Earth-Science Reviews 162 (2016) 433–450

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Invited review

Five decades of triggered earthquakes in Koyna-Warna Region, western India – A review

Amrita Yadav [a], Brijesh K. Bansal [a], Ajeet P. Pandey [a,*]

[a] Ministry of Earth Sciences (MoES), New Delhi, India

ARTICLE INFO

Article history:
Received 1 April 2015
Received in revised form 13 September 2016
Accepted 23 September 2016
Available online 26 September 2016

Keywords:
Triggered earthquakes
Seismicity
Water reservoir
Borehole
Pore pressure
Physical properties
Poroelastic models

ABSTRACT

We review Reservoir Triggered Seismicity (RTS) in the Koyna-Warna region of India since the impoundment of the Koyna reservoir in 1962 until the year 2015. We include seismicity that occurred farther south in response to the impoundment of Warna reservoir in 1993, about 35 km to the south of Koyna reservoir. The on-going earthquake activity for more than five decades in a small seismic volume of about $30 \times 20 \times 10$ km^3 has characterized the Koyna-Warna region as globally unique and significant. To date, 22 earthquakes of $M \geq 5$, about 200 earthquakes of $M \geq 4$ and several thousand smaller earthquakes have been recorded by a dense network of stations in the region. Various seismological, geophysical and hydrological studies have been carried out to understand the phenomenon of triggered seismicity including source mechanism, fault geometry, crustal structure, earthquake processes, causal relationship with reservoir water level changes and anomalous water level fluctuations in cased bore-wells. The present review takes stock of all such studies undertaken so far to summarise the understanding on various geo-scientific issues and milestone achievements with regard to mechanism of triggered seismicity and source processes, fault plane solutions commensurate with geometry of faulting, source parameters, seismogenic depth, crustal structure and the role of reservoir water level. Two-stage increase in seismic energy release coinciding with peaks of annual filling and draining cycle of reservoir with one month delay vis-à-vis spurt of moderate earthquakes ($M > 5$) due to (i) rapid rise in reservoir level (12 m/week) (ii) reservoir water level exceeding the previous maxima and (iii) duration for which high reservoir level is retained, are characteristic features. Numerical models simulating diffusion of pore fluid pressure fronts during the filling stage of reservoir suggest stress perturbations of the order of 0.75–2.25 bar at hypocentral depth, triggering earthquakes on critically stressed pre-existing faults. In the year 2005, a 13-station digital seismometers network became functional that characterized the distribution of epicentres in the area with increased accuracy, and suggested four major seismic zones with well-defined clusters. Scientific drilling carried out recently provide several new information regarding the subsurface geology and structure in the Koyna region, such as (i) thickness of Deccan Traps (933 in the Koyna area and 1185 m in the Warna area) (ii) presence of granite-gneiss basement directly underlying the Deccan Traps (iii) absence of infratrappean sediments and (iv) temperature not exceeding 150 °C at hypocentral depth. It is planned to establish a deep borehole observatory close to the seismic source zone for direct measurements of physical and mechanical properties of rocks, pore fluid pressure, hydrology, thermal condition and other parameters of an intra-plate active fault zone in the near field of earthquakes before, during, and after their occurrence. Results from such experiment and long term in-situ monitoring of critical parameters would enhance our understanding on the mechanism of triggered earthquakes and the role of reservoir water level fluctuations.

Contents

* Corresponding author.
E-mail address: ajeet.moes@gmail.com (A.P. Pandey).

http://dx.doi.org/10.1016/j.earscirev.2016.09.013
0012-8252/

1. Introduction

The Koyna-Warna region located about 50 km inland from the west coast of India offers a classic example of triggered seismicity that started soon after the impoundment of the Koyna reservoir behind the Koyna dam in 1962 (Narain and Gupta, 1968a; Gupta, 1992). The Koyna dam, situated close to Koynanagar, is a major concrete gravity dam with a height of 103 m built on the Koyna river. Small to moderate tremors continued to occur in the vicinity of the reservoir and eventually culminated into the largest triggered earthquake of M6.3 on 10 December 1967 that devastated the region by claiming more than 200 human lives and causing severe damage to Koynanagar (Gupta and Rastogi, 1976). Another artificial water reservoir, the Warna reservoir started impounding behind the Warna dam in 1985 and was completed in the year 1993. The height of the Warna dam is 80 m. The reservoir, located about 35 km to the south of Koyna dam, further intensified the earthquake activity in the region. Although earthquakes continued to occur in the vicinity of the Koyna dam, a prominent southward migration of seismicity was observed (Rastogi et al., 1997). The on-going earthquake activity for more than five decades in a small seismic volume of about 30 × 20 × 10 km^3, primarily confined between the downstream of Koyna reservoir and upstream of Warna reservoir, has characterized the Koyna-Warna area as a unique natural laboratory to test hypotheses concerning the genesis of reservoir triggered earthquakes.

The triggering phenomenon characterizes initiation or enhancement of seismicity due to impoundment of reservoirs in an area with threshold ambient stresses close to rock failure along pre-existing faults. Carder (1945) for the first time pointed out triggering of earthquakes by artificial water reservoirs at Lake Mead in the United States of America. Thereafter, more than ninety sites have been identified worldwide where earthquakes were triggered on impoundment of artificial water reservoirs (Gupta, 2002).

Various seismological, geophysical, and hydrological studies have been carried out since the late 1960s to understand reservoir triggered earthquakes in the region and also to know the possible triggering mechanism associated with such earthquakes (Guha et al., 1966; Gupta et al., 1972a; Gupta, 1983; Talwani, 1995, 2000; Talwani et al., 1996; Rastogi et al., 1997; Bansal, 1998; Bansal and Gupta, 1998; Rajendran and Harish, 2000; Gupta, 2001, Pandey and Chadha, 2003; Chadha et al., 2003; Gahalaut et al., 2004; Chadha et al., 2008; Durá-Gómez and Talwani, 2010; Gavrilenko et al., 2010; Yadav et al., 2015). The studies until the year 2000 emphasized the dominant role of artificial water reservoirs in a region having ambient stresses close to failure for triggering earthquakes. The later studies focused on understanding the causal relationship between seasonal fluctuations in reservoir water level and continued triggered seismicity using quantitative statistical and numerical approaches. The triggered earthquakes at depths of about 6–8 km in the Koyna region was attributed primarily to the diffusion of excess pore pressure fronts, which lead to small stress perturbations of the order of 0.75–2.25 bar and are sufficient to cause failure on critically stressed pre-existing fault (Pandey and Chadha, 2003).

Gupta (2005) perceived several important features categorically and envisaged the Koyna–Warna region as an ideal site for detailed investigations by establishing a network of boreholes to better comprehend the physics of the triggered earthquakes and possibly to forecast them. A few such features are – (i) earthquakes occur in a small area with focal depths limited to about 10 km and there is no other seismically active zone in the vicinity (ii) the Koyna-Warna seismic zone is accessible for deployment of all kinds of experiments and making observations (iii) earthquakes have been occurring regularly following an increase of water level in the reservoirs during monsoons and later during emptying stage of the reservoir (Rajendran and Harish, 2000; Gupta, 2001; Pandey and Chadha, 2003) (iv) spurt of M ≥ 5 earthquakes due to reservoir loading rate of 12 m/week (Gupta, 1983) and exceeding the previous maxima of the reservoir water level (Gupta, 2002) (v) an increase in foreshock activity some 15 days before an M ≥ 5 earthquake (Gupta, 1992; Gupta and Iyer, 1984) (vi) a quasi-dynamic nucleation process found to occur some 100 h before an M ≥ 4 earthquake (Rastogi and Mandal, 1999) (vii) co-seismic changes in water levels for four earthquakes of M > 4.3 along with precursory decrease observed in the bore wells of the Koyna–Warna region (Chadha et al., 2003).

Despite improved knowledge and understanding acquired through the previous studies, many important issues remain unanswered such as geometry of causative faults, physical processes, crustal velocity model representing disconformities sandwiched with low/high velocity layers, focal depths and identification of precursors of seismological, geophysical, geochemical and hydrological origin. To address such relevant issues more efficiently, the Ministry of Earth Sciences (MoES), India has launched a deep scientific drilling experiment in the region with an objective to set up two geo-scientific deep borehole observatories in close proximity to the source zone. The results from the preparatory phase studies, carried out as part of this experiment, are detailed in a later section.