of Mid-Holocene high strandline position at Mandapam Foreland and its matching ages with other coastal segments of the east coast of India envisage that the area around Mandapam did not undergo any significant vertical movement. Hence it is a neotectonically unaffected block.

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Drained and undrained responses for Koyna–Warna earthquakes from 1993 to 1994 following impoundment of the Warna reservoir in India

Chandrani Singh* and R. K. Chadha

National Geophysical Research Institute, Uppal Road, Hyderabad 500 007, India

The Koyna region along the west coast of India in Maharashtra, is a unique case of reservoir triggered seismicity, where seismicity has been reported since 1963 after the initial impoundment of the Shivajisagar reservoir behind Koyna dam in 1961. The region was further destabilized following the filling of the Warna reservoir, situated 25 km south of Koyna, during the late 1980s. Increase in pore pressure by drained and undrained effects is known to weaken the substratum below a water reservoir, facilitating the onset of seismicity. Although their relative influences may vary with time and space, it is difficult to separate their individual contributions. The present study, using the well-located earthquakes of $M \geq 5$ for the period 1993–94, is a preliminary attempt to identify these effects after impoundment of the Warna reservoir. It could provide a good opportunity for further modelling the strength changes due to reservoir impoundment.

Keywords: Drained and undrained responses, earthquakes, impoundment, Koyna–Warna reservoir, pore pressure.

EARTHQUAKE activity in the Koyna region was triggered in 1963 following the initial impoundment of the Shivajisagar reservoir behind Koyna dam in 1961. Later, following impoundment of another reservoir in Warna, which began during the monsoon season in 1987 and afterwards in 1988, seismicity increased in the region. In 1993, seismicity increased significantly after attaining the highest water level in Warna reservoir. During 1993–94, a southward shift in the concentration of seismicity was noticed from Koyna to Warna reservoir[1]. Pore-pressure changes occur in the vicinity of a reservoir in response to lake-level changes. This change occurs in two ways; the rapid effect due to the undrained processes (rapid increase in pore pressure in response to load) and the delayed effects due to diffusion[2]. Although these processes are at work in the vicinity of almost all reservoirs, only at some locations do they lead to perceptible seismicity. The mechanism of reservoir triggered seismicity (RTS) is controlled by various factors like the ambient stress field, availability of faults/fractures, hydrogeologic properties of the medium and the hydraulic and spatial characteristics

*For correspondence. (e-mail: chandranigoswami@rediffmail.com)

of the reservoir[3,4]. Bell and Nur[5] showed that anisotropy in rock permeability and relative changes in groundwater play an important role in reservoir-induced seismicity (RIS) (previously RTS was known as RIS). Scholz *et al.*[6] had described that the mechanism for RTS is through pore-pressure diffusion. Talwani and Rastogi[7], and Talwani[8] evaluated worldwide available data and suggested that pore-pressure diffusion is the preferred mechanism for RTS. Simpson *et al.*[2] classified seismicity for different reservoirs as due to rapid or delayed response. They further argued that the mechanism of RTS depends on initial filling and subsequent loading cycles[9]. Later Roeloffs[4] described the changes in the stability in response to water load of a reservoir for four different fault configurations. Rajendran and Talwani[10] applied these ideas and demonstrated that the seismicty in Monticello Reservoir, USA, was a mixed response to drained and undrained effects, but initial onset of seismicity was attributed to the weakening of rocks due to undrained conditions. Although the general mechanism of triggered seismicity can be explained by the above process, observations also suggest the site-dependency of triggered sequences. For example, Rajendran and Harish[11] put forward a conceptual model based on diffusion of reservoir water through the vertically permeable fault zone present in the Koyna–Warna site to explain the ongoing seismicity, a situation rather specific to this region.

How each of these factors influences the seismicity associated with a reservoir is difficult to assess after the initial onset of activity. However, where the annual refilling is significant and earthquakes follow a temporal pattern, it can be correlated with the rate of loading[12]. In this communication, we make an attempt to understand the effect of drained and undrained responses after the filling of the Warna reservoir at Koyna–Warna region. We analysed earthquakes of $M \geq 5$ for 1993 to 1994 (Figure 1) when the filling rate was high for the Warna reservoir (Figure 2). We have assumed that the bottom of the reservoir is permeable and the crust is fractured and porous, due to repeated earthquakes in the region, so that water from the reservoir is permitted to flow into the fractures, as outlined by Bell and Nur[5]. Our study is focused on the responses of the growth of pore pressure by drained (delayed) and undrained (reservoir loading) effect due to step-wise increase in reservoir water level. We have used the fully coupled equations of elasticity and pore fluid flow for 1D to compute the different responses as given by Roeloffs[4]. We have calculated the hydraulic diffusivity (α_S) from the best possible distance between the source of the pressure front (the reservoir) and the epicentre, and from the delay t, between generating this front (filling or draining the reservoir) and the onset of seismicity, using the technique discussed by Talwani and Acree[13] with some modification. Talwani and Acree have considered the distances in 1D, i.e. without considering the depth. We have however taken the actual diagonal path of diffusion from the reservoir using the focal depth of the earthquake (Figure 2). Since the primary objective of this communication is to present a preliminary analysis, the models are much simplified to draw a general conclusion, which could be further analysed in conjunction with data from the deep observational wells operational in the region.

If we make the assumption that diffusion of pore pressure is the operative mechanism of transmitting pore-pressure changes to hypocentral depths, it is possible to estimate α_S from the observed time lag[13]. We have calculated the α_S from 1993 onwards using the formula given by Talwani and Acree[13]:

$$\alpha_S = L^2/t, \tag{1}$$

where L is the distance between the reservoir and the epicentre of the earthquake, and t is the time taken to dif-

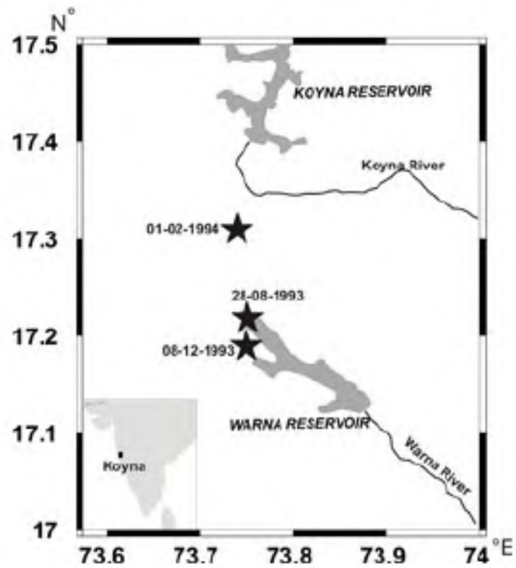

Figure 1. Epicentre location of earthquakes studied with $M \geq 5.0$ for the period 1993–94.

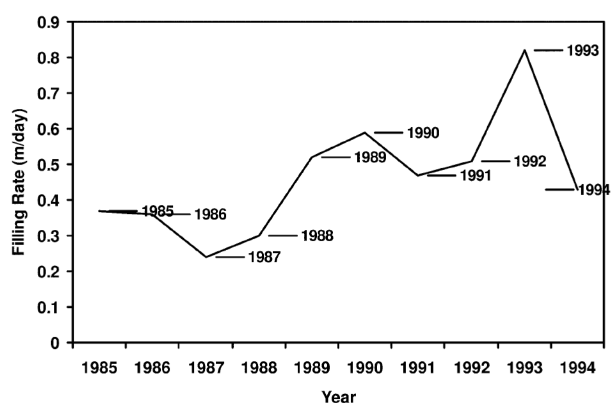

Figure 2. Initial filling rate at Warna from 1985 to 1994.

fuse. In eq. (1) we have made some modification in choosing L. Instead of taking the horizontal distance between the source of the pressure front (the reservoir) and the location of seismicity, we have taken the diagonal path (hypocentre distance) of diffusion. The value of α_S for the earthquake of 28 August 1993 is a little higher, i.e. 4×10^5 sq. cm/s, but is in the range given by Talwani and Acree[13]. If we take the time delay between the end of filling and growth of seismicity, in that case diffusivity would be higher (of the order of 10^6 sq. cm/s) than that given by Talwani and Acree[13]. Simpson *et al.*[2] explained that the increase in seismicity immediately after attaining high water level in the reservoir is related to increase in pore pressure at hypocentral depth and does not require any diffusion from the bottom of the reservoir, but is related to processes within the hypocentral zone itself[1]. The obtained high value of diffusivity may be associated with the formation of new cracks or fractures[13] during destabilization of the region due to the newly filled Warna reservoir. Simpson *et al.*[2] suggested that higher diffusivity value also implies that fractures, and not the whole rock properties, are the primary controlling factors in fluid flow throughout the crust.

Bell and Nur[5] defined the incremental strength ΔS across a fault plane by the following equation:

$$\Delta S = \mu(\Delta\sigma - \Delta P_P) - \Delta\tau, \tag{2}$$

where $\Delta\tau$ is the change in shear stress on the fault in the direction of slip, $\Delta\sigma$ the compressive normal stress across the fault due to the water load, μ the coefficient of friction and ΔP_P is the incremental pore pressure. From eq. (2) it can be seen that failure occurs when ΔS decreases below a threshold level. Decrease in ΔS can be brought about by a decrease in $\Delta\sigma_n$ (unloading) or an increase in pore pressure. This can happen through two mechanisms; undrained and drained responses. Discussions on these two responses are available elsewhere[10,14]. Here we reproduce a summary of those sections.

The undrained response is the increase in pore pressure in the substratum due to elastic compression. The undrained response may be defined as:

$$\Delta P_{UD} = B\sigma_{kk}/3, \tag{3}$$

where B is the Skempton's constant[15,16], σ_{kk} the mean stress and ΔP_{UD} is the increase of pore pressure due to undrained response. The increase in ΔP_{UD} will be proportional to the load and is therefore greatest beneath the reservoir. The largest undrained responses can occur when B is close to 1 and the pore spaces are isolated[10]. Development of pore pressure depends on the rate of filling of the reservoir water level and also on the duration of retaining the highest water level in the case of undrained response.

The drained response is the delayed change in pore pressure due to diffusion with respect to the initial impoundment and this delay depends on the hydromechanical properties of the surrounding rocks. One-dimensional diffusion of pore pressure is governed by the following equation:

$$\delta^2 P_D/\delta z^2 = 1/c(\delta P_D/\delta t), \tag{4}$$

where P_D is the pore pressure due to diffusion, Z the depth, t the time and C is the coefficient of diffusivity.

$$C = k/\varphi\eta\beta, \tag{5}$$

where k is the permeability of the rock, η the viscosity of the pore fluid, φ the porosity of fractured rock, and β is the effective compressibility of the fluid.

Equation (5) has a solution of the form

$$P_D(Z, t) = 1 - \mathrm{erfc}(Z/\sqrt{4ct}), \tag{6}$$

where $P(0, 0)$ is the pressure at the surface due to the load of the reservoir at $t = 0$ and erfc is the complementary error function.

The coupled effect is due to the combined effect of drained and undrained responses. Roeleffs[4] has modified the eq. (6) by incorporating the term due to undrained response. For a 1D case, pore pressure

$$P(Z, t) = (1 - \alpha)\mathrm{erfc}[Z^2/4ct]^{1/2} + \alpha H(t)$$
$$\text{at a given depth } Z \text{ and time } t. \tag{7}$$

$H(t)$ is Heaviside unit step function and $\alpha = B(1 + V_u)/(1 - V_u)$, where V_u is the undrained Poisson ratio. Replacing the step function by a discrete series of step we get[10]

$$\begin{aligned} P(z,t) &= \alpha P(z,t) + (1-\alpha) \\ &\quad \times \sum_{n=1}^{N_f} \mathrm{erfc}[Z^2/4c(N-n)\Delta t]^{1/2} \\ &\quad \times [P(0, n\Delta t) - P(0, (n-1)\Delta t)]. \end{aligned} \tag{8}$$

Here it is assumed that the reservoir was filled on day t_f ($t_f = N_f\Delta t$) and was maintained at the level afterwards for $N > N_f$. We put $H(t) = P(0, t) = ny\rho g$ for undrained response, where y is the change in water level per day, ρ the density of water taken to be 0.9982 g/cubic cm at 20°C and g is the acceleration due to gravity. The first term in eq. (8) is the undrained response evaluated at the surface and the second term represents the pore pressure due to diffusion directly beneath the reservoir for different times and depths. We have done the analysis at hypocentral depth of each earthquake. Equation (8) does not predict accurately the value to which pore pressure rises beneath the subsurface of a reservoir, but it gives an idea of the relative times at which pore pressure rises at a particular depth, due to a step-wise filling pattern[10].

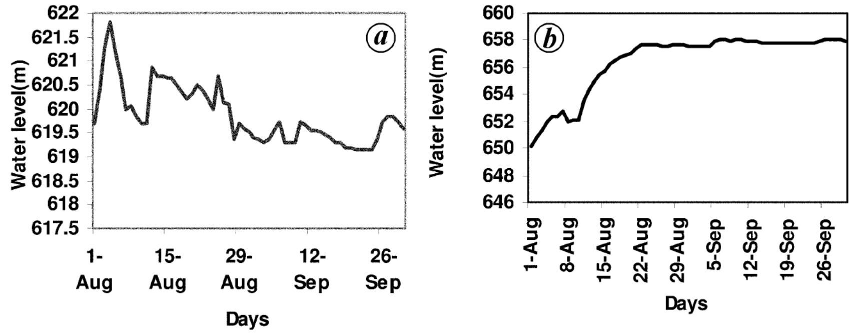

Figure 3. Water level for the entire period of analysis for 28 August 1993 earthquake for (***a***) Warna and (***b***) Koyna reservoirs.

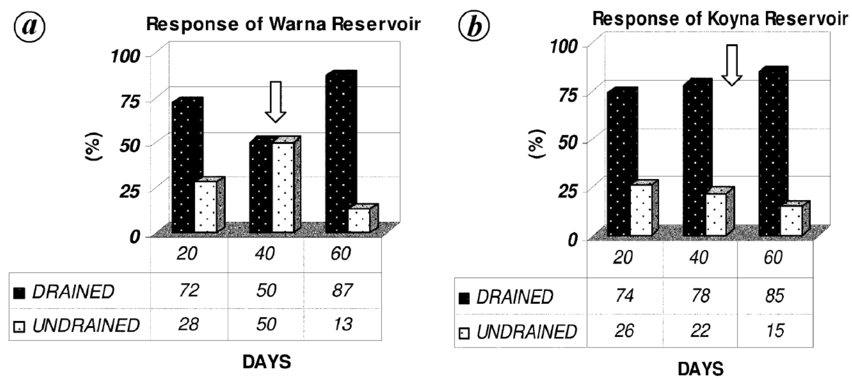

Figure 4. Percentage of drained and undrained responses of (***a***) Warna and (***b***) Koyna reservoirs for the 28 August 1993 earthquake. The period of 60 days starting from 1 August 1993 is divided into 20-day intervals for homogeneity. The response of 20-day period is shown. Arrow shows time of the earthquake.

We have critically analysed the data from 1993 to 1994 for earthquakes of $M \geq 5$ after the highest impoundment of the Warna reservoir. The total time series of reservoir water levels taken for the present analysis have been divided into three time windows of 20 days each for homogeneity. The period of analysis is so chosen that any abnormal changes in water level of any one of the reservoirs prior to the occurrence of the earthquake can be seen. Finally we have compared the stability changes due to these two reservoirs.

A southward shift in the concentration of seismicity was reported for the period 1993–94, from Koyna to Warna reservoir[1]. After impoundment of the Warna reservoir, seismic activity started near this new reservoir. The filling rate in 1993 followed by monsoon suddenly shows a high peak[8] (Figure 2) and water column at Warna reservoir reached to 621.79 m on 4 August 1993 (Figure 3 *a*). After 24 days, the area experienced an earthquake of magnitude 5.3 on 28 August 1993. The water level for the Koyna reservoir during that period is shown in Figure 3 *b*. Our calculations suggest that for this earthquake about 50% of the total pore pressure was contributed by the undrained response of the Warna reservoir (Figure 4 *a*), and reached a maximum at the peak reservoir level. The Koyna reservoir does not show any significant response, although there is a small increase in undrained effect (Figure 4 *b*), which may be attributed to the increase in water level in the Koyna reservoir from the middle of the August 1993 (Figure 3 *b*). On the other hand, the drained response for both the reservoirs was the predominant factor for the event *M* 5.2 on 8 December 1993 (Figure 5 *a* and *b*). Both the reservoirs showed fall in water levels (Figure 6 *a* and *b*) during this period. For the 1 February 1994 *M* 5.4 earthquake, we again see that diffusion (Figure 7 *a* and *b*) is the responsible parameter. Reservoir water levels for Warna and Koyna do not show any significant variation (Figure 8 *a* and *b*). It appears to be the result of increased fluid pressures at the hypocentral location due to diffusion of fluid pressure. Comparison of different responses of both the reservoirs shows that the destabilization caused due to the Warna reservoir was more during the entire period of analysis (Figure 9).

The undrained response of the 28 August 1993 earthquake was about 50% of the total pore pressure, which has contributed substantially to its weakening. The sudden increase in filling rate of the Warna reservoir (Figure 2)

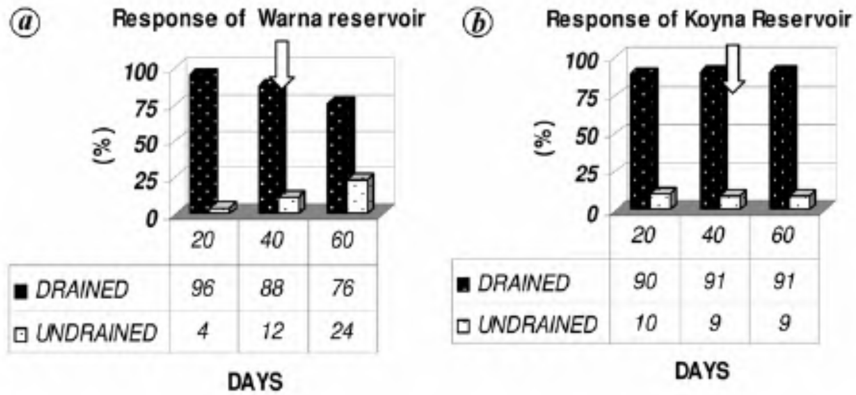

Figure 5. Percentage of drained and undrained responses at (***a***) Warna and (***b***) Koyna reservoirs for the 8 December 1993 earthquake. The period of 60 days starting from 1 November 1993 is divided into 20-day intervals for homogeneity. The response of 20-day period is shown. Arrow shows time of the earthquake.

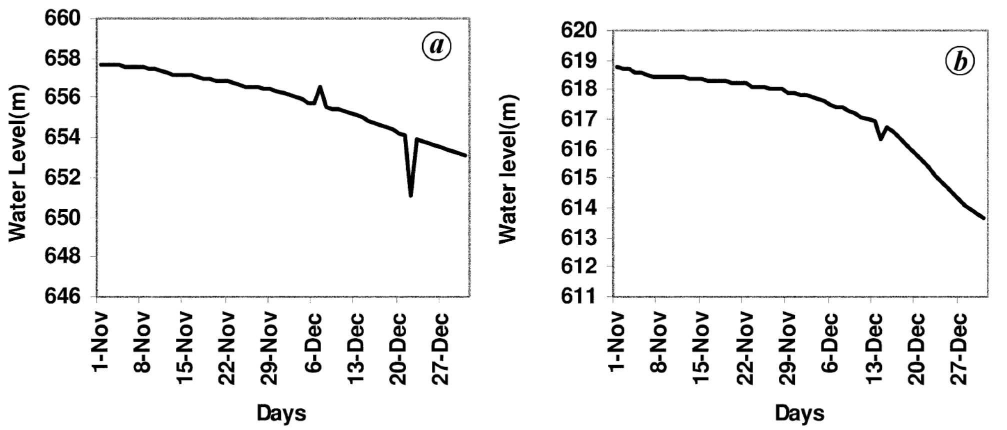

Figure 6. Water level for the entire period of analysis of the 8 December 1993 earthquake for (***a***) Koyna and (***b***) Warna reservoirs.

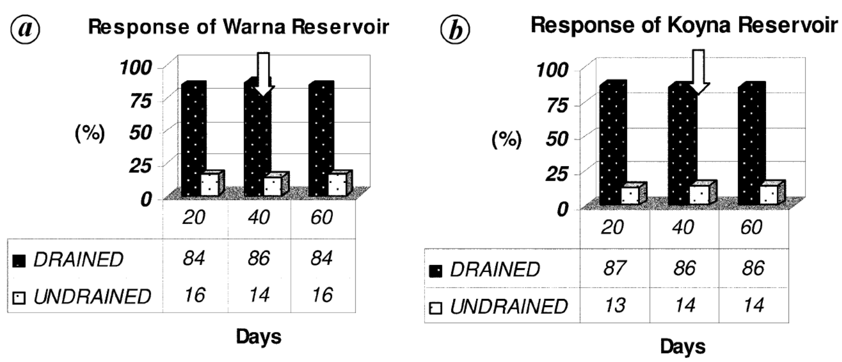

Figure 7. Percentage of drained and undrained responses at (***a***) Warna and (***b***) Koyna reservoirs for the 1 February 1994 earthquake. The period of 60 days starting from 1 January 1994 is divided into 20-day intervals for homogeneity. The response of 20-day period is shown. Arrow shows time of the earthquake.

is reflected in the increase in undrained response percentage, which increased during this period proportionally decreasing the drained response. Although loading and unloading seem to be responsible for earthquake triggering during August–September and February–March respectively, diffusion is one of the main factors in the

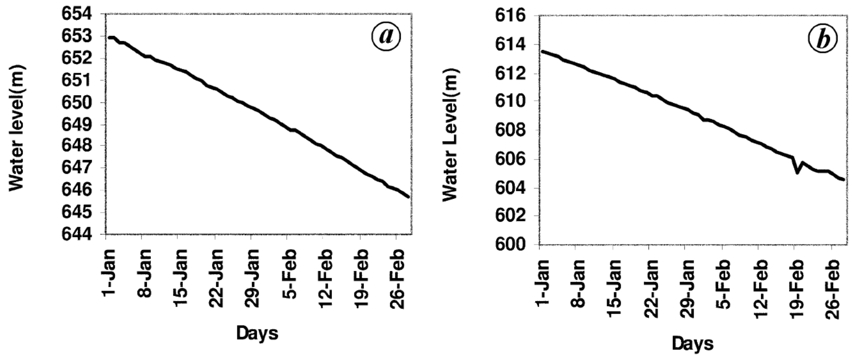

Figure 8. Water level for the entire period of analysis of the 1 February 1994 earthquake for (***a***) Koyna and (***b***) Warna reservoirs.

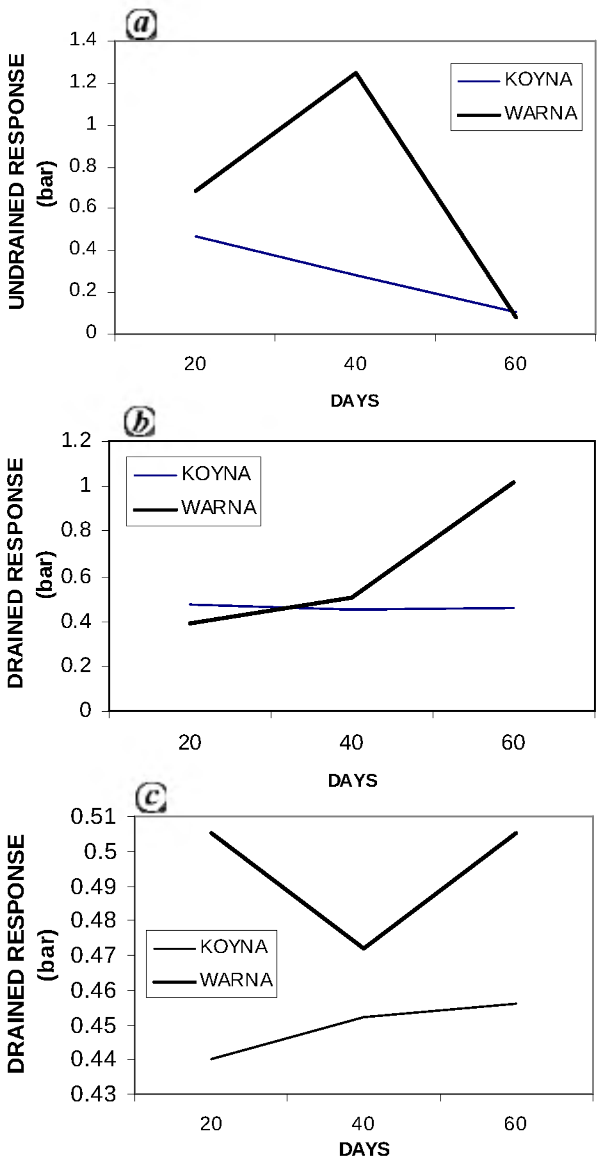

Figure 9. Comparison of different responses of both reservoirs for (***a***) 28 August 1993 (***b***) 8 December 1993 and (***c***) 1 February 1994 earthquakes plotted against the 20-day time window of analysis.

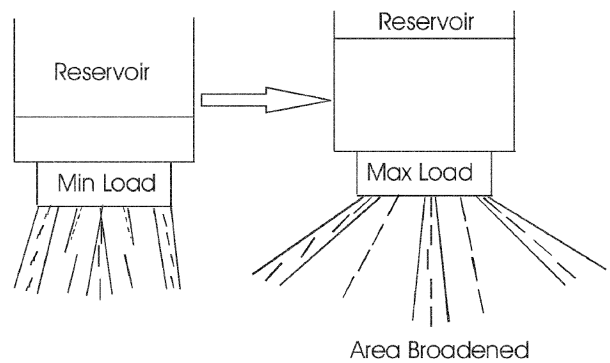

Figure 10. Schematic diagram to explain the mechanism of reservoir triggered seismicity.

region. It has also been observed that the dominant mechanism during the period of the 8 December 1993 and 1 February 1994 earthquakes, is the drained response amounting to about more than 75%, which is in agreement with the diffusion processes which are ongoing in this region[17]. Pandey and Chadha[17] found that two stages of energy release associated with peaks and troughs of annual reservoir levels were comparable with a systematic pattern. We have observed that as we move from August to February, the diffusion effects become more dominating.

RTS is the result of water–rock interaction. Reservoir load may induce relative displacement along a fault that causes severe localized strain and deformation. Bell and Nur[5] described that if a highly permeable fault, irrespective of the nature of faulting, was connected to the bottom of the reservoir, zones of weakening were found to intensify and widen. Rajendran and Harish[11] put forward a model for the Koyna region, based on diffusion of reservoir water through vertically permeable fault zone present in the area, to explain the continued occurrence of earthquakes. Pandey and Chadha[17] gave a diffusion model, assuming a highly permeable near-vertical fault zone in the basement below the Deccan traps, connected to the reservoir through fissures, fractures and vesicles in the overlying basalts. We suggest a simple schematic model for the region (Figure 10) to describe why the spatial extent of earthquakes is much smaller during January–May, compared to the time of refilling, when earthquakes cover a larger area[11]. At the time of highest water loading/refilling during the monsoon period, the zone of weakening in the fractures faults beneath the reservoir is widened. As a result, the diffusion rate also becomes high through these zones. But during February–March when the reservoir water level is at minimum, the diffusion mechanism solely plays a role in triggering the earthquakes. Due to lower levels in the reservoir unloading rate, the affected areas may shrink. Rapid unloading, i.e. when the reservoir is being emptied faster than the pore pressure can relax, can also cause instantaneous crustal weakening by adding stress[5]. For the Nurek reservoir site it is seen that increased seismic activity follows abrupt decrease in filling rate, with delays as short as 1–4 days[9]. Hence our speculative model does not fit when unloading rate is too high.

It is clearly seen from the present study that during 1993–94, the seismicity in the Koyna–Warma region was mainly dominated by the Warna reservoir, which also supports the study by Pandey and Chadha[17]. Studies of reservoir triggered earthquake could help resolve how destabilization occurs due to the presence of a reservoir. It may have also some implications for the proposed new reservoir.

We analysed data for three earthquakes of $M \geq 5.0$ that occurred during 1993–94, to understand the relative roles of load and pore-pressure diffusion in triggering seismicity in the Koyna–Warna region. After impoundment of the Warna reservoir in 1993, the energy release episode till 1996 indicated that the annual fluctuations of water level in this reservoir influenced seismicity[17]. The present study also reveals that the load on the Warna reservoir played a predominant role in the seismicity during the initial period just after highest attainment of water level.

The higher value of α_S in 1993 could be associated with the formation of new cracks or fractures[13] during destabilization of the region due to the newly filled Warna reservoir. For the high loading rate at Warna in 1993, the maximum increase in pore pressure was of the order of 2.5 bars, assuming $B = 0.9$ and $\alpha = 0.5$ and the initial undrained response was about 50% of the total pore pressure, which contributed substantially to the weakening. So the initial seismicity was due to a mixed response to load and diffusion effects, but later drained response became the dominating mechanism in triggering seismicity.

The present study reveals the response of the substratum during the initial filling period of the Warna reservoir. It offers a controlled setting to understand the physics of the earthquake process at the beginning. In the recent scenario, seismic activity after 1996 is controlled by two reservoirs at Koyna and Warna in the region. However, the present study is encouraging for future modelling. Bore-well data could also allow us to reinvestigate the hydro-geologic parameters, which could bring a new understanding about the response of the medium associated with continuous seismicity in the Koyna–Warna region.

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