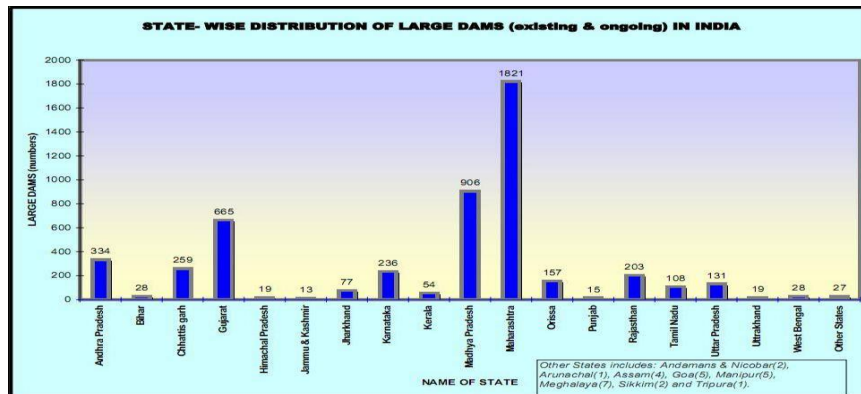


Figure 2: Bar chart showing State – wise distribution of large dams (existing and ongoing) in India [NRLD – 2009]

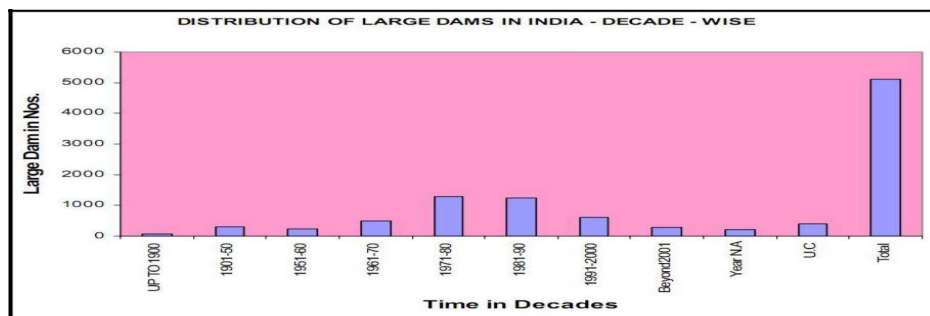


Figure 3: Distribution of large dams in India - decade wise [NRLD – 2009]

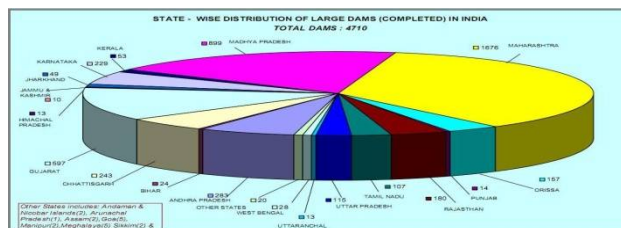


Figure 4: Pie graph showing State – wise distribution of large dams (completed) in India [NRLD – 2009]

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VI. IMPORTANCE OF SEISMIC STUDY ON LARGE DAMS IN INDIA

India is a seismically active country, with history of major earthquakes occurred in the past. North-eastern and north-western parts of India are seismically very active as the Indo-Australian plate is sub-ducting under Eurasian plate at this region. 1967 Koyna earthquake, 1988 Bihar earthquake, 1991 Uttarkashi earthquake, 1993 Killari earthquake, 1997 Jabalpur earthquake, 1999 Chamoli earthquake, 2001 Bhuj earthquake, 2002 Andaman earthquake, 2004 Sumatra earthquake, 2005 Kashmir earthquake, 2011 Sikkim earthquake are the major earthquakes in the recent past, which resulted in catastrophes, with loss of life and property. These earthquakes also witnessed the failures of different range of structures from small buildings to major dams. The 1967 Koyna earthquake because of reservoir induced seismicity caused damage to the upstream and downstream side of dam with lot of cracks. However, there was no flooding. The 2001 Bhuj earthquake also resulted in failure of large number of earth dams due to liquefaction. However, there was no severe flooding as the region was under drought since 2 year during the time. There were several other occasions where the dams in India have performed poorly because of earthquakes.

The well-defined and documented seismic sources, published in the Seismotectonic Atlas-2000 are the works done by Geological Survey of India. Seismotectonic details in this atlas include geology, rock type, fault orientation with length, lineaments with lengths, shear zones with length and seismic earthquake events. Geological survey of India has compiled all the available geological, geophysical and seismological data for the entire India and has published a seismotectonic map in 2000. Using a software package OpenJUMP GIS, seismic zonation of India, fault data given by GSI and National Importance Dams given by NRLD are integrated. Fig. 7 shows the seismic zonation map of India, with faults and national importance dams. Fig. 8 shows the seismic zonation map of India with national importance dams and top 100 active faults. The top 100 active faults are selected based on the energy released around these faults in the events of earthquakes from 1064 AD – 2009 AD.

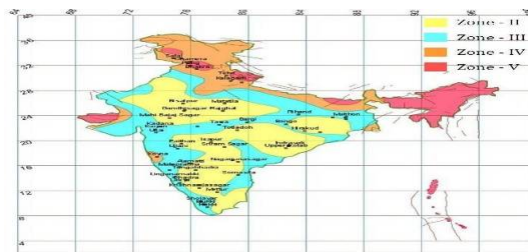


Figure 8: National Importance Dams of India on Seismic Zonation Map plotted with top 100 active faults

VII. NUMERICAL METHOD

Numerical methods for the analysis of structures can be broadly classified in to two. Continuum mechanism is the basis of the first method. Finite Element Method (FEM) [Jr. William Weaver, James M. Gere, 1966] is one such example. However, it cannot perform the analysis up to collapse because of limitations that exist in representation of cracks and separation distance between elements. FEM can answer only one question “will the structure fail or not?” it can’t tell how the structure collapse

On the other hand, second category of numerical methods is based on discrete element methods, like Extended Discrete Element Method [Williams J.R, Hocking G, and Mustoe G.G.W, 1985; A.A. Balkema, Rotterdam, 1985] for nonlinear analysis of structures. This method can track the behavior from zero loading to total collapse of structure. However, this method is less accurate than FEM in small deformation range. So this can answer only the second question “how does the structure collapse?”

To follow total structural behavior from small deformation range to complete collapse, a unique, efficient and accurate technique is required. Tagel Din Hatem (1988) gave a new method of analyzing the structural behavior from zero loading, crack initiation & propagation, separation of structural members till the total collapse with reliable

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accuracy, and with relatively simple material models. The method is now known as “Applied Element Method” (AEM) and is widely in usage.

VIII. CONCLUSIONS

In a country with 5,200 large dams and 1,050 active faults cover 60% of land mass and make it prone to earthquakes. It is always possible for severe earthquakes in highly seismic zones to affect the performance of dams. In this regard, a discrete element modeling has to be carried out where the behavior of structure can be observed from zero loading, crack initiation to complete collapse of structure

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