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GUEST EDITORIAL

Understanding anthropogenic earthquakes

Some anthropogenic activities can lead to triggering of earthquakes under favourable geological conditions. These include filling of artificial water reservoirs, hydrocarbon production, underground coal and metal mining, geothermal energy production, underground storage of CO_2, etc. Among these, artificially created water reservoir triggered seismicity (RTS) has a significant social and economic impact. Over the years, RTS has been observed at hundreds of sites globally (Gupta, H. K., In *Encyclopedia of Solid Earth Geophysics*, Springer, 2021, 2nd edn, pp. 19–32), and at least at five sites, earthquakes exceeding magnitude 6 have occurred. Koyna, Maharashtra, India is one of the most prominent among them, where the 10 December 1967 earthquake of M 6.3 claimed over 200 lives and reduced the Koyna township into shambles (Narain, H. and Gupta, H. K., *Nature*, 1968, **217**, 1138–1139). It has been debated whether the M 7.9 Sichuan earthquake of China on 12 May 2008, which claimed over 80,000 lives was triggered due to filling up of the nearby Zipingpu reservoir.

Earthquakes started to occur soon after the impoundment of the Shivaji Sagar Lake in Maharashtra after building of the Koyna Dam in 1962. Interactions with senior citizens living in the region revealed that they had never experienced such tremors before. Unlike in most RTS sites globally, where triggered earthquakes ceased to occur within a few years time, seismic activity has continued at Koyna till now. In 2002, it was inferred that RTS at Koyna is likely to continue for the next 3–4 decades.

Way back in 2001, a case was made that short-term earthquake forecast may be feasible at Koyna. Consequently, a seven-station monitoring seismic network was set up in 2005 by the CSIR-National Geophysical Research Institute (NGRI), Hyderabad for real-time monitoring of earthquakes in the Koyna region. Foreshocks are one of the most important precursors of earthquakes. It is also known that foreshock activity is a part of the nucleation process leading to the main shock. The real-time monitoring of Koyna seismicity made it possible to recognize this nucleation and permitted making short-time forecasts. It was found that $M \geq 4$ earthquakes on 30 August 2005, 13 November 2005, 26 December 2005 and 17 April 2006 were preceded by well-defined nucleation contained within 10 km radius lasting from 110 to 400 h. Following this learning phase, a nucleation pattern was identified on 16 May 2006 and forecast for the occurrence of a M 4+ earthquake was made. An earthquake of M 4.2 occurred on 21 May 2006 within the specified parameters. Since 2006, eight forecasts have been made in the Koyna region and all have come true. However, it must be mentioned here that all $M \geq 4$ earthquakes in the Koyna region since 2006 have not been forecast. These forecasts were not made public to avoid any fear. Moreover, earthquakes of $M \sim 4$ are not damaging. It had been earlier inferred, in 2002, that damaging earthquakes like the 10 December 1967, may not occur again in the Koyna region.

The changes brought about by loading/unloading of a reservoir on the prevalent stress field are very small. A pre-requisite for RTS to occur is that the region in the vicinity of the artificial water reservoir must be stressed close to critical, so that the small loading/unloading created perturbation could trigger earthquakes. Mostly, the tectonic processes are responsible for the generation and accumulation of stresses that are released by RTS. Global studies have established the relation between loading/unloading of a reservoir and RTS. The lack of knowledge of the physical properties of rocks and fluids in the fault zone does not permit us to comprehend the mechanism of RTS.

There are almost no near-field studies of earthquakes all over the world. Earthquake models developed so far lack field validation. Seismic belts like the San Andreas Fault Zone, California, USA, the Himalayan earthquake belt and several others run into thousands of kilometres, and earthquakes occur from depths of a few to ~100 km. Therefore, it is difficult to address the cause and effect of the observed physical parameters and earthquake occurrence in such large natural seismic zones.

It was argued that the Koyna region is an ideal site for near-field studies of earthquakes as RTS at Koyna is restricted to a small area of 20 km × 30 km; earthquakes occur frequently at shallow focal depth, mostly ranging from 2 to 9 km. There is no other seismic source in the vicinity of the Koyna region. The shallow crust is cool, with estimated temperatures not exceeding 130°C at a depth of 6 km and the area is accessible for all kinds of observations and measurements. The suitability of Koyna for setting up of a borehole laboratory for near-field studies of earthquakes was addressed by the International Continental Drilling Programme (ICDP) workshop held at CSIR-NGRI and Koyna from 21 to 25 March 2011. The workshop was attended by about 100 scientists, including 26 from Canada, France, Germany, Italy, Japan, New Zealand, Poland, Taiwan and USA. Experts who attended the workshop had experience of working at the San Andreas Fault Observatory at Depth (SAFOD) in California, 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. The ICDP workshop supported the idea of setting up of a deep borehole laboratory at Koyna and made suggestions for several additional scientific studies in advance.

The suggested studies were carried out. These included drilling of nine boreholes which penetrated up to 500 m of the granitic basement below the basalt cover in the Koyna area; with airborne gravity gradient and magnetic surveys covering the entire Koyna RTS area to help delineate 3D shallow structure; detailed magneto-telluric surveys to estimate thickness of the basalt cover and its lateral variations; lidar surveys for the entire RTS area for providing a bare Earth model and to obtain high-resolution topographic information; instrumenting six boreholes with three components matched seismographs placed well below the basalt cover; and detailed heat-flow measurements and modelling subsurface thermal structure. One of the major discoveries was that although the region in the vicinity of Koyna has topographic variations of up to 1000 m, the basement is more or less flat with a depth of about 300 m below the present sea level. The operation of the borehole seismic network improved the earthquake location capability to ~300 m, a significant improvement from the earlier location capability of ~800 m. This network is indeed unique. The results of these studies were presented during the second ICDP workshop held from 16 to 18 May 2014 at Koyna, with 49 participants, including 12 from abroad. There was unanimous conclusion that Koyna is one of the best sites in the world to study the genesis of triggered earthquakes from near-field observations, and a broad framework leading to drilling the pilot borehole was spelled out.

For choosing the location of a 3 km-deep pilot borehole, a total of six possible sites were examined using the geological/geophysical data. Based on seismicity and logistics, a 2 km × 2 km block in the immediate vicinity of the Donachiwada Fault, that hosted the 10 December 1967 M 6.3 and several $M \sim 5$ earthquakes, was chosen. The pilot borehole was spudded on 20 December 2016 and completed on 11 June 2017. The basement was reached at a depth of 1247 m. Like the other boreholes drilled under this project, no sediment rocks were found below the basalt cover. Several zones of immense fluid loss were encountered. A suite of studies was conducted during the drilling phase. Measurements of *in situ* stress at such depths have not been made before in India. A post-operation ICDP workshop was held during 14–16 October 2017 where 67 participants, including 19 from abroad, reviewed the establishment of the Pilot Borehole Laboratory and the future course of action. The results obtained thus far formed the basis of future course of action and setting up of the proposed 7 km deep borehole laboratory.

It is indeed heartening that India has been able to set up the first and so far the only 3 km deep Pilot Borehole Laboratory to study the genesis of RTS. Scientific and financial support has been provided for this project by CSIR-NGRI, Borehole Geophysics Research Laboratory, Karad, Maharashtra, the Ministry of Earth Sciences, Government of India and ICDP. Studies carried out so far have provided valuable knowledge about the structure of the Koyna region, characteristics of RTS that discriminate it from natural earthquakes, processes preceding the nucleation and propagation of the fault zone rupture, etc. It is hoped that in the near future the 7 km-deep Borehole Laboratory would be set up that will shed further light on the genesis of RTS. This would be of global importance as it would pave way for proper understanding of RTS in particular and genesis of earthquakes in general.

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