RESERVOIR-TRIGGERED SEISMICITY: RELEVANCE TO NORTH EAST INDIA

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ABSTRACT

The often neglected issue of reservoir-triggered seismicity (RTS) received due attention the world over following the earthquake, which jolted Wenchuan County in Sichuan Province of China on 12th of May 2008. It is alleged that the earthquake was responsible for the death of over 60,000 people. Following the event, a major question raised was whether the earthquake was related to the impoundment of the nearby Zipingpu reservoir or even the Three Gorges reservoir on the river Yangtze. Reservoir-triggered seismicity (RTS), also referred to as reservoir-induced seismicity (RIS), is the triggering of earthquakes by the physical processes that accompany the impoundment of large reservoirs. As far as dam building and subsequent creation of reservoir in the north-eastern region of India is concerned, this aspect bears significance as the region falls under Seismic Zone-V characterized by frequent seismic activities due mainly to geological formations. Although there are a number of different views on the issue of RTS, it is envisaged that the ongoing discussion presents a review of such events across the globe and emphasizes the importance of the seismic safety of dams, while promoting further research on the subject.

1. Introduction

Seismically speaking, Northeast India is one of the most active regions of the world. Two large earthquakes in the recent past, one in the Shillong Plateau in the year 1897 and the other on the Assam-Tibet border in 1950 have been strong indicators of this. It is intriguing that on one hand the Government has initiated disaster preparedness plans and training exercises are being carried out across the region, while on the other the same Government is working to install big dams in the same region, almost simultaneously. If even for one moment, we forget all the other destructive impacts big dam construction has on local people, environment and ecology, the seismic status of the Northeast region should be reason enough for any government, at state or Center, to not even think of such suicidal 'development projects'. Experts opine that any mega dam in the region, will be a time bomb that will tick all the way to imminent destruction; firstly because of the inherent risk of these dams being located in Zone-V and second, because of probability of RTS. When both combine, the result can be devastating. This paper presents a discussion on the RTS and is primarily intended for readers without much background on geology or dam and reservoir engineering.

A leading scholar on the topic of RTS is Harsh K. Gupta who defines the occurrence as: "earthquakes occurring in the vicinity of artificial water reservoirs as a consequence of impoundment." Gupta, in his review of studies on RTS, highlights the following points: Globally, there are over 90 identified sites of earthquakes triggered by the filling of water reservoirs. The largest and most damaging earthquake triggered by a man-made reservoir was in 1967 in Koyna, India. The magnitude of the earthquake was a 6.3. He opines that the depth of the water in the reservoir is the most important factor in RTS. This in other words means, greater the height of a dam, the more is the potential to trigger earthquake. Additionally, the volume of the water also pays a significant role in triggering an earthquake. One characteristic of RTS is that the magnitude of the foreshock is higher than the magnitude of the aftershock and both values are generally higher than in cases of natural earthquakes. The largest quake in a cluster is the main shock, and those after it are called aftershocks. According to the USGS, some large quakes are preceded by foreshocks.

2. General Concepts of Reservoir-Triggered Earthquake

Seismic events have been found to occur near large dam sites or in reservoir areas, and may have been triggered by changes in the physical environment as a result of impounding and operation of reservoirs. For example, seismicity was observed following the 1929 impounding of the Marathon reservoir in Greece (dam height of 60m). Earthquake activity was also observed in 1935 after the impounding of the Hoover dam in the US (dam height of 220m). Since then, over 100 large dams may have experienced RTS. There are still disputes however as to when RTS has actually occurred. In the ICOLD Bulletin on Reservoirs and Seismicity – State of Knowledge (Bulletin 137, 2009) prepared by ICOLD's Committee on Seismic Aspects of Dam Design, 39 cases of RTS are presented. Considering this, the number of RTS cases worldwide is very small compared to the total number of reservoirs worldwide with RTS suspected in a higher portion of large dams. Most RTS events are small magnitude events. However, there are a few cases with magnitudes exceeding 5. So far, there are four major RTS events with a magnitude over 6.0. They are: (i) 103m high Koyna gravity dam in India (M=6.3); (ii) 120m high Kremasta embankment dam in Greece (M=6.3); (iii) 105m high Hsinfengkiang buttress dam in China (M=6.1); (iv) 122m high Kariba arch dam in Zambia (M=6.25). The highest observed earthquake magnitude was 6.3.

3. The Premise and the Mechanism of RTS

The basic premise of RTS is that a full reservoir lubricates active faults by increasing pore pressure at focal point depths and that subsequent reservoir water drawdown reduces the stabilizing force of friction caused by the mass of the water in the reservoir. The most widely accepted explanation of how dams cause earthquakes is related to the extra water pressure created in the micro-cracks and fissures in the ground under and near a reservoir. When the pressure of the water in the rocks increases, it acts to lubricate faults which are already under tectonic strain, but are prevented from slipping by the friction of the rock surfaces.

The complicated mechanisms of RTS are not well understood and may differ from case to case. The main reasons for this are the very limited knowledge of the rheology of crustal material and groundwater movement under high pressures and high temperature conditions in the hypocenter region. Therefore, in the absence of instrumental data, it is difficult to establish and calibrate a physical model to describe this complicated process. At present, this is studied using statistical methods, computer simulations, and increased monitoring of areas where RTS has been observed.

As mentioned above, the actual mechanisms of RTS are not well understood for reasons beyond the comprehension of present knowledge. It is therefore impossible to predict accurately which dams (or type of dam) will induce earthquakes or how strong the tremors are likely to be because of impoundment of a particular reservoir. Most of the strongest cases of RTS have been observed for dams over 100 m high but smaller dams are also believed to have induced quakes. Reservoirs can both increase the frequency of earthquakes in areas of already high seismic activity and cause earthquakes to happen in areas previously thought to be seismically inactive. The latter effect is the most dangerous as structures in areas thought to be quiescent are not built to withstand even minor earthquakes.

4. The Extent and Pattern of RTS

For most well-studied cases of RTS, the intensity of seismic activity increased within around a radius of 25 km of the reservoir as it was filled. The strongest shocks normally occurred relatively soon-often within days but sometimes within several years-after the reservoir reached its greatest depth. After the initial filling of the reservoir, RTS events normally continued as the water level rose and fell but usually with less frequency and strength than before. The pattern of RIS is, however, unique for every reservoir.

5. Disaster Cases due to RTS

Although, no large dams are known to have failed due to RIS, there is clear evidence that dams can trigger seismic activity and, in turn, be damaged themselves by the self-induced tremors as we will see here.

Case-1:

The most powerful earthquake thought to have been induced by a reservoir is a magnitude 6.3 tremor which flattened the village of Koynanagar in Maharashtra, western India, on 11 December, 1967, killing around 180 people, injuring 1,500 and rendering thousands homeless. The dam was seriously damaged and power cut off to Bombay, causing panic among its populace, who were able to feel the quake 230 km from its epicentre. The epicentre of the tremor and numerous fore– and aftershocks were all either near the Koyna Dam or under its reservoir.

Case-2:

RIS is suspected to have contributed to one of the world's most deadly dam disasters, the overtopping of Vaiont Dam in the Italian Alps in 1963. The 261m Vaiont- the world's fourth highest dam-was completed in 1960 in a limestone gorge at the base of Mount Toc. As soon as the reservoir started to fill, seismic shocks were recorded and a mass of unstable rock debris on the side of the mountain started to slide toward the reservoir. After reaching a maximum depth of 130 m in late 1960, the reservoir was partially drained, and the seismic activity and slope movement almost stopped. The reservoir was then filled again, provoking a new increase in tremors. Despite the tremors, engineers and geologists, according to a later engineering report, decided "that the mass would keep moving so slowly that no problems would occur". The experts were wrong. Heavy late summer rains in 1963 swelled the reservoir. In the first half of September, 60 shocks were registered and the movement on Mount Toc started to accelerate. On the night of 9 October, 350 million cubic metres of rock broke off Mount Toc and plunged into the reservoir. The gargantuan wave resulting from the impact overtopped the dam by 110 m – the height of a 28–storey building. About two minutes later the downstream town of Longarone was levelled and almost all its inhabitants killed. Altogether 2,600 people died. The actual relationship between the seismic activity and the landslide is not certain, but it is likely that the numerous shocks at the very least hastened the collapse of the mountainside.

In addition to the above major events of RTS, the following table provides examples of RTS by date, location and magnitude.

Name of Dam/Reservoir	Location	Year	Magnitude of Earthquake
Marathon	Greece	1938	M = 5.7
Hoover	USA	1939	M = 5.0
Lake Crowley	USA	1941	M = 6.0
Kurobe	Japan	1961	M = 4.9
Xinfengjiang	China	1962	M = 6.1
Canelles	Spain	1962	M = 4.7
Kariba	Zambia	1963	M = 6.2
Monteynard	France	1963	M = 4.9
Grandval	France	1963	M = 4.7
Akosombo	Ghana	1964	M = 4.7
P. Colombia/Volta Grande	Spain	1964	M = 4.1
Kremasta	Greece	1966	M = 6.2
Benmore	N. Zealand	1966	M = 5.0
Piastra	Italy	1966	M = 4.4
Koyna	India	1967	M = 6.3
Banjina-Basta	Yugoslavia	1967	M = 4.5-5.0
Kastraki	Greece	1969	M = 4.6
Nanshui	China	1970	M = 2.3
Kerr	USA	1971	M = 4.9
Vouglans	France	1971	M = 4.4
Qianjin	China	1971	M = 3.0
Nurek	Tajikistan	1972	M = 4.6
Zhelin	China	1972	M = 3.2
Danjiangkou	China	1973	M = 4.7
Shenwo	China	1974	M = 4.8
Clark Hill	USA	1974	M = 4.3
Nanchong	China	1974	M = 2.8
Huangshi	China	1974	M = 2.8
Oroville	USA	1975	M = 5.7
Manicouagan	Canada	1975	M = 4.1
Lake Pukaki	N. Zealand	1978	M = 4.6
Monticello	S. Carolina	1978	M = 4.1
Hunanzhen	China	1979	M = 2.8
Aswan	Egypt	1981	M = 5.3
Srinakharin	Thailand	1983	M = 5.9
Bhatsa	India	1983	M = 4.9
Dengjiaqiao	China	1983	M = 2.2
Shengjiaxia	China	1984	M = 3.6
Khao Laem	Thailand	1985	M = 4.5
Wujiangdu	China	1985	M = 2.8
Lubuge	China	1988	M = 3.4
Dongjiang	China	1991	M = 3.2
Tongjiezi	China	1992	M = 2.9
Killari or ‘Latur’	SW India	1993	M = 6.1
Dahua	China	1993	M = 4.5
Geheyan	China	1993	M = 2.6
Yantan	China	1994	M = 3.5

Shuikou	China	1994	M = 3.2

6. Dam Industry and RTS

The dam industry would probably strongly oppose any such measures, which would raise awareness of RTS. Seismologist Harsh Gupta, Vice–Chancellor of Cochin University, India and a professor at the University of Texas, notes that “there is a general reluctance in parts of the engineering community, worldwide, to accept the significance or even the existence of the phenomenon of reservoir–induced seismicity." Action in the courts could force the dam industry to accept the importance of RTS. A 1994 article in the *Journal of Environmental Law and Litigation* concluded that people who suffer from induced quakes would have grounds under US law to sue the operators of a reservoir. The US Commission on Large Dams has states that RTS should be considered for reservoirs deeper than 80-100m.

7. The Cause of Fear for the People of Brahmaputra Basin

In Tibet and Arunachal Pradesh, there is a large regional stress field causing crustal motion of 30-50 mm/yr to the north, northeast, east, and southeast due to the relatively rapid northward motion of the Indian subcontinent as illustrated in Figure below.

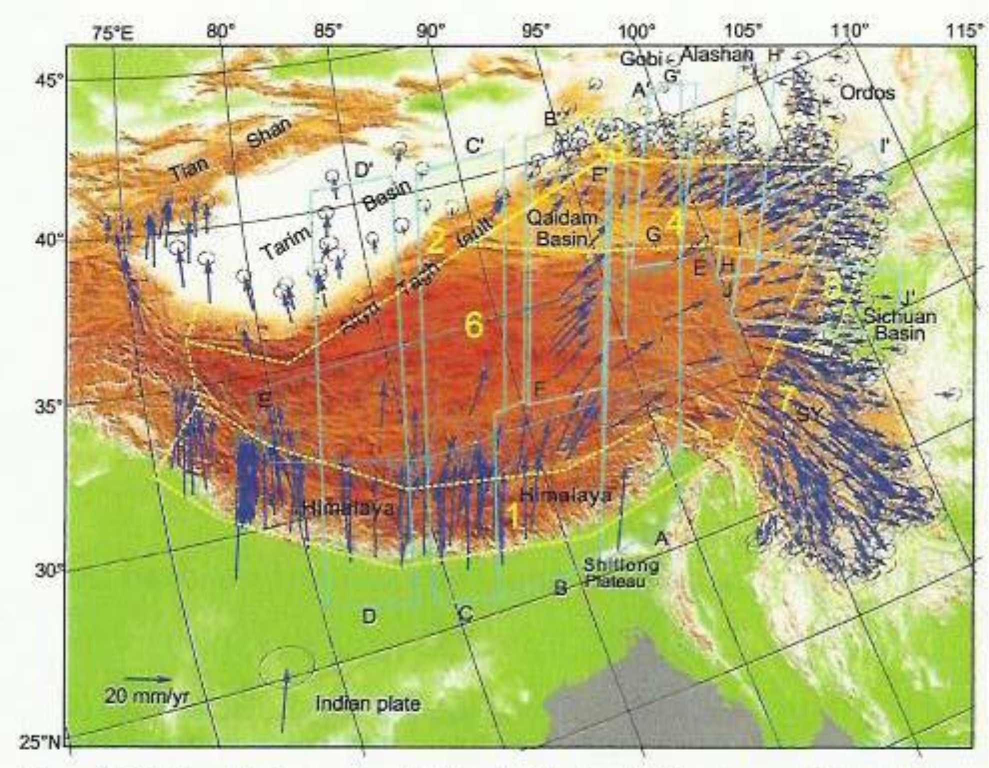

Figure 1. Global positioning system (GPS) velocities (mm/yr) in and around Tibetan Plateau with respect to stable Eurasia, plotted on shaded relief map using oblique Mercator projection. Ellipses denote 1σ errors. Blue polygons show locations of GPS velocity profiles in Figures 3 and DR1 (see footnote 1). Dashed yellow polygons show regions that we used to calculate dilatational strain rates. Yellow numbers 1–7 represent regions of Himalaya, Altyn Tagh, Qilian Shan, Qaidam Basin, Longmen Shan, Tibet, and Sichuan and Yunnan, respectively.

By constructing more than 130 large dams in a region of known high seismicity, China is embarking on a major experiment with potentially disastrous consequences for its economy and its citizens. As far as Tsangpo/Brahmaputra basin is considered, China intends to build twenty (20) dams to generate 60,000 MW of power. Eleven (11) of the twenty (20) projects on the Brahmaputra will be located between its source and the Great Bend where the Brahmaputra turns northwards, executes a huge ‘U’ turn and falls from an elevation of 3,500 m in Tibetan plateau to about 700 m in the undulating hills of Arunachal Pradesh in India.

Dams on the straight course will generate 20,000 MW, while the balance of 40,000 MW will be generated at the Great Bend itself. Additionally, twenty (20) smaller dams are planned upon its tributaries to generate another 5,000 MW. Thus, the total generation planned is 65,000 MW. Most of these projects are large projects and have the potential to trigger earthquake. As in China, India too is planning to have around 170 dams on the tributaries of Brahmaputra, most having potential for RTS. Ironically, these plans are being made with little concern for the wider health of the river system or the interests of the millions of people who have depended on it for thousands of years. This is not an argument against development, but a concern that wrong kind of development, pursued in competition, risks destroying vital ecosystems that we only partially understand. It is a race in which everyone risks becoming a loser. Governments, to date, have not been sincere. It is time that we stop ruthless exploitation of the river and its tributaries and start examining this system comprehensively applying principles of Ecological Engineering and not of "hydrocracy".

Finally, it can be concluded that given the rapid pace of large dam construction in the drainage basins of the Tsangpo there is a high risk of damage to dams and causalities among populations downstream from naturally occurring and reservoir-induced seismicity. It is strongly felt that a regional scientific study of earthquake hazards (both natural and RTS) pertaining to large dams should be conducted to assess this risk and assess the potential for catastrophic failure of one or more dams. The study should be carried out by seismologists who are independent of both the Government bureaucracy and the hydropower industry. As there is no precedence in human history for the construction of over 130 large dams in such a highly seismic area – no other program to build cascades of large dams in areas of high seismicity exists to draw upon – the China and India examples stand alone as a very risky experiment. Therefore, the recommended study must be carried out and results disclosed to the public, so the people of the basin can hold the country's power-sector investors, law-makers, and regulators to account for the financial and human costs of hazardous dam building in Brahmaputra basin.

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