Artificial water reservoir-triggered earthquakes with special emphasis at Koyna

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Globally, about one hundred sites are known where filling of artificial water reservoirs triggered earthquakes. It is noteworthy that a majority of the sites where triggered earthquakes exceeding magnitude 5 have occurred are in Stable Continental Regions. The triggered seismicity at Koyna, India is a classical example where such events have continued to occur for over 41 years since impounding of the Shivaji Sagar Lake in 1962. Detailed investigations in the Koyna region have shown that triggering of earthquakes is influenced by rate of loading, the highest water levels reached and the duration of retention of high water levels as well as Kaiser effect. It is also proposed that increase in heterogeneity in the Koyna region and occurrence of 18 earthquakes of magnitude 5 or more may not have left a large enough fault segment for re-occurrence of another *M* 6.3 earthquake as in 1967. However, we believe that smaller earthquakes will continue to occur here for another 3 to 4 decades making this an ideal site for monitoring earthquake precursors, which may lead to forecast of *M* ~ 5 earthquakes. This optimism is based on the fact that earthquakes in the Koyna region are restricted to a small area of 30 × 20 km and within a focal depth of 12 km, and there are no other seismically active regions in the near vicinity.

ARTIFICIAL water reservoirs are created all over the world for generation of hydroelectric power, irrigation and flood control purposes. Triggering of earthquakes by artificial water reservoirs was reported for the first time at Lake Mead in the United States of America by Carder[1]. During the 1960s, damaging triggered earthquakes exceeding *M* 6 occurred at Hsinfengkiang, China (1962); Kariba, Zambia–Zimbabwe Border (1963); Kremasta, Greece (1966) and Koyna, India (1967). The earthquake of *M* 6.3 on 11 December (10 December according to GMT) 1967 at Koyna is so far the largest and the most damaging reservoir-triggered earthquake. It claimed about 200 human lives, injured about 1500 and rendered thousands homeless. During the last 40 years, several review articles and books have addressed the problem of reservoir-triggered earthquakes. Gupta and Rastogi[2] and Gupta[3] have made comprehensive reviews of global examples and mechanisms leading to reservoir-triggered earthquakes. Over the last decade, several other reviews[4–7] along with many other interesting articles[8–11] have appeared . In this paper an emphasis is laid on the importance of studying triggered earthquakes at Koyna, India. This paper draws from three recent publications[12–14].

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Triggered *vis-a-vis* induced earthquakes

In a very interesting paper, McGarr and Simpson[11] observed that ‘triggered’ and ‘induced’ are very often used interchangeably whenever we talk of ‘artificially stimulated earthquakes’ and it is necessary to draw a distinction between the two. They argue that the term ‘triggered seismicity’ should be used only when a small fraction of stress changes or energy associated is provided by the causative activity whereas ‘induced seismicity’ should be used where the causative activity is responsible for most of the stress changes or most of the energy required to produce the earthquakes. Under this classification, the earthquakes occurring in the vicinity of a water reservoir fall in the category of ‘triggered seismicity’ since the stress level changes associated with the filling of the some of the deepest reservoirs are of the order of 1 MPa or so, whereas stress drops associated with earthquakes are much larger. This is a very reasonable and an acceptable classification.

Worldwide distribution

In a recent review, Gupta[14] listed 95 sites globally where ‘RTS’ (reservoir triggered seismicity) has been reported. These can be grouped into the following categories: (1) Sites of $M \geq 6$ (4 cases); (2) Sites of *M* 5–5.9 (10 cases); (3) Sites of *M* 4–4.9 (28 cases); (4) Sites of $M < 4$ (53 cases).

Figure 1 depicts sites where triggered earthquakes have occurred, and a few sites where increase/decrease in micro earthquake activity was observed consequent to impoundment of artificial water reservoirs.

Since the review by Gupta[14] no major new incidences of RTS site have been reported, however there are a few cases of smaller magnitude earthquakes being triggered in the vicinity of artificial water reservoirs. It may also be noted that a substantial number of these sites are located in the stable continental regions. Noteworthy among these are Koyna (India), Kariba (Zambia and Zimbabwe border), Hsinfengkiang (China), Aswan (Egypt), etc.

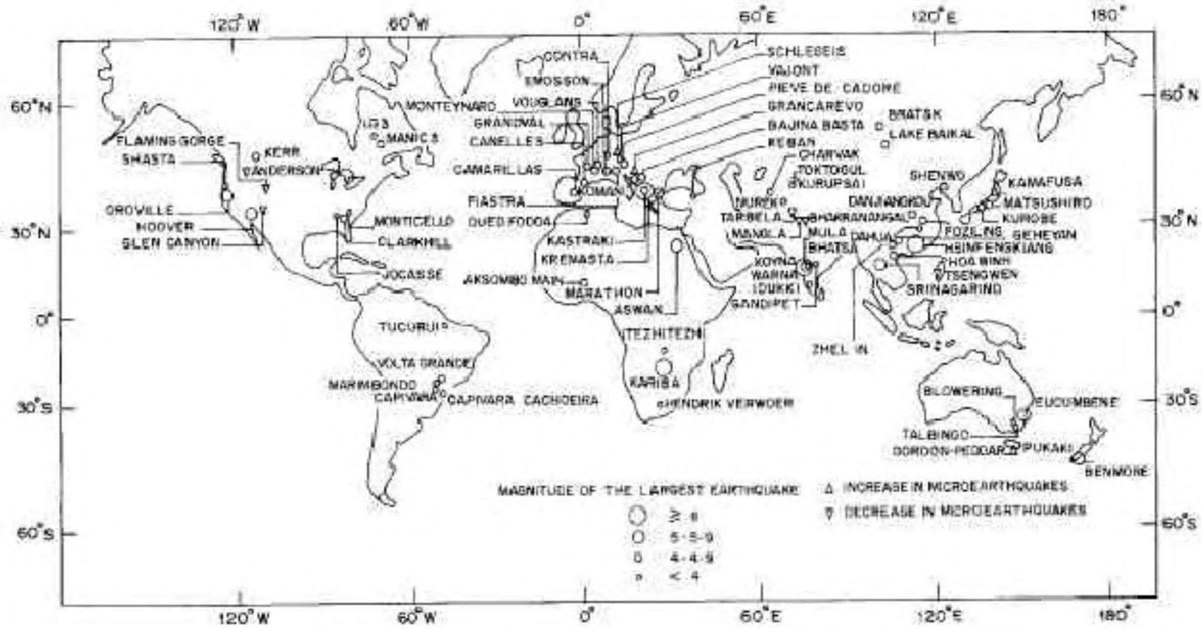

Figure 1. Worldwide distribution of reservoir-triggered changes in the seismicity.

How long will triggered earthquakes continue at Koyna?

Koyna, located near the west coast of India, is known globally as the most significant site of triggered seismicity. Earthquakes started occurring soon after the initiation of filling of the lake in 1961 and have continued over the past 42 years. The largest triggered earthquake of M 6.3 occurred on 10 December 1967, seventeen earthquakes of $M \geq 5$ and over 150 earthquakes of $M \geq 4$ and several thousand smaller events have occurred in this region. Impoundment of another reservoir, Warna, about 30 km south of Koyna, started in 1985 and it was filled to a depth of 60 m in 1993. Earthquakes exceeding M 5 have occurred during 1967–68, 1973, 1980, 1993–94 and 2000. Figure 2 from ref. 13 depicts tectonic features of Koyna–Warna region deduced from detailed field observation after the 1967 Koyna earthquake; it also shows detailed interpretation of geophysical and geological studies discussed by Talwani[13,15]. The main features are the Koyna River Fault Zone (KRFZ) in the west, and the Patan Fault (PI) traced from satellite imagery in the east. The area between KRFZ and Patan Fault is intersected by a number of NW–SE fractures, extending to hypocentral depths; these are shown as Ll, L2, L3 and L4 in Figure 2. The features namely KRFZ, Patan Fault (PI), Ll, L2, L3 and L4 are around the boundaries of crustal blocks and provide access for fluids to flow to hypocentral depths[16].

Table 1 provides the focal parameters of $M \geq 5$ earthquakes of Koyna–Warna region for eighteen events plotted in Figure 2. Gupta *et al.*[13] have done a detailed study of water levels and derived statistics to show that events exceeding $M \geq 5$ occur when the previous maxima in the

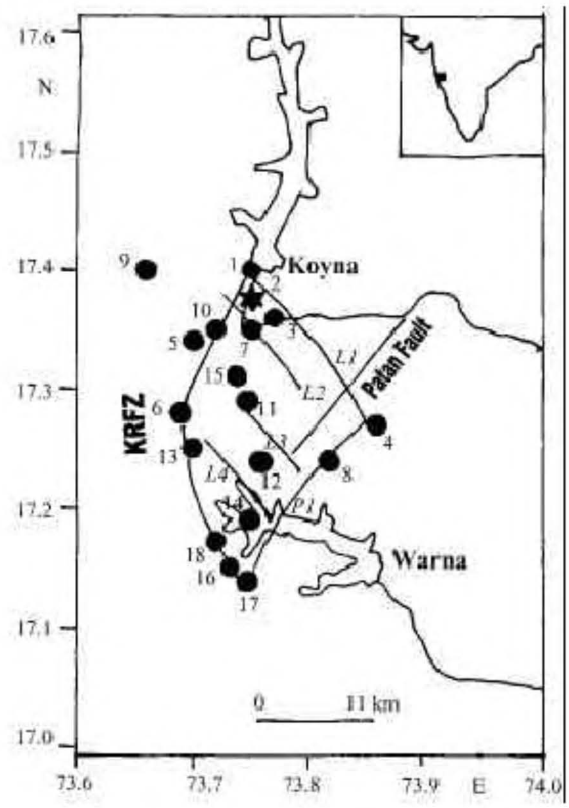

Figure 2. Epicentral locations of $M \geq 5$ Koyna–Warna earthquakes along with a key map for the region. The epicentral location of 1967 main shock is shown by star symbol, whereas the epicentres of other $M \geq 5$ events are shown by solid circles. The numbers represent $M \geq 5$ earthquakes as mentioned in Table 1. KRFZ and P1 represent the Koyna River Fault Zone and a NE–SW trending fault parallel to the Patan Fault, respectively. L1, L2, L3 and L4 are NW–SE trending fractures representing steep boundaries of crystal blocks. Fault geometry is after Talwani[15].

Table 1. A list of $M \geq 5.0$ Koyna–Warna earthquakes (1967–2000) after Gupta *et al.*[13]

			OTIME				Magnitude					
M	D	Y	HR	MIN	Lat. (N)	Long. (E)	NGRI	MERI	USGS	Focal depth (km)	Focal mech. solution	Mag. used
09	13	67	06	23	17.40	73.75		5.2			S–S	5.2(Gu*)
12	10	67	22	51	17.38	73.75	6.3	7.0	6.0	10.0	S–S	6.3
12	10	67	23	52	17.36	73.77		5.0				5.0
12	11	67	20	49	17.27	73.86		3.5	5.2			5.2
12	12	67	06	18	17.34	73.70		3.6	5.4		Normal	5.4
12	12	67	15	48	17.28	73.68		3.6	5.0			5.0
12	12	67	18	20	17.35	73.75		4.7	5.0			5.0
12	24	67	23	49	17.24	73.82		5.0	5.5			5.5
12	25	67	17	37	17.40	73.66		4.6	5.1			5.1
10	29	68	10	00	17.35	73.72		5.2	5.4	5.0		5.4
10	17	73	15	24	17.29	73.75	5.2	5.2	5.0	5.9	S–S	5.2
09	02	80	16	39	17.24	73.76	5.3	4.3	4.9	8.0	5.3	
09	20	80	10	45	17.25	73.70	5.9	4.9	5.3	12.0	Normal	5.3
12	08	93	01	42	17.19	73.75	5.2	5.1	5.0	8.4	Normal	5.2
02	01	94	09	31	17.31	73.74	5.5	5.4	5.0	10.6	S–S	5.4
12	03	2K	18	03	17.16	73.73	5.6	5.2	4.9	5.0	S–S + minor Nor.	5.2
06	04	2K	22	30	17.15	73.74	5.1	4.8	5.0	7.8	S–S + minor Nor.	5.1
05	09	2K	00	32	17.17	73.75	5.6	5.2	5.3	6.9	Normal	5.3

Gu*: Guha *et al.*[30]. There is some discrepancy in the magnitudes among those reported by the Maharashtra Engineering Research Institute (MERI), National Geophysical Research Institute (NGRI) and USGS. The last column gives the re-estimated magnitudes.

reservoir water level is exceeded indicating that these events are influenced by the Kaiser effect[17].

Gupta *et al.*[18] had reported that globally, the water reservoir triggered earthquake sequences share the following common characteristics.

1. The foreshock b-value is higher than the aftershock b-value both being in general, higher than the b-values for natural earthquake sequences in the regions concerned and the regional b-values.
2. In addition to a high b-value, the magnitude ratio of the largest aftershock to the main shock is also high.
3. Aftershocks decay comparatively at a lower rate.
4. Foreshock patterns are identical and correspond to Type-II of Mogi's model, whereas the normal earthquake sequences in the concerned regions belong to Type-I of Mogi's model.

All these characteristics are governed by the mechanical properties of the medium. Deviation of these characteristics for the triggered earthquake sequences from the normal earthquake sequences indicates a change in the mechanical properties of the media as a consequence of artificial water reservoir impoundment.

After the Latur earthquake of 1993, a detailed discussion was held on the largest probable earthquake in the Indian Shield Region. On the basis of the stable continental region (SCR) earthquake occurrences elsewhere, it was concluded that the largest probable earthquake in the Indian Shield Region could be of magnitude 6.8 (ref. 19). The seismic activity in the Koyna region, on the basis of the distribution of the epicentres of $M \geq 5$ earthquakes is limited to an area of 30 km × 20 km. The KRFZ as delineated in Figure 2 is about 33 km in length and could have generated an earthquake of $M \sim 6.8$. However, the heterogeneity introduced by fluids in the hypocentral zone changed the mechanical characteristics and therefore, earthquake sequences belonging to Type-II of Mogi's model occur instead of Type-I. Gupta *et al.*[13] presume that KRFZ was stressed close to critical at the time of impoundment of the Koyna Dam in 1961 and thus was capable of generating an M 6.8 earthquake. However, the heterogeneity introduced by the filling of the reservoir divided the rock volume into smaller volumes, each being capable of releasing its energy as and when its competence was exceeded. It may be noted in Figure 2 that no epicentre of $M \geq 5$ earthquakes has repeated at the same location. Considering that one M 6.3, seventeen $M \geq 5$ earthquakes and over one hundred and fifty $M \geq 4$ earthquakes have occurred so far, it may be concluded that about one half of the energy of a possible M 6.8 earthquake in the rock volume bounded by the Patan Fault in the east and KRFZ in the west has already been released. It is therefore, concluded by Gupta *et al.*[13] that seismic activity at Koyna region would continue for another 2–3 decades. It is further noted that no intact fault segment long enough (~10 km) to generate another earthquake of $M \sim 6$ like the 10 December 1967 is left. However, $M \sim 5$ and smaller events will continue to occur and their occurrence will be governed by Kaiser effect, rate of loading of the reservoirs and the duration of retention of high levels.

Koyna: an ideal site for earthquake forecast studies

Here I wish to make a case for detailed investigations in the Koyna region for understanding the physics of the triggered earthquakes and possibly forecast the same for the following reasons:

- The earthquakes occur in a small area of 30 km × 20 km with the focal depths limited to 12 km. There is no other seismically active region in the near vicinity and the epicentral region is accessible for deployment of all kinds of experiments and making observations.
- Earthquakes have been occurring every year following an increase of water level in the reservoirs during monsoons and later during emptying of the reservoir[20,21].
- Earthquakes of $M \geq 4$ occur every year and so far over 160 such earthquakes have occurred.
- A rate of loading of 12 m/week appears to be a necessary but not sufficient condition for a $M \geq 5$ earthquake to occur[22]. It also appears that exceeding the previous maxima of water level (Kaiser effect) plays a very important role in the occurrence of $M \geq 5$ earthquake[13].
- There is an increase in foreshock activity some 15 days before an $M \geq 5$ earthquake[3,23].
- Some of the Koyna main shocks are preceded by swarms[24].
- Some precursory changes in *b*-value, spatial/temporal fractal dimensions, stress drop and corner frequency have been noted prior to moderate size Koyna events[25,26].
- A quasi-dynamic nucleation process is seen to occur some 100 h before an $M \geq 4$ earthquake[27].
- An instrumented network of boreholes to examine water level changes and its correspondence with earthquakes exist in Koyna region[28].
- Coseismic changes in water levels for 4 earthquakes of $M > 4.3$ along with precursory decrease are observed in the deep bore wells in the Koyna–Warna region[29].

The above features also make the Koyna region an ideal site for putting the deep bore hole to a depth of 3 to 4 km to comprehend geological processes associated with the occurrence of triggered earthquakes.

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