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Koyna, India, an Ideal site for Near Field Earthquake Observations

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ABSTRACT

The Koyna earthquake of M 6.3 on December 10, 1967 is the largest artificial water reservoir triggered earthquake globally. It claimed ~ 200 human lives and devastated the Koyna township. Before the impoundment of the Shivaji Sagar Lake created by the Koyna Dam, there were no earthquakes reported from the region. Initially a few stations were operated in the region by the Central Water and Power Research Station (CWPRS). The seismic station network grew with time and currently the National Geophysical Research Institute (NGRI), Hyderabad is operating 23 broadband seismographs and 6 bore hole seismic stations. Another reservoir, Warna, was created in 1985, which provided a further impetus to Reservoir Triggered Seismicity (RTS). Every year following the monsoon, water levels rise in the two reservoirs and there is an immediate increase in triggered earthquakes in the vicinity of Koyna-Warna reservoirs in the months of August – September. Peak RTS is observed in September and later during December. Another spurt in triggered earthquakes is observed during the draining of the reservoirs in the months of April- May. A comparative study of RTS earthquake sequences and the ones occurring in nearby regions made it possible to identify four common characteristics of RTS sequences that discriminate them from normal earthquake sequences. As the RTS events continue to occur at Koyna in a large number in a limited area of 20 km x 30 km, at shallow depths (mostly 2 to 9 km), the region being accessible for all possible observations and there being no other source of earthquakes within 100 km of Koyna Dam, it was suggested to be an ideal site for near field observations of earthquakes. This suggestion was discussed by the global community at an ICDP sponsored workshop held at Hyderabad and Koyna in 2011. There was an unanimous agreement about the suitability of the site for deep scientific drilling; however, a few additional observations/experiments were suggested. These were carried out in the following three years and another ICDP workshop was held in 2014, which totally supported setting up a borehole laboratory for near field investigations at Koyna. Location of a Pilot Bore-hole was decided on the basis of seismic activity and other logistics. The 3 km deep Pilot Borehole was spudded on December 20, 2016 and completed on June 11, 2017.

INTRODUCTION

Artificial water reservoirs are created globally for flood control, irrigation and power generation. Reservoir Triggered Seismicity (RTS) is an anthropogenic effect observed in the vicinity of a few reservoirs. Carder (1945) provided the first scientifically accepted case of RTS at Lake Mead, Colorado, USA. In early 1960's RTS events exceeding M 6 were reported (Gupta et al., 1972 a & b) from Hsingfenking, China (1961); Kariba, in the vicinity of Zambia-Zimbabwe (1963); and Kremasta in Greece (1966). On December 10, 1967 an earthquake of M 6.3 occurred in the vicinity of the Shivaji Sagar Lake, created by Koyna Dam. Earthquakes began to occur in the vicinity of this lake soon after its impoundment in 1962 (Guha et al., 1970). The frequency of these tremors increased considerably from the middle of 1963 onwards. These tremors were often accompanied by sounds similar to blasting (Mane, 1967). There were no earthquakes reported from the region before the impoundment of the Shivaji Sagar Lake. Although there were no seismic stations in the immediate vicinity of the Koyna Dam, a seismic station operating at India Meteorological Department at Pune would have recorded any M ~ 3 earthquake from the Koyna region. To monitor these earthquakes a close network of 4 seismic stations was installed in the immediate vicinity of the Koyna Dam (Gupta et al., 1969). The hypocenters were found to cluster near the lake and were very shallow. Before the December 10, 1967 earthquake, 5 other earthquakes occurred during 1967 that were strong enough to be recorded by several Indian seismic stations, including the September 13, 1967 earthquake of M 5.5. In 1985 another reservoir Warna, some 20 km south of the Koyna reservoir was impounded (Fig.1). This gave a further impetus to RTS in the region. It may however be noted that even before the impoundment of Warna reservoir, several RTS events of magnitude ~ 4 had been reported in the vicinity of Warna reservoir (Talwani, 1997). In this article the RTS associated with Koyna and Warna reservoirs is termed as Koyna RTS.

The December 10, 1967 earthquake claimed over 200 human lives and the Koyna Nagar Township was in shambles (Narain and Gupta, 1968). So far this is the largest RTS event globally. It is very unique with the Koyna region that seismic activity has continued since 1962, including over 20 earthquakes of M ~ 5, some 400 earthquakes of M ~ 4 and several thousand smaller earthquakes. All these earthquakes occur in a small region of 20 km x 30 km. The latest M ~ 4 earthquake occurred on June 3, 2017. Koyna region has been found to be the most suitable site for near field observations of earthquakes. Two International Continental Drilling Program (ICDP) workshops were held to discuss the suitability of the Koyna region for setting up a borehole laboratory. There was an over-whelming support for setting up such a facility.

In this communication, the relation between water levels in Koyna and Warna reservoirs and RTS; how RTS earthquake sequences differ from normal earthquake sequences in the concerned regions; how long RTS will continue at Koyna; is Koyna a suitable site for deep scientific drilling; brief mention of the two ICDP Workshops held in 2011 and 2014 to address RTS at Koyna and deep scientific drilling; location of the Pilot Borehole and completion of the 3 km deep Pilot Borehole are briefly presented.

[!] (The work reported here is carried out in collaboration with several colleagues at NGRI on Koyna earthquake related problems. These include Indra Mohan, B. K. Rastogi, Prantik Mandal, C. V. Ram Krishna Rao, Uma Maheshwar Rao, S. V. S. Sarma, R. K. Chadha, D. Srinagesh, D. V. Reddy, P. C. Rao, Sukanta Roy, Virendra Tiwari, H. V. S. Satyanarayana, Kusumita Arora, Prasanta K. Patro, D. Shashidhar, M. Uma Anuradha and K. Mallika).

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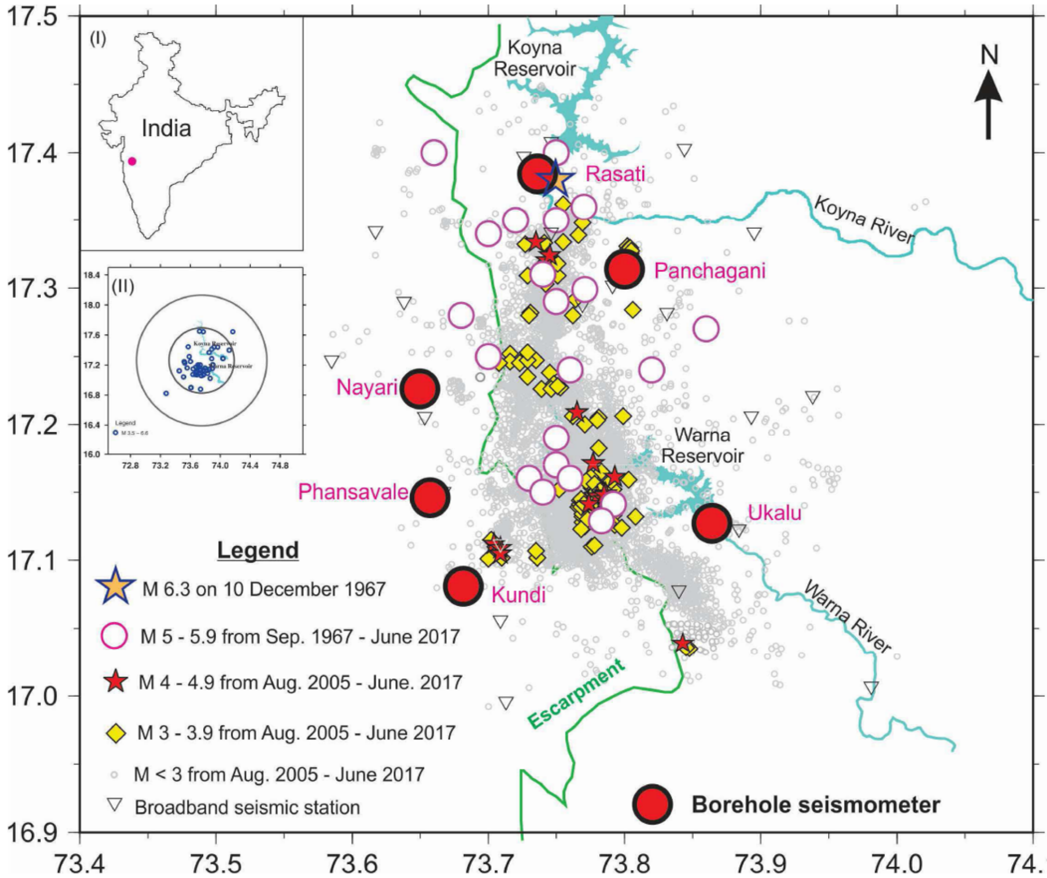

Fig.1a. (Updated from Gupta et al. (2017). Koyna- Warna region near west coast of India. Location of the Koyna main earthquake of December 10, 1967; earthquakes of M ~ 5 during August 1967 through June 2017; smaller earthquakes from August 2005 through June 2017; surface and borehole seismic stations; green curve indicates the WGE (Western Ghat Escarpment). (I) Koyna location in India; (II) Distribution of $M \geq 3.7$ earthquakes for 1967- 2015 (USGS) in the vicinity of Koyna and an outer circle of 100 km radius indicating that there is almost no seismic activity outside the Koyna region.

EARTHQUAKES IN KOYNA-WARNA REGION

Figure 1(a) gives the details of the location of Koyna and the Warna reservoirs near the west coast of India. All earthquakes of M ~ 5 since the beginning of RTS in the region including the M 6.3 earthquake of December 10, 1967 and smaller magnitude earthquakes for the period August 2005 to June 2017 are plotted. It may be noted that no M ~ 5 earthquake epicenter has repeated. The figure also depicts the location of 23 broad-band seismic stations as well as the 6 borehole seismic stations. It is noteworthy that most of the RTS is restricted in the vicinity of the reservoirs and limited to an area of 20 km x 30 km. Earthquakes are basically confined within 50 km radius area and no earthquakes are reported from 50 to 100 km radius (the inset) from the Koyna Dam. Figure 1(b (i) and (ii)) are the depth sections of M ~ 5 earthquakes in N-S and E-W directions respectively. The alignment of these hypocenters on 73.7° E longitude is noteworthy. Figure 1(b (iii) and (iv)) are similar plots for the period August 2005 through June 2017. Concentration of hypocenters along 73.7° E longitude is noteworthy here also. This is consistent with the surface expression of the Donachiwada Fault (Fig. 7a), which has been recognized to have hosted the December 10, 1967 M 6.3 earthquake and most of the M ~ 5 earthquakes in Koyna region.

What is the Relationship between the Water Levels in the Koyna and Warna Reservoirs and RTS?

There is a rapid loading of the reservoirs following the onset of monsoon during the months of June-July. The peak water levels are reached in August. Although the monsoon get over by September but inflow to the reservoirs continues and near peak water levels are

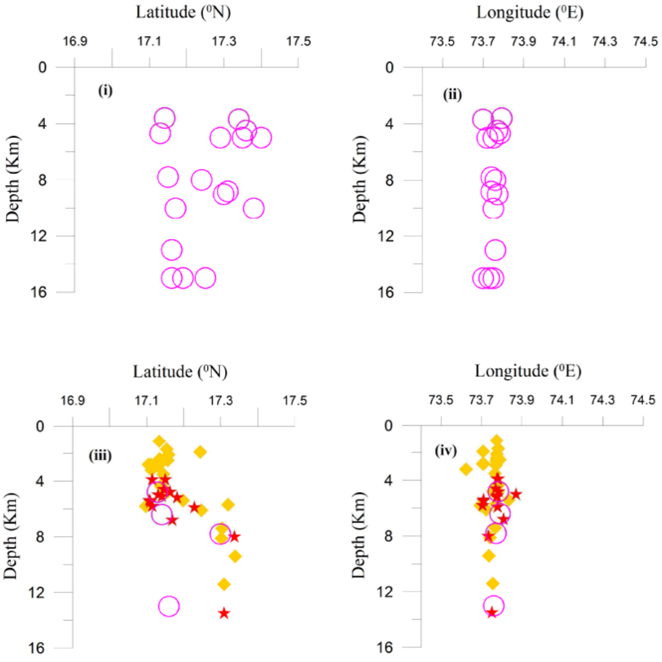

Fig.1b. Depth section of M ~ 5 earthquakes (epicenters shown in (Fig.1a)) along latitudes (**i**) and longitudes (**ii**); and depth sections of $M \geq 3.5$ earthquakes along latitude (**iii**) and longitude (**iv**). Symbols same as in (Fig.1a). The concentration of hypocenters along 73.75° E is noticeable that corresponds to Donachiwada Fault (Fig.7).

maintained during August to October/November. From December onwards water levels fall reaching a bottom during May end and June beginning every year (Fig. 2(a) and (b)). Figure 3 depicts the month wise distribution of number of M ≥4 earthquakes for the period 1967 to 2016. As ~ 200 M ~4 earthquakes have occurred in the region over the past 50 years, we take M ~ 4 temporal distributions as a major of the monthly RTS in the region. It may be noted that from a near minimum number of earthquakes in July, seismic activity increases in August. It reaches a peak in September, which is soon after the peak water levels are reached in the two reservoirs. It may be noted that the first M > 5 RTS event in the region occurred on September 13, 1967. Another peak is reached in December, which is not as prominent as the September peak. The largest M 6.3 earthquake in 1967 also occurred in December. There were several M ~ 5 aftershocks of the main December 10, 1967 earthquake that had a magnitude of M 6.3. However, in later years only two M ~ 5 earthquakes occurred in the month of December. The frequency of M ≥4 earthquakes in January is quite low and later a peak is seen in March, which corresponds to a higher rate of emptying the reservoir. In a recent study (Shashidhar et al., 2016), a spurt in seismic activity in the month of March 2015 was observed, and it was pointed out that when unloading rate in the Koyna Reservoir increased from 0.053 to 0.170 m/day and in the Warna Reservoir from 0.065 to 0.106 m/day during the 3rd week of March 2015, there was a spurt in RTS.

In some earlier studies (Gupta et al., 1972 a & b; Gupta and Rastogi, 1974), it was observed that factors like rate of loading, highest water level reached and duration of retention of high water levels directly affected RTS at Koyna. In another study, it was found that a rate of loading of 13 m/week was a necessary but not a sufficient condition for M ≥ 5 earthquakes to occur in the Koyna region (Gupta, 1983). It was also seen that whenever the previous water level maxima was exceeded at Koyna/Warna reservoirs and/or high water levels were retained for longer durations, M ~ 5 earthquakes occurred (Gupta et al., 2002).

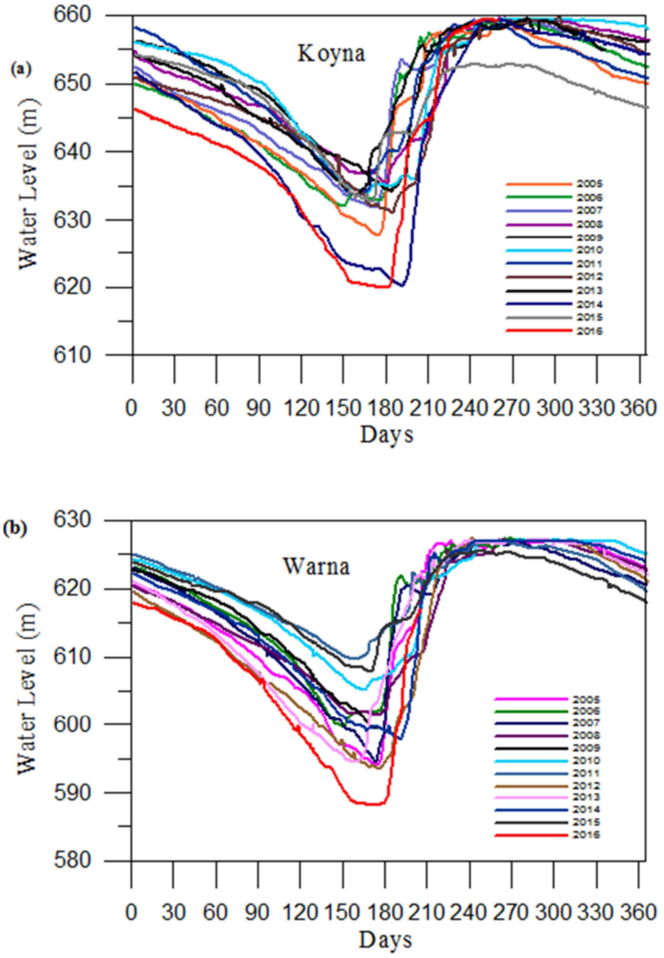

Fig.2. Annual cycles of loading and unloading of the Koyna **(a)** and Warna **(b)** reservoirs for the period of 2005 through 2016 (updated from Gupta et al., 2017). The reservoirs get loaded following the monsoon (for details see the text).

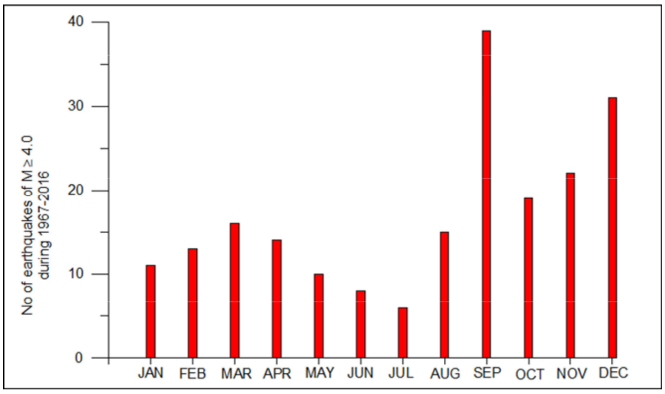

Fig. 3. Monthly number of M ≥ 4 earthquakes in the Koyna region for the period 1967 through 2016. There is a spurt in seismic activity soon after loading of the reservoirs (end of August-September). Another peak appears in December. The third peak is associated with fast draining of the reservoirs in March.

How the RTS Earthquake Sequences Differ from Normal Earthquake Sequences?

By early 1970s, over a dozen cases of RTS were known. A major question had been to discriminate a RTS event from a normal event. Detailed studies of these RTS sequences lead to identification of four common characteristics which discriminate RTS sequences from the normal regional earthquake sequences occurring in close by regions, but not associated with the reservoirs (Gupta et al., 1972 a & b). These are: (i) In the earthquake frequency-magnitude relation (log N= A-*b* M, where N is the number of earthquakes with magnitude ≥M, and A and *b* are constants), the foreshock and aftershock *b* values of the RTS sequences are higher than the regional and normal earthquake sequences *b* values. (ii) The ratio of the magnitude of the largest aftershock to the main shock is high. (ii) The decay of aftershocks in the RTS is slower. (iv) The foreshock-aftershock pattern of RTS sequences belongs to Type II of Mogi's Model (Fig.4), whereas the natural earthquake sequence pattern belongs to Type I. These characteristics are governed by the mechanical properties of the media, and their deviation from the normal implies that the filling of the reservoir has changed them by introducing heterogeneity in the media. This can be best illustrated from Figure 4. In Figure 4 (II) "A" is a homogenous media rock volume. When the stress exceeds the strength of the rock, there would be a major earthquake releasing most of the strain, followed by peripheral adjustment aftershocks. In such a sequence, there would not be any foreshocks, the aftershock activity would be over in a short time, the ratio of the largest aftershock to the main event would be low, and the *b* value would be also low. This is typically the situation with the earthquake sequences in stable continental regions not associated with the reservoir loading. Due to filling of the water reservoir, the heterogeneity of the media increases (Figure 4 (II) "B"), and the rock volume gets fragmented. As a consequence the accumulated strain is released through smaller rock volumes. In such a situation, the earthquakes would start occurring as and when the strength of an individual rock volume is exceeded. The main earthquake would correspond to the largest rock volume and there would be foreshocks and aftershocks, changing the pattern from Type I of Mogi's (1963) Model to Type II. These criteria are helpful in

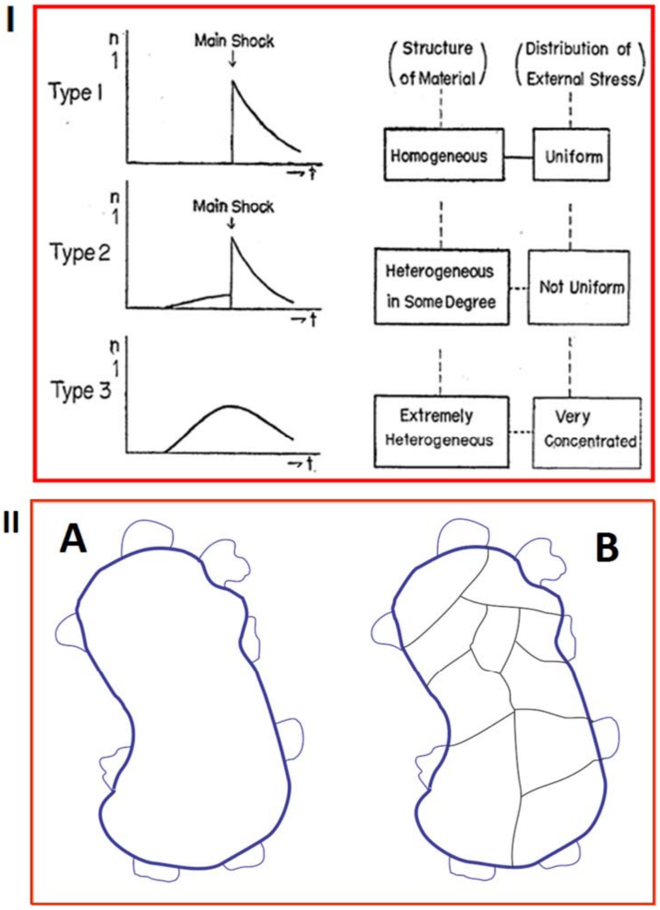

Fig.4. (I) Depicts Mogi's (1963) classification of the earthquake sequences into three broad categories (Mogi, 1963b). **(II)** Cartoon for (A) homogenous rock mass, and (B) fragmented rock mass. For details see the text.

identifying whether an earthquake sequence occurring in the vicinity of a reservoir is triggered or normal. Safer sites for locating artificial water reservoirs are determined by doing in-situ-stress measurements and assessing how close to critical a site is stressed, and whether filling of the reservoir would trigger the earthquakes (Gupta, 1992). This model of RTS, developed in 1970's was based on the observations at about a dozen RTS sites. Now over 120 sites are globally known where RTS has been observed and these criteria are found to be applicable (Gupta, 2011). One of the recent examples is reported from Vietnam (Cao Dinh Trieu et al., 2014).

It would be appropriate at this stage to point out that Stable Continental Regions (SCR) are very quite parts of the continent. It is estimated that the strain accumulation in such regions is of the order of (10^{-9}) to (10^{-10}) per year as compared to (10^{-7}) to (10^{-9}) for the intra-plate region and (10^{-5}) to (10^{-7}) at the plate boundaries (Johnston, 1993; Gupta and Johnston, 1998). RTS is mostly found to be occurring in SCRs. The occurrence of M 6.2 Latur earthquake on September 29, 1993 in the same Deccan Volcanic Province, some 300 km east of the Koyna earthquake of December 10, 1967 provided an excellent opportunity to compare the two earthquake sequences. The Latur earthquake occurred at 22h 25m UTC on 29th Sept. 1993 (corresponding to 3h 55m IST on 30 Sept). The earthquake claimed some 11,000 human lives becoming the deadliest SCR earthquake till then (Gupta et al, 1997). It may be noted that DVP is basically a thrust fault regime (Rajendran et al., 1992). The Latur earthquake focal mechanism is also trust fault dominated (Gupta et al., 1997). However, the earthquakes in the Koyna region are basically left – lateral strike-slip and/or normal fault dominated (Rao and Shashidhar, 2016). Rastogi (1994) compared the Latur earthquake sequence with the Koyna earthquake sequence and found that the Latur sequence had low '*b*' values, low largest aftershock magnitude to the main shock magnitude ratio; in addition to not having foreshocks and the seismic activity getting over in a rather short time, contrary to the characteristics of Koyna earthquake sequences.

How Long RTS will Continue at Koyna?

At most of the RTS sites, triggered earthquakes start to occur soon after the impoundment of the reservoir and continue for different lengths of time varying from a few years to a decade or so. The Hsingfengkiang Reservoir, China was impounded in 1959 and soon after that triggered earthquakes started to occur. The largest triggered earthquake of M 6.1 occurred on March 19, 1962 (Chung-Kang et al., 1974). However, while in early sixties thousands of earthquakes occurred every month, their number dropped to a few by 1978 (Ishikawa and Oike, 1982; Gupta, 1992). Lake Kariba, Zambia-Zimbabwe border, was impounded in 1958. The levels kept increasing every year and a peak level was reached in 1963. This was followed by an immediate burst of triggered earthquakes, including the M 6.2 earthquake on April 23, 1963 (Pavlin and Langston, 1983). In the following years, a few M ~ 5 earthquakes occurred in the vicinity of the lake. However, the activity ceased in the following years (Gupta, 1992). Same is the case with the Lake Kremasta in Greece, which was impounded in 1965, with very rapid loading in January 1966 and the largest triggered earthquake of M 6.2 occurred on February 5, 1966. In the months to follow the earthquake frequency dropped considerably (Galanopoulos, 1967; Stein et al., 1982).

Unlike the above mentioned cases of RTS where M≥6 earthquakes had occurred and RTS stopped within a few years to a decade, triggered earthquakes have continued to occur at Koyna till now, that is some 55 years after the impoundment of the Shivaji Sagar Lake created by the Koyna Dam. The latest M ~ 4 earthquake occurred on June 3, 2017. The magnitude and frequency of the largest possible earthquakes in the stable continental region has been debated (for example Johnston, 1994). It has been hypothesized that the maximum credible earthquake in the Koyna region is of M 6.8 and the region was stressed close to critical before the impoundment of the Koyna Dam (Gupta et al., 2002). As explained in the earlier section of this article, creation of the reservoir introduces heterogeneity in the media and earthquakes start to occur as and when the strength of an individual rock volume is exceeded. Considering that so far 22 M ~ 5, some 200 M ~ 4 and thousands smaller earthquakes have occurred in the region, the following is a simple calculation:

Energy Released in Koyna Region

The Maximum Credible Earthquake (**M$_{\mathbf{CE}}$**) considered for Koyna: **M = 6.8**

Empirical relation used: ***Log E = 1.5 M + 11.8***, (M = magnitude)

Using the above relation $E_{MCE} = 10^{22}$ ergs

Energy released so far:

- *Case 1:* Average magnitude of 22 M ~ 5, and 200 M ~ 4 events taken as 5.5 and 4.5:

  $E = 1 \times E_{M6.3} + 22 \times E_{M\,5.5} + 200 \times E_{M\,4.5}$

  $= 10^{(21.25)} + 22\times10^{(20.05)} + 200\times10^{(18.55)} = 10^{21.94}$

  Percentage of $M_{CE} = 10^{21.94} / 10^{22} = 87\ \%$

- *Case 2:* Average magnitude of 22 M ~ 5, and 200 M ~ 4 events taken as 5.3 and 4.3:

  $E = 1 \times E_{M6.3} + 22 \times E_{M\,5.3} + 200 \times E_{M4.3}$

  $= 10^{(21.25)} + 22\times10^{(19.75)} + 200\times10^{(18.25)} = 10^{21.51}$

  Percentage of $M_{CE} = 10^{21.51} / 10^{22} = 32\ \%$

Considering the average of the two extreme scenarios, about 60% energy of an M 6.8 earthquake has been released in the Koyna region. It is further noted that no M ~ 5 earthquake epicenter has repeated in the region (Fig.1). This leads to a conclusion that RTS in Koyna region shall continue for another 2 to 3 decades.

Is Koyna a Suitable Site for Scientific Deep Drilling?

A number of studies have already established the association of monsoon driven loading and unloading of the Koyna and Warna reservoirs with the RTS in the Koyna region. However, the triggering mechanism is poorly understood. We know precious little about the physical properties of the rocks and fluids in the fault zone and what role they play in sustaining triggered earthquakes for over 5 decades due to lack of near field observations. The earthquakes occur in a small area of 20 km x 30 km, are shallow (mostly between 2 and 9 km depth), the region is totally accessible, the RTS has continued for over 5 decades and there is no other earthquake source within 50 to 100 km of Koyna Dam. This makes Koyna physically and logistically a very suitable location for the near field observation of earthquakes. It was felt necessary to share this view with the international community and an International Continental Drilling Program (ICDP) workshop was held at Hyderabad and Koyna during March 21-26, 2011 (Gupta and Nayak, 2011). The objectives were: (1) To provide an international forum for sharing and exchange of lessons learned from investigations on RTS worldwide including Koyna, (2) To brain storm on the scientific motivation behind deep drilling in an active fault zone down to focal depths, at a classical RTS site in an intra-plate setting, (3) To prepare a complete drilling plan, (4) To plan the entire array of measurements/ monitoring opportunities provided by deep drilling in consultation with national and international experts, (5) To develop a full proposal on scientific drilling at Koyna. The workshop was attended by 26 participants from abroad and 50 participants from India. They have had experience with San Andreas Fault Observatory at Depth (SAFOD); the Chelungpu Fault Drilling Project in Taiwan; the Nojima Fault Drilling in Japan; the Gulf of Corinth in Greece; and the Latur Fault in India. All the participants at the workshop agreed that Koyna is a world-class geological site and a natural earthquake laboratory to conduct a deep bore hole experiment to study earthquakes in near field. The Ministry of Earth Sciences (MoES) declared full support to the Koyna Project and ICDP offered to provide all technical support. Based on the presentations in the workshop and the experience of the participants, several suggestions for scientific work were made before initiating the deep drilling program. These included improving hypocenter location capabilities in the Koyna region; airborne gravity-gradient and magnetic surveys; seismic reflection studies; LiDAR; Magneto-telluric surveys; study hydraulic connectivity and based upon the results of the above surveys, plan the Deep Borehole Drilling Project.

During the period 2011-2014, the suggested investigations were undertaken through support of the MoES. These included: (1) Drilling 9 exploratory boreholes penetrating the basalt cover and getting 300-500 m into the granitic basement for studying sub-surface geology and rock properties; (2) Airborne gravity gradiometry and magnetic surveys to delineate 3D subsurface structure in the Koyna region, specifically covering the RTS area; (3) Magnetotellurics to map subsurface electrical conductivity and estimate the thickness of Deccan Traps; (4) Airborne LiDAR surveys to get high resolution topographic information and prepare a bare earth model; (5) Heat-flow measurements and modeling of the subsurface temperatures; and (6) Instrumenting 6 bore holes with 3-component seismometers at depths of ~ 15,00 m to better estimate earthquake parameters. Figure 5 adopted from Gupta et al. (2017) shows the installation and deployment of various experiments. The major discoveries of this phase are as follows (Gupta et al., 2014, 2017):

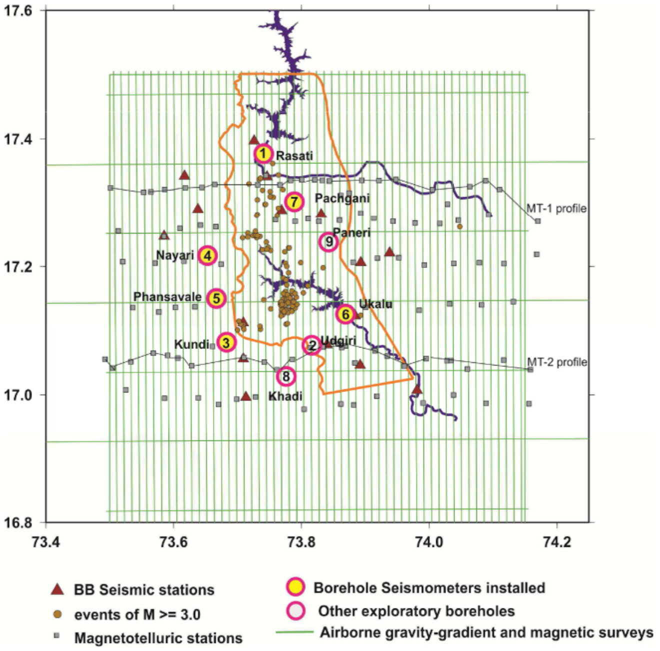

Fig.5. The study area indicating the installation or deployment plan of the various experiments undertaken in the preparatory phase of the deep drilling programme. Earthquakes of M ≥ 3.0 occurred during August 2005 to December 2013. MT-1 and MT-2 indicate the magnetotelluric profiles passing through Rasati in the north and Udgiri in the south, respectively. The area covered by LiDAR is enclosed by the brown line (Gupta et al., 2014).

a) There has been a long debate about the presence of Mesozoic sediments below the basalt cover. No such sediments were found.
b) It was discovered that the thickness of the basalt column is directly related with topography. Although, the topography in the area covered is almost ~1000 m, the basement is almost flat with variation of no more than 100 m, and lies about 300 m below the present mean sea level.
c) One of the requirements for setting up a borehole laboratory is not to have very high temperatures. The temperature was estimated to be ~ 150° C at 6 km depth.
d) The basalt-basement contact was clearly identified through MT response. A direct correspondence was found in resistivity as inferred from MT surveys and the week zones in the region.
e) Hypocenters are associated with sharp density contrast and resistivity changes.
f) Geological/geophysical logging in 8 boreholes has revealed the alignment of prominent faults.
g) LiDAR surveys led to developing bare earth model of the region and identification and demarcation of the Donachiwada Fault which hosted the 1967 earthquake and most M ~ 5 earthquakes in the region.
h) Operation of borehole seismometers reduced the absolute errors in location of earthquakes from ~ 800 m to 300 m.

The above work was discussed in the 2nd ICDP workshop held at Koyna during 16 to 18 May 2014 (Gupta et al., 2014). The workshop was attended by 12 participants from abroad and 37 from India. The work carried out since the first workshop in 2011 was presented and discussed. A plan for Pilot Borehole(s) drilling was also presented. There were detailed discussions on various aspects of drilling, location and completion of the Pilot Borehole(s). Based on the hypocenter locations 5 possible sites for the location of the Pilot Borehole(s) were suggested. It was unanimously concluded that Koyna is one of the best sites anywhere in the world to investigate genesis of RTS from near field observations.

Location of the Pilot Borehole

Based on the hypocenters during 2009 to 2014 in the RTS in Koyna region, 5 blocks for possible location of the Pilot Borehole(s) were identified (Gupta et al., 2017). It was kept in mind that there should be enough repeating earthquakes with in a depth of 5 km of magnitude M 2, being the magnitude of the target earthquake. Two of these locations (A and B in Fig.6) were south of Warna Reservoir and the remaining 3 north of Warna Reservoir (C, D, & E) just short of the Koyna Reservoir (Fig.6). Considering several logistic constraints, particularly to be out of the demarcated forest cover, finally a location within site D was selected (Fig.7). It may be noted in Fig.7 that the Donachiwada Fault zone is in the immediate vicinity of this site. During the period August 2005 through December 2015, the site hosted 3 earthquakes of M 3.0 to 3.9 and 59 earthquakes of M 2.0 to 2.9.

THE PILOT BOREHOLE

The Pilot Borehole was spudded on December 20, 2016 and the drilling of 3000 m was completed on 11th June 2017. Figure 8 provides the well configuration and a general lithology of the pilot borehole. The basement was reached at a depth of 1247 m. It may be noted that in a nearby borehole at Panchgani the basement was at a depth of 1252 m. Here also, no sediments were encountered at the bottom of the basalt column. It is interesting to note that several zones with immense fluid losses were encountered. Detailed geophysical logging has been carried out. With the help of ICDP, on-line-gas analyses (OLGA) facility had been set up. Cores were recovered from depths of 1679, 1892 and 2091 m depths. These are 9 m long and 4 inch diameter cores and there was almost 100% recovery. In-situ stress measurements have been carried out at depths of 1600 m and deeper. All the data acquired are being analyzed.

CONCLUDING REMARKS

RTS that got initiated in 1962 soon after the filling of the Shivaji Sagar Lake created by the Koyna Dam has continued till now. RTS is seen to be mostly occurring in Stable Continental Regions. For the Koyna region it is hypothesized that the region was critically stressed before the impoundment of the reservoir(s) and it could host an M 6.8 earthquake. However, heterogeneity introduced by the reservoir has fragmented the rock mass. So far about 60% energy of an M 6.8 earthquake has been released. Loading and unloading of Koyna and Warna reservoirs influences RTS in the region. RTS is influenced by rate of loading, highest water levels reached and duration of retention of high water levels. Whether previous water maxima is exceeded or not is related to the occurrence of M ~ 5 earthquakes. Global study of RTS sequences has led to discovering their common characteristics that differentiate them from normal earthquake sequences occurring in the same region. Occurrence of an M 6.2 Latur earthquake on 29th September 1993 in same DVP some 300 km from Koyna gave an excellent opportunity to compare the two earthquake sequences and demonstrate the difference between the two. As earthquake epicenters

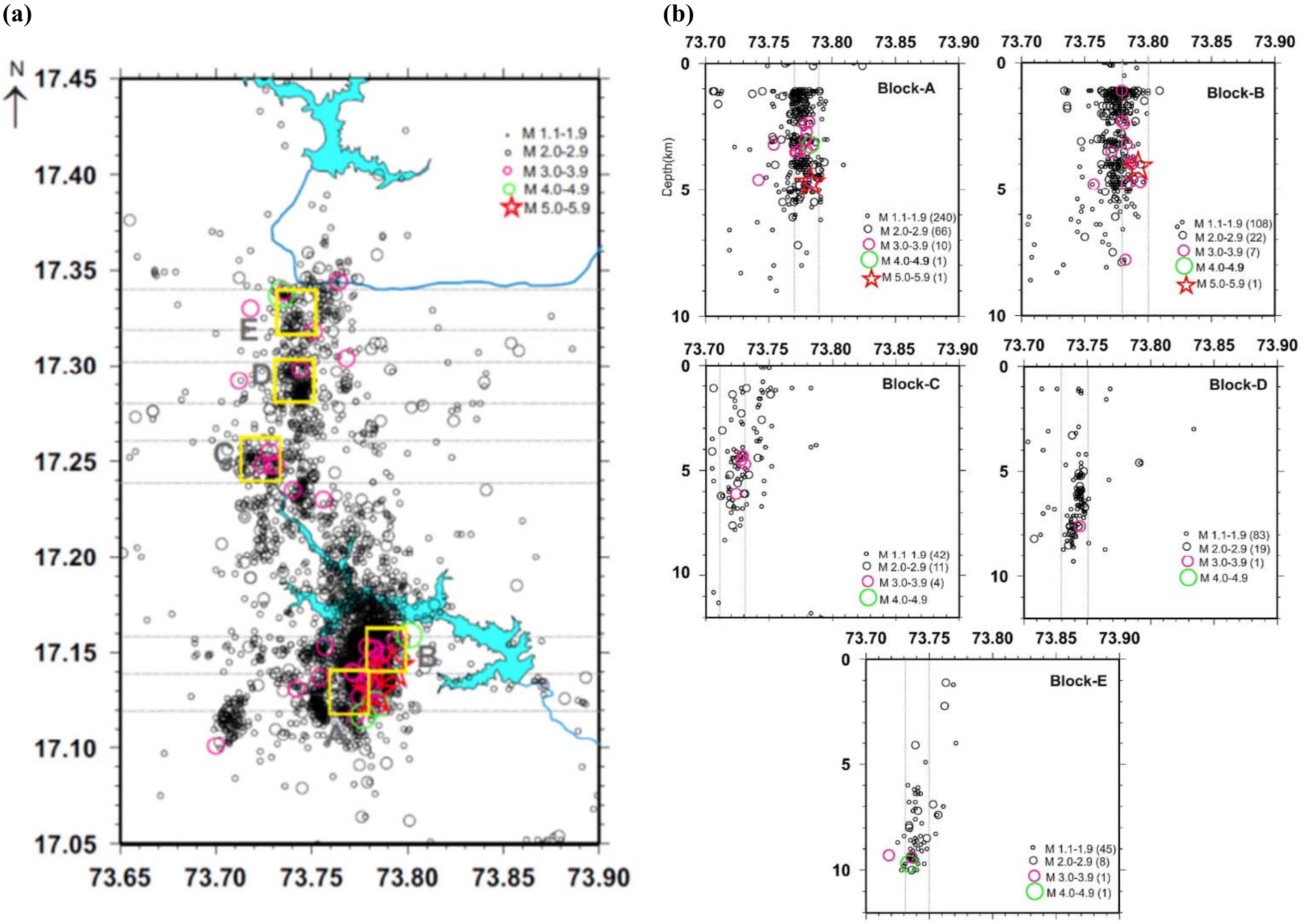

Fig.6. (a) Seismicity of the Koyna-Warna region during 2009-2014. The five Blocks A, B, C, D and E are each 2 X 2 km^2 in area. Dotted lines indicate a swath of 2 km area at each Block. **(b)** Depth sections for 2 km swath for the 5 blocks. With in brackets are indicated the number of earthquakes that occurred in each of these blocks.

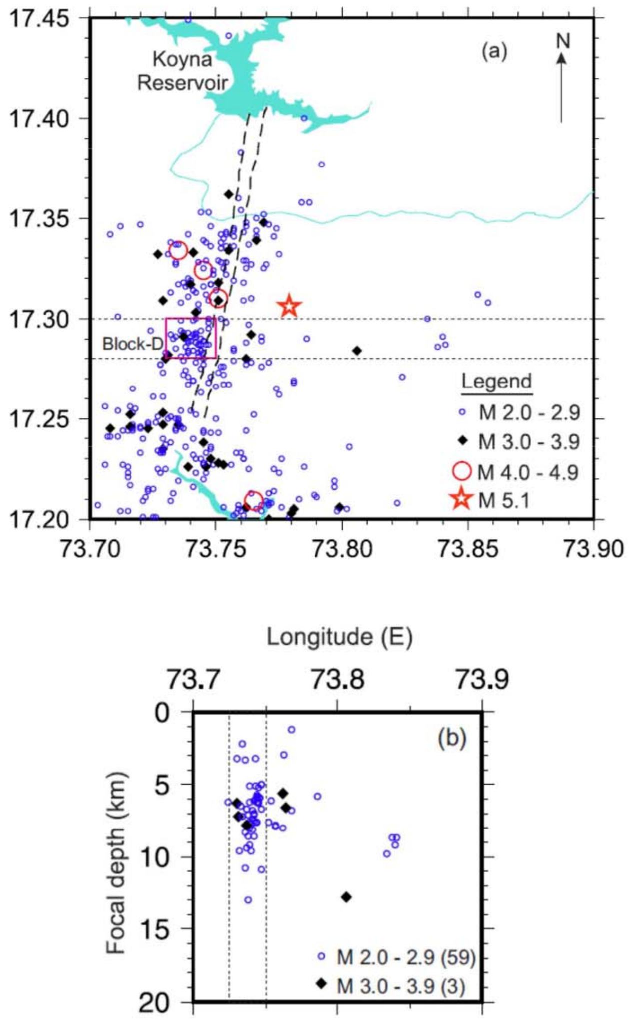

Fig.7. (a) Earthquakes of magnitude ≥2.0 that occurred during August 2005-December 2015. Dotted lines indicate a swath of 2 km area of the Block-D. Dashed line indicates the Donachiwada fault zone. **(b)** Depth section for the 2 km wide swath in (a) above. Dotted lines indicate the area 2 X 2 km^2.

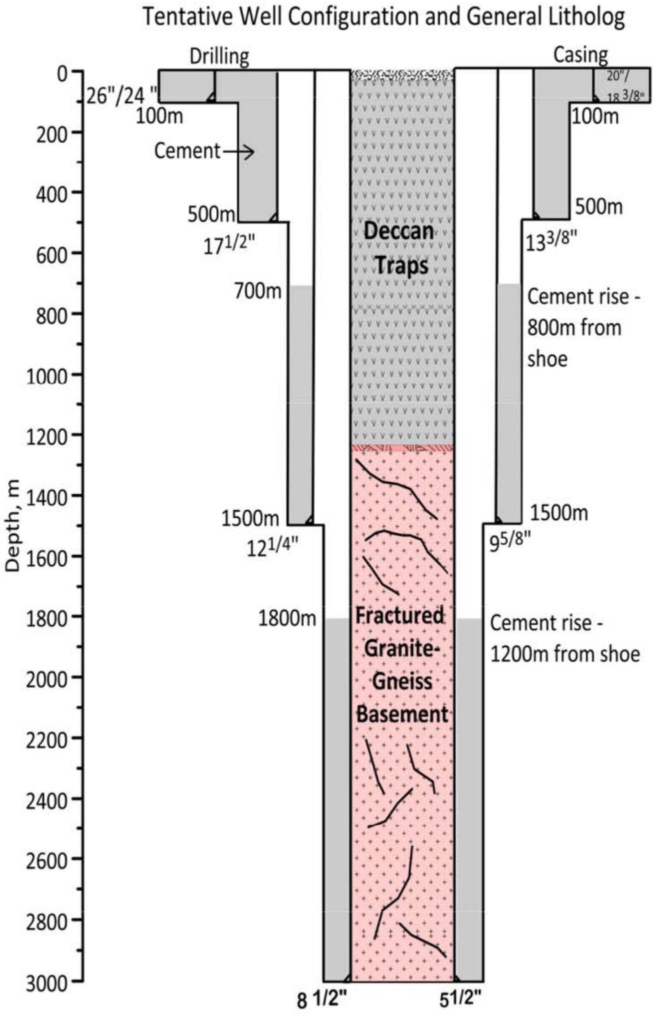

Fig.8. Generalized configuration of the 3000 m deep pilot borehole, giving the drilling and casing details. The borehole entered the basement at a depth of 1247 m after penetrating through the basalt column. Practically no sediments were encountered below the basalt column, which is lying directly on the pre- Cambrian granite-gneiss basement.

are confined to an area of 20 km x 30 km, the focal depths being mostly between 2 and 9 km, the accessibility to Koyna region and the fact that there is no other seismic source within 100 km of Koyna Dam, make it a suitable site for near field studies of earthquakes. This was discussed in the first ICDP Workshop, where the site was found to be very appropriate for near field studies. However, a few suggestions for further work were made to be under taken before setting up deep bore hole drilling program. These were carried out during 2011 to 2014 with support from MoES. In the second ICDP workshop in 2014, the results of the work having been carried out as well as plan of the Pilot Borehole were presented. These were supported and during 2014 to 2017, the location of the Pilot Borehole was finalized and the 3 km deep Pilot Bore Hole was completed with all the necessary measurements having been carried out. The analysis of the measurements having been made in the Pilot Borehole is under progress.

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References

Cao Dinh Trieu, Cao Dinh Trong, Le Van Dung, Thai Anh Tuan and Dinh Quoc Van, Ha Vinh Long (2014) Triggered Earthquake study in Tranh River No.2 (Vietnam) Hydropower Reservoir.

Carder, D.S. (1945) Seismic investigations in the Boulder Dam area, 1940 – 1944, and the influence of reservoir loading on earthquake activity. Bull. Seismol. Soc. Amer., v.35, pp.175-192.

Chung-Kang, S., Hou-chun. C., Chu-han, C., Li-Sheng, H., Tzu-chiang, L., Chen-yung, Y., Ta-chun, W. and Hsueh-hai, L. (1974) Earthquakes induced by reservoir impounding and their effect on the Hsingengkiang Dam. Science Sinica, v.17(2), pp.239-272.

Galanopoulos, A.G. (1967) The large conjugate fault system and the associated earthquake activity in Greece. Ann. Geol. Pays Helleniques (Athens), v.18, pp.119-134.

Guha, S.K., Gosavi, P.D., Varma, M.M., Agarwal, S.P., Padale, J.G. and Marwadi, S.C. (1970) Recent seismic disturbances in the Shivajisagar Lake area of the Koyna Hydro-electric Project. Maharashtra, India, 2. Rep. C.W.P.R.S., 25p.

Gupta, H.K., Narain, H., Rastogi, B.K. and Mohan, I. (1969) A study of the Koyna earthquake of Dec.10, 1967, Bull. Seismol. Soc. Amer., v.59, pp.1149-1162.

Gupta, H.K., Rastogi, B.K., and Narain, H. (1972a) Common features of the reservoir associated seismic activities. Bull. Seismol. Soc. Amer., v.62, pp.481-92.

Gupta, H.K., Rastogi, B.K. and Narain, H. (1972b) Some discriminatory characteristics of earthquakes near the Kariba, Kremasta and Koyna artificial lakes. Bull. Seismol. Soc. Amer., v.62, pp.493- 507.

Gupta, H.K. and Rastogi, B.K. (1974) Will another damaging earthquake occur in Koyna? Nature, v.248, pp.215-216.

Gupta, H.K. (1983) Induced seismicity hazard mitigation through water level manipulation at Koyna, India: A suggestion. Bull. Seismol. Soc. Amer., v.73, pp.679-682.

Gupta, H.K. (1992) Reservoir Induced Earthquakes. Elsevier Scientific Publishing Company, Amsterdam, 364p.

Gupta, H.K (2011) Artificial Water Reservoir Triggered Earthquakes, Encyclopedia of Solid Earth Geophysics, Springer+Business media, 1, pp.15-24.

Gupta, H.K., Rastogi, B.K., Indra Mohan, Rao, C.V.R.K., Sarma, S.V.S. and Rao, R.U.M. (1997) An investigation into the Latur Earthquake of September 29, 1993 in Southern India. Tectonophysics, v.287, pp.299-318.

Gupta, H.K. and Johnston, A.C. (1998) Stable Continental Regions Are More Vulnerable to Earthquakes than Once Thought' (Chapman Conference Report), EOS Transactions, AGU, v.79(27), pp.319-321.

Gupta, H.K and Nayak, S. (2011) Deep Scientific Drilling to Study Reservoir-Triggered Earthquakes in Koyna, Western India, Scientific Drilling, No.12, pp.53-54.

Gupta, H.K., Prantik Mandal and Rastogi, B.K. (2002) How long will triggered earthquakes at Koyna, India continue? Curr. Sci., v.82,(2), pp.202-210.

Gupta, H.K., Purnachandra Rao, N., Sukanta Roy, Kusumita Arora, Tiwari, V.M., Patro, B.P.K., Satyanarayana, H.V.S., Shashidhar, D., Mallika, K., Vyasulu V. Akkiraju, Goswami, D., Vyas, D., Ravi, G., Srinivas, K.N.S.S.S., Srihari, M., Mishra, S., Dubey, C.P., Raju, Ch. V., Ujjal Borah, Chinna Reddy, K., Narendra Babu, Sunil Rohilla, Upasana Dhar, Mrinal Sen, Bhaskar Rao, Y.J. (2014) Investigations related to scientific deep drilling to study reservoir-triggered earthquakes at Koyna, India. Internat. Jour. Earth Sci., DOI: 10.1007/s00531-014-1128-0.

Gupta, H.K., Shashidhar, D., Mahato, C.R., Satyanarayana, H.V.S., Mallika, K., Purnachandra Rao, N., Maity, B.S. and Navitha, K. (2017) Location of the pilot borehole for investigations of reservoir triggered seismicity at Koyna, India. Gondwana Res., Elsevier, v.42, pp.133-139.

Ishikawa, M. and Oike, K. (1982) On reservoir-induced earthquakes in China, Zishin, v.35(2), pp.171-181.

Johnston, A.C. (1994) Report on the Session on Latur Earthquake at IASPEI XXVII General Assembly by H.K.Gupta. IUGG Chronicle, N 221, April/May 1994, pp.80.

Johnston, A.C. (1993) Average stable continental earthquake source parameters based on constant stress drop scaling, Abstracts, 65th Annual meeting, Eastern Section. Seismol. Soc. Amer., SRL, v.64(3-4), pp.261.

Mane, P.M. (1967) Earth tremors in the Koyna Project area. 9th Congr. On Large Dams, Istanbul, 1967. Commission Internationale des Grands Barrages, Paris, pp.509-518.

Mogi, K. (1963) Some discussions on aftershocks, foreshocks and earthquake swarms-the fracture of a semi-infinite body caused by an inner stress origin and its relation to the earthquake phenomena. Bull. Earthquake Res. Inst., v.41, pp.615-658.

Narain, H. and Gupta, H.K. (1968) The Koyna earthquake. Nature, v.217, pp.1138-1139.

Pavlin, G.B. and Langston, C.A. (1983) An integrated study of reservoir induced seismicity and Landsat. Imagery of Lake Kariba, Africa. Photogramm. Engg. Remote Sensing, v.49, pp.513-525.

Rajendran, K., Talwani, P. and Gupta, H.K. (1992) State of Stress in the Indian Subcontinent: A review. *In:* Special Issue on Seismology in India–an Overview. Curr. Sci., v.62, Nos.1&2, pp.86-93.

Rao, N.P. and Shashidhar, D. (2016) Periodic variation of stress field in the Koyna–Warna reservoir triggered seismic zone inferred from focal mechanism studies. Tectonophysics, Elsevier, v.679, pp.29-40.

Rastogi, B.K. (1994) Latur Earthquake: Not Triggered. *In:* Latur Earthquake. Mem. Geol. Soc. India, no.35, pp131-137.

Shashidhar, D., Satyanarayana, H.V.S., Mahato, C.R., Mallika, K., Rao, N.P. and Gupta, H.K. (2016) Borehole Network at Koyna India. Seismological Research Letters, Early edition.

Stein, S., Wiens, D.A. and Fujita, K. (1982) The 1966 Kremasta reservoir earthquake sequence. Earth Planet. Sci. Lett., v.59, pp.49-60.

Talwani P. (1997) On the nature of reservoir induced seismicity. Pure Appld. Geophys., v.150, pp.511-550.