# Can Dams and Reservoirs Cause Earthquakes?

## Triggering of Earthquakes

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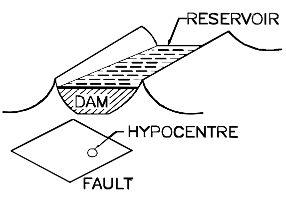
**No! Not on their own. But, stresses and pore pressure due to natural causes may already have accumulated in crustal rocks at some dam sites to near critical levels for fresh faulting or renewed slip on nearby pre-existing faults. The stresses and pore pressure induced by impoundment of reservoirs there may marginally abet the tendencies to such failures and even trigger or *induce* earthquakes by being the proverbial last straw.**

### Introduction

Can dams and reservoirs cause earthquakes? While lay persons find the question fascinating, civil engineers engaged in the task of designing and constructing new dams find it awkward and meddlesome. The main difficulty in settling the question objectively is that source regions of reservoir induced earthquakes are not accessible to direct human observations (*Figure* 1). Results of indirect investigations of these regions are subject to inevitable multiple interpretations. Still, a measure of understanding about reservoir induced earthquakes has been achieved. It is my aim to put the phenomenon in a perspective on this basis.

***Figure 1. A cartoon to illustrate the spatial relationships between dam, reservoir, fault and hypocentre.***



### I saw the Koyna Earthquake Recorded

Koyna earthquake of December 10, 1967 is regarded as the most important Indian example of reservoir induced seismicity, RIS for brevity. I was at that time a PhD student at the Lamont–Doherty Geological Observatory of Columbia University at Palisades, some distance outside New York. More than two dozen seismographs were operated day and night at the observatory. Records from most of the seismographs were obtained photographically in dark rooms. A few pen and ink recorders were used for monitoring purposes. Any passerby, observing that an earthquake was being recorded, would give a shout. That would bring a handful of seismologists rushing to the monitors, and they would compete to estimate the epicentre and magnitude of the earthquake. This was seismology in real time and a great learning experience for us graduate students. Thus, on that December afternoon local time, within about thirty minutes of its occurrence, when all the seismic phases had reached Palisades after traversing the earth along their diverse paths, we knew that a major earthquake had occurred on the western margin of the Indian peninsula.

The Koyna case is unusual in that seismicity persists more than three decades after initial impoundment of the reservoir.

## Some Facts About RIS

The possibility of RIS has been taken seriously by many earth scientists since the nineteen sixties. However, the number of alleged instances of RIS around the world is still around the century mark. The word 'allege' is used because the onus of proof about each new case of RIS still rests with those who suggest it, and a proof in earth sciences does not have the same infallibility and persuasiveness as in Euclidean geometry. The most well-known are the instances of seismicity induced by reservoirs behind the Hoover and Oroville dams in USA, Kariba dam on the Zambia–Zimbabwe border, Nurek dam in Tadzhikistan, Hsinfengkiang dam in China and Koyna dam in India. The above mentioned Koyna earthquake, with an estimated magnitude of 6.3, has been the most damaging reservoir induced earthquake so far. Also, the Koyna case is unusual in that seismicity persists more than three decades after initial impoundment of the reservoir.

## The Mechanism of Induced Earthquakes

Tectonic earthquakes are the most common of all natural earthquakes. Each one of them is associated with faulting in rocks, a fault being a shear fracture in which rocks on its two sides undergo relative slip parallel to the discontinuity surface. Although some of them may be associated with formation of fresh

***Figure 2. Seismogram of a tectonic earthquake. Axis parallel to traces indicates time from left to right. The interval between two dots is one minute. Axis normal to traces measures vertical component of ground displacement, of the order of a few microns. P, PP, S, SS and LR are different phases or waves arriving at the station along different paths from the hypocentre (see text under 'I saw the Koyna earthquake recorded'). At this station, the first ground motion in P was towards the hypocentre for this earthquake.***

faults in rocks, at the present moment in the 4.5 billion-year history of the earth, most tectonic earthquakes occur due to renewed slip on pre-existing faults.

A fault plane solution provides important evidence on the mechanism of an earthquake. It involves analysis of particle motions in the earth during the passage of the very first *P*, or longitudinal elastic waves radiated in different directions from the hypocentre or focus of the earthquake (*Figure* 2). Hypocentre is the point of origin of an earthquake. In the case of a tectonic earthquake, the hypocentre is located in the causative fault (*Figure* 1) and it coincides with the point where the first slip occurs .

The fault plane solution for the Koyna earthquake has all the characteristics seismologists observe in the fault plane solutions for natural tectonic earthquakes. Hence, Koyna earthquake belongs to this category, and we may infer with considerable confidence that the renewed slip on a pre-existing fault near the Koyna reservoir was involved. Similar conclusions may be drawn for many other allegedly reservoir induced earthquakes for which fault plane solutions have been obtained.

Thus we have a reasonable basis to assume that reservoir induced earthquakes are also tectonic earthquakes except that they occur near new reservoirs after their impoundment.

## Conceptual Basis for Rationalization about RIS

Investigations about the formation of new faults or incidence of renewed slip on pre-existing ones belong to the domain of rock mechanics. Anderson explained the formation of new faults in terms of elastic stresses acting in rocks. Subsequently the influence of pore pressure was included in the analysis. Pore pressure is the pressure exerted by fluids, mostly water, if present in the pore spaces of rocks. Renewed slip on a pre-existing fault is similarly attributable to elastic stresses and pore pressure. Only non-hydrostatic stress states, i.e., stress states in which all three principal stresses are not equal, are relevant for these purposes.

Impoundment of a new reservoir causes perturbations of the stress and pore pressure regimes in the rocks around it. Depending upon local circumstances, the perturbations may to a small degree either facilitate or inhibit renewed slip on pre-existing faults in the region. Snow, in a landmark article in 1972, provided on this basis a theoretical justification for the underlying unity in the mechanisms of natural tectonic and reservoir induced earthquakes. I feel that he could have furthered the cause of a rational view on RIS by introducing the term 'reservoir induced tectonic earthquake' in place of the current 'reservoir induced earthquake'.

However, whereas Snow modeled the reservoir as a water layer of finite vertical thickness and infinite horizontal extent, our discussion here is free of this assumption.

## Condition for Renewed Slip on a Fault

Let $t$ represent time and $\mathbf{r}$ the position vector of a point in a pre-existing fault. Let $\sigma(\mathbf{r}, t)$ be the normal stress, $\tau_m(\mathbf{r}, t)$ the motive shear stress and $p(\mathbf{r}, t)$ the pore pressure acting on the fault at $\mathbf{r}$ at $t$ (*Figure* 3). The word motive is used to emphasise that this shear stress promotes slip on the fault. We may add in passing that the frictional stress on the fault is a shear stress that inhibits slip. Let $\tan\phi$ be the coefficient of friction on the fault, $\phi$ being the angle

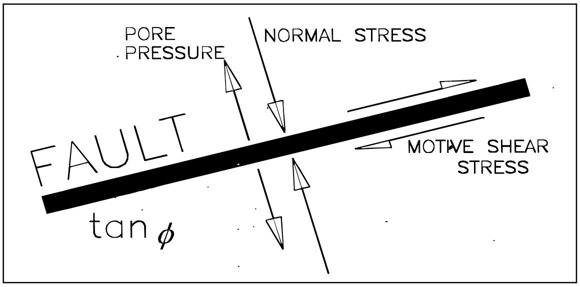


***Figure 3. Quantities required to specify condition for slip on a fault. All refer to the same point in the fault.***

of friction. Then the frictional strength $\tau_f(\mathbf{r}, t)$, defined as the limiting value of force per unit area due to static friction between rocks on either side of the fault, may be expressed as

$$\tau_f(\mathbf{r}, t) = \{\sigma(\mathbf{r}, t) - p(\mathbf{r}, t)\} \tan\phi. \quad (1)$$

The fault is in equilibrium at **r** as long as the frictional strength exceeds the motive shear stress. The tendency of the fault to slip again increases if, due to temporal changes in the stresses and pore pressure acting on it, the magnitude of motive shear stress approaches that of the frictional strength. The fault will undergo renewed slip at **r** if and when the motive shear stress exceeds the frictional strength.

A natural tectonic earthquake will occur if and when, due to accumulation of ambient stresses and ambient pore pressure at the hypocentre, the ambient motive shear stress acting on the fault exceeds its frictional strength.

## Occurrence of a Natural Tectonic Earthquake

At any given instant of time, stresses due to many natural causes may act on the fault at the hypocentre of an impending tectonic earthquake. They include, at the very least, the stresses due to the weight of rock superjacent to the hypocentre and a group of stresses that I shall call here collectively as stresses of plate tectonic origin. Also, pore pressure may arise if fluids exist in the pore spaces of rocks around the hypocentre. While stresses due to the weight of the rock may be considered constant on the time scales of interest here, namely, decades to millennia, stresses of plate tectonic origin may vary and in general accumulate with time. These stresses and pore pressure due to natural causes are often referred to collectively as ambient stresses and ambient pore pressure, respectively.

It follows from the preceding section that a natural tectonic earthquake will occur if and when, due to accumulation of ambient stresses and ambient pore pressure at the hypocentre, the ambient motive shear stress acting on the fault exceeds its frictional strength (*Box*1).

## Occurrence of a Tectonic Earthquake Near a New Reservoir

Similarly, the condition for a tectonic earthquake to occur near a

**Box 1.**

I give here a few simple mathematical expressions relevant to the ideas considered in the article. All but one of the main symbols used below has been described already. $\mathbf{r}_h$ is the position vector of the hypocentre. Subscripts a, c and r stand for ambient, cumulative and reservoir induced respectively.

Thus, the expression for frictional strength at $\mathbf{r}_{h,}$ under ambient stresses and pore pressure, from (1) of the main text, is

$$\tau_{fa}(\mathbf{r}_h, t) = \{\sigma_a(\mathbf{r}_h, t) - p_a(\mathbf{r}_h, t)\} \tan\phi, \qquad \text{(A1)}$$

Corresponding expressions for frictional strength due the reservoir alone and under the cumulative influence of ambient and reservoir induced stresses and pore pressure are

$$\tau_{fr}(\mathbf{r}_h, t) = \{\sigma_r(\mathbf{r}_h, t) - p_r(\mathbf{r}_h, \mathrm{t})\} \tan\phi, \qquad \text{(A2)}$$

$$\tau_{fc}(\mathbf{r}_h, t) = \{\sigma_c(\mathbf{r}_h, t) - p_c(\mathbf{r}_h, \mathrm{t})\} \tan\phi, \qquad \text{(A3)}$$

In turn,

$$\tau_{fc}(\mathbf{r}_h, t) = \tau_{fa}(\mathbf{r}_h, t) + \tau_{fr}(\mathbf{r}_h, t) \qquad \text{(A4)}$$

$$\sigma_c(\mathbf{r}_h, t) = \sigma_a(\mathbf{r}_h, t) + \sigma_r(\mathbf{r}_h, t) \qquad \text{(A5)}$$

$$p_c(\mathbf{r}_h, t) = p_a(\mathbf{r}_h, t) + p_r(\mathbf{r}_h, t) \qquad \text{(A6)}$$

$$\tau_{mc}(\mathbf{r}_h, t) = \{\tau_{ma}^2(\mathbf{r}_h, t) + \tau_{mr}^2(\mathbf{r}_h, t) + 2\,\tau_{ma}(\mathbf{r}_h, t)\,\tau_{mr}(\mathbf{r}_h, t)\cos\theta\}^{0.5}. \qquad \text{(A7)}$$

The rules used in writing (A4) to (A7) are as follows. Frictional strengths are added algebraically because the corresponding frictional stresses mobilised must have the same line of action, i.e., opposite to the resultant of the ambient and reservoir induced motive shear stresses. Normal and motive shear stresses acting on the fault due to ambient causes and the reservoir are added vectorially. Since the ambient and reservoir induced normal stresses on the fault have the same line of action at $\mathbf{r}_h$, an algebraic summation is adequate in (A5). The two pore pressures in (A6) are to be added as scalars. Since, in general, the ambient and reservoir induced motive shear stresses on the fault may act in directions making an angle $\theta$ with each other, the formula for the magnitude of the resultant of two vectors is used in (A7).

new reservoir is that the cumulative motive shear stress acting on the fault at the hypocentre should exceed its cumulative frictional strength. Cumulative motive shear stress is the resultant of ambient and reservoir induced motive shear stresses (see (A7)), and cumulative frictional strength of the fault is the frictional strength under the combined influence of ambient and reservoir induced normal stresses and pore pressure (see (A3)).

An earthquake near a new reservoir may be called properly as a *reservoir induced earthquake* if, in addition to this condition, at the instant of earthquake occurrence, the ambient motive shear stress is suitably less than the frictional strength under ambient normal stress and pore pressure. Otherwise, the earthquake should be called a *reservoir inhibited earthquake*, although this term is used rarely. One of my research students and I have argued that some earthquakes near the Tarbela reservoir on the Indus river in Pakistan belong to the second group.

In short, natural and reservoir induced tectonic earthquakes have similar mechanisms and their occurrence can be rationalised similarly in terms of motive shear stresses and frictional strengths of faults. Still it may not be taken for granted that all earthquakes near a new reservoir are induced earthquakes.

## Discussion

A reservoir may not cause a tectonic earthquake on its own. At best, under suitable conditions, it may trigger one or more such earthquakes in its vicinity.

***The Smallness of the Influence due to a Reservoir:*** A cardinal fact, germane to the present theme, is that reservoir induced stresses and pore pressure are each one or more orders smaller than the respective ambient stresses and pore pressure required at the time of a natural tectonic earthquake. The plausibility of this statement may be judged from the following example. Consider a hypocentre at a depth of 5 km in the rocks beneath a 100m deep reservoir. Assuming a nominal value for rock density, the vertical normal stress due to weight of overlying rocks would be 130 MPa at the hypocentre. The hydrostatic pressure at the bottom of the reservoir is only 1 MPa or 10 atmospheres. The stresses and pore pressure induced by it at 5 km depth would be smaller still. Thus a reservoir may not cause a tectonic earthquake on its own. At best, under suitable conditions, it may trigger one or more such earthquakes in its vicinity.

***Ambient Stresses should be near Critical:*** Another cardinal fact is that, for an induced earthquake to occur, ambient stresses and pore pressure at a hypocentre near a new reservoir should accumulate to such a degree and in such a proportion that the fault is close to slip even without the influence of the reservoir. In other words, the ambient motive shear stress on the fault should be less than but sufficiently close to its frictional strength. I estimate that this difference may be expressed conveniently in KPa even for a reservoir as deep as 260 m.

***Friction on a Fault:*** The fault friction model adopted by Snow, and retained here, is the simplest possible. It has been used in rock mechanics and seismology for quite some time and has provided reasonable first estimates of the quantities involved. The coefficient of friction, which has been assumed constant here, may vary with time in some cases.

***Reservoir Induced Pore Pressure:*** A reservoir may induce pore pressure at the hypocentre of a near by earthquake in two distinct ways. Firstly, if pore fluids exist around the hypocentre already, then the reservoir load may cause an increment of pore pressure due to compression of pore spaces. Secondly, if the entire rock mass between the reservoir and the hypocentre is porous, and if water can leak through the reservoir bottom, then pore pressure around the hypocentre may increase also through a process of diffusion.

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***On Predicting RIS:*** Can we predict whether the construction of a proposed dam and impoundment of its reservoir will lead to induced earthquakes? I answer this question in two parts. Firstly, the arguments given above may be used in conjunction with further rock mechanics theory to assess whether the reservoir will have a stabilising or destabilising influence on specific faults in its vicinity. As may be anticipated, the accuracy of such assessment will depend on the accuracy of relevant information about the reservoir, the faults and the intervening rocks. Secondly, addressing the question more directly, I have cited above fault plane solutions to argue that there is an intrinsic similarity in natural tectonic and reservoir induced earthquakes. Thus the problem of predicting RIS near a dam site is fundamentally related to the problem of predicting natural tectonic earthquakes. I believe that, as of today, no individual or group, anywhere in the world, is capable of predicting natural tectonic earthquakes routinely using the accepted principles and methods of science. Predicting RIS should be even more difficult because the levels of ambient stresses and pore pressure as well as the influence of a given reservoir on nearby seismogenic faults cannot be assessed with the required certainty using the observational and theoretical tools at hand. If they wish to be on the safe side, concerned civil engineers may adopt the worst case scenario in regard to the possibility of RIS at a proposed site and incorporate requisite safety features in their designs for the dam and the reservoir.

Geologists recognize three basic types of faults, namely, thrust, normal and strike slip faults, depending upon the sense of relative slip between rocks on two sides of the discontinuity.

***Another Anecdote:*** Geologists recognize three basic types of faults, namely, thrust, normal and strike slip faults, depending upon the sense of relative slip between rocks on two sides of the discontinuity. Anderson identified the three basic types of stress regimes that promote the respective basic types of faulting in the rocks. The simplified analysis by Snow reveals that an infinite reservoir would inhibit renewed slip on thrust faults and promote it on normal and strike slip faults.

Thrust faults are by far the most common in the Himalayas. Also, the fault plane solutions of most tectonic earthquakes in the Himalayas show evidence of thrust faulting. Thus a thrust fault type stress regime existed in the Himalayas in the past and it continues to be active today. This fact, coupled with the above conclusion from Snow, has been used by civil engineers and many earth scientists involved with river valley projects to repeat ad nauseum that RIS cannot occur in the Himalayas.

About ten years ago, while I could not deny the evidence for a thrust fault type stress regime in the Himalayas, I felt constrained to seek a weakness in the argument about the presumed lack of RIS there. Indeed, there were theoretical arguments and observational evidence in the literature that I seized upon and wrote some articles about. I even got a PhD student to do numerical simulations to resolve the dilemma specifically in the context of the Himalayas. The weakness in the anti-RIS argument is this. Snow's infinite reservoir will either inhibit or promote slip uniformly at all points of a fault. On the other hand, a finite reservoir may have a stabilising influence on some sections and destabilising influence on other sections of the same fault, be it a thrust, normal or strike slip fault. Thus the possibility of RIS may not be ruled out in the Himalayas merely on account of the prevalent thrust fault stress environment. But our simulations for the proposed Tehri reservoir showed that it should stabilise critical sections of the thrust faults in its vicinity. As far as RIS is concerned, I am a sobered individual today.

> Thus the possibility of RIS may not be ruled out in the Himalayas merely on account of the prevalent thrust fault stress environment.

## Conclusion

I have emphasised the following ideas in this article.

1. Natural tectonic and reservoir induced earthquakes have similar mechanisms.
2. Dams and reservoirs represent an additional source of stresses and pore pressure at the hypocentres of subsequent tectonic earthquakes near them.
3. Reservoir induced stresses and pore pressure are miniscule in comparison to those required to cause tectonic earthquakes. Thus dams and reservoirs cannot cause such earthquakes on their own.
4. Reservoirs can trigger tectonic earthquakes if they promote renewed slip on nearby faults and the magnitudes of ambient motive shear stresses are already sufficiently close to the frictional strengths of the respective faults.
5. Every tectonic earthquake near a new reservoir need not be an induced earthquake.

## Suggested Reading

**[1] Gupta H K, *Reservoir induced earthquakes,* Elsevier, Amsterdam, 1992.**

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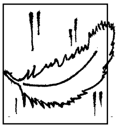

Anyone who is not shocked by quantum theory has not understood it.

Niels Bohr