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RESERVOIR INDUCED SEISMICITY

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INTRODUCTION. The literature on reservoir induced seismicity begins with the discussion of the seismic events at Lake Mead (Hoover Dam) on the Nevada-Arizona border (Carder, 1945), which was the first time such seismic phenomena had been clearly recognized. In retrospect, it appears that an even earlier example had occurred at Lake Marathon, Greece, where induced earthquakes were felt in 1931, two years after filling began, coinciding with the first time peak water level had been obtained (Gupta and Rastogi, 1976). Since that time the number of clearly identifiable cases of reservoir induced seismicity has exceeded 60, out of perhaps 11,000 reservoirs existing in the world. The state of information on the subject as of 1976 has been comprehensively covered in the book by Gupta and Rastogi, Dams and Earthquakes. More recent developments have been treated in two review articles (Gupta, 1985; Simpson, 1986) and in a book (Scholz, 1990). The object of the present article is to briefly summarize the current understanding of the subject, with special emphasis on more recent investigations.

About a dozen examples of reservoir induced seismicity have now been studied in sufficient detail so that the basic mechanisms involved are beginning to be understood. For each reservoir displaying such behavior, however, there are hundreds of similar size and tectonic environment that do not show appreciable changes in seismicity. The particular set of circumstances required to produce such alterations in local seismicity is still not completely defined, although considerable progress has been made in describing certain common factors which seem to be involved in most of the notable examples. In the following, we shall first note some of these common factors and general principles, and then shall describe in some detail several specific examples.

GENERAL PRINCIPLES. Some common characteristics of reservoir induced seismicity which have been generally noted may be summarized as follows (Gupta and Rastogi, 1976).

(1) The frequency of occurrence of earthquakes shows some kind of correlation with reservoir water levels.

(2) Focal depths of induced earthquakes are shallow, and the hypocenters are in the near vicinity of the reservoir.

(3) Foreshocks and aftershocks follow a pattern which for natural earthquakes implies a tectonic stress field which is moderately heterogeneous, with non-uniform external stresses.

(4) In the expression logN = a-bM, where N is the number of events equal to or greater than the magnitude M, and a,b are constants, the slope b is greater for both foreshocks and aftershocks than for normal earthquakes in the region of the reservoir. This means that the average magnitude of the shocks in the sequences is lower than that associated with natural earthquakes in the region.

(5) The aftershocks of reservoir induced earthquakes have a relative slow rate of decay compared to normal earthquakes in the region.

(6) The amplitude ratio of the largest aftershocks to the mainshock is higher than for most natural earthquakes, approximately 0.9.

To these points some other general observations can be added. For all of the larger induced earthquakes, focal plane solutions have shown that the stress systems involved are in agreement with pre-existing tectonic stress fields in the region (Castle, et al, 1980). The induced earthquakes are of a strike-slip or normal type, with no notable cases so far of large induced earthquakes of a thrust type. Most cases have been in areas of low to moderate natural seismicity, perhaps because in regions of high seismicity natural events may mask the smaller effects of induced seismicity. In all cases the induced seismicity seems to be a triggered process. There is general agreement that the main energy in the induced earthquakes comes from the stored elastic strain energy in the whole region of the reservoir, and cannot be accounted for entirely by the loads imposed by the reservoir weight. Unless the tectonically stored energy were already near the level at which a natural earthquake might occur, it is difficult to see how the relatively small effects produced by the reservoir itself could cause the earthquakes. The reservoir has perhaps just hastened the natural event, which might otherwise have waited some thousands of years to happen. The maximum size of the induced earthquakes corresponds to the size of the strained tectonic volumes, and is never larger than likely natural earthquakes in the same region.

The distribution of induced seismicity in time seems to follow two different types of response (Simpson, et al, 1988). In some reservoirs induced seismicity follows immediately upon the initial filling of the reservoir, while at others there may be a considerable delay, sometimes of many years, and the induced seismicity may not become apparent until a number of seasonal filling cycles have occurred. These differences are believed to be connected with a balance of factors involved in the basic mechanism of the process. It is these cases of delayed seismicity which have raised the greatest uncertainties as to the reality of the reservoir-earthquake relationships, which we will encounter in our discussion of the Aswan Dam and the Oroville earthquakes. The study of time correlations has been greatly hampered by the fact that for most of the reported cases of reservoir induced seismicity there has been no pre-impoundment monitoring of seismic activity. Recently, however, several large dam projects have been fully instrumented with local seismic networks several years before impoundment, so that a complete record of pre-impoundment seismicity is available.

BASIC MECHANISMS. Two basic mechanisms of stress modification have been suggested as the important factors in the triggering of seismic events at reservoirs: (1) the direct effect of the weight of the reservoir in increasing the elastic shear stress in the rocks, and (2) the effect of increased pore pressure in decreasing the effective normal stress and thus moving the system closer to shear failure. The increased pore pressure at depth can result as a diffusion of pressure from the reservoir, or because the compression of the rock reduces pore volume. In many reservoirs both the loading and pore pressure effects are evidently operating, with one or the other being the dominant effect. That pore pressures alone many trigger earthquakes is demonstrated by the Denver, Colorado, earthquakes, which followed the injection of waste fluid under high pressure into a deep well (Healy, et al, 1968), and also by experiments at the Rangely, Colorado, oil field in controlling the occurrence of small earthquakes by fluid injection in deep wells in an oil field (Rayleigh, et al, 1976).

The time required for diffusion of pore pressure changes through the rock medium provides a logical explanation for some of the observed time delays between reservoir level changes and seismic activity. It should be noted that the fluid injection pressures involved in the Denver and Rangely events were of the order of several hundred bars, much larger than the pore pressures induced by reservoirs, which are some 10 bars for a 100 meter depth of water typical of many reservoirs. Similarly, the direct shear stresses caused by the weights of typical reservoirs are of the order of 1-10 bars, and these low values of stress and pressure reinforce the idea that the reservoir can only trigger earthquakes in a highly stressed region not far from failure. It is known that high tectonic stresses (300-1000 bars) exist in many regions, and it is also known that the stress drops involved in natural earthquakes are only a matter of a few bars, comparable to the stresses involved in reservoir loading.

The orientation of the principal stresses in the region of the reservoir determines the type of faulting, and the magnitude of the principal stresses indicates how close the system is to failure. The main component of the reservoir loading stress, which is vertical, is added to the maximum, intermediate, or minimum principal stress corresponding to the cases of normal, strike-slip, or thrust faulting. The effect of the vertical load is thus to increase the tendency to trigger earthquakes for a region of normal faulting, to have no effect for strike-slip faulting, and to inhibit the tendency for thrust faulting. An increase in pore pressure will through its effect in reducing effective normal stress, always move the system towards failure (Simpson, 1976; Scholz, 1990). This appears to offer an explanation for the absence of induced seismicity for reservoirs impounded in regions of tectonic compression (thrust faulting) and the fact the induced seismicity usually involves normal or strike-slip faulting.

ILLUSTRATIVE EXAMPLES. To illustrate the above general principles, a number of notable specific cases of reservoir induced seismicity will be briefly discussed. Each of these examples has contributed much to an understanding of the subject, and each involves continuing investigations which will add to our knowledge.

Koyna Dam. This is the classic case of reservoir induced seismicity, which first demonstrated in a conclusive way that large destructive earthquakes could be caused by reservoir impoundment. It remains the most interesting, the most carefully studied, and the best reported event. The Koyna earthquake of December 10, 1967 of magnitude 6.5 was the largest reservoir induced seismic event so far reported. It was centered very close to the 103 meter high dam, and occurred some five years after impounding began in 1962. Significant damage was caused to the concrete dam which required repair and strengthening, but which did not suffer catastrophic failure. Considerable damage to buildings in the region resulted in more than 200 deaths, more than 1500 injuries, and rendered several thousand persons homeless. The reservoir was in a region of low seismicity which had been considered to be free of significant seismic activity, and which in the 1962 seismic zoning map of India had been considered aseismic. Historical records have shown, however, that during the past 600 years several earthquakes had occurred in the western part of the Indian peninsular shield which was generally considered to be a very stable tectonic structure. With remarkable farsightedness, engineers had installed in the dam before the main shock several strong-motion accelerographs, which recorded during the earthquake an acceleration of 0.63g, at that time the largest earthquake acceleration that had ever been recorded anywhere in the world. Koyna Dam remains the most notable example of significant damage to a concrete gravity dam and associated power plant equipment for which the forces causing the damage have been directly measured. After the initial filling of the reservoir in 1962, felt earthquakes were increasingly noticed in the area, and from 1963 on the region was closely monitored by a local network of seismic observatories. Since that time a notable series of foreshocks and aftershocks for a sequence of events have been recorded, and numerous illuminating investigations have been carried out.

The more recent investigations have been summarized in a review paper (Gupta, 1985). Using improved techniques, many aftershocks and smaller events have been relocated with much increased accuracy with the results that faults in the region have been more clearly revealed and delineated. Two broad trends of epicenters have been defined, and focal mechanism studies have shown strike-slip faulting for the NNE trend, and normal faulting for the NW trend. Focal depths are of the order of 12 km, somewhat shallower than had been originally supposed. The fault trends revealed by these improved techniques match those observed by Landsat imagery. Recent studies have also indicated the importance of rate of loading in triggering earthquakes at the Koyna Reservoir (Gupta, 1983). It appears that the necessary but not sufficient condition for triggering of earthquakes of $M \geq 5$ is a weekly rate of reservoir loading of ≥ 40 ft. This suggests that by a suitable control of reservoir water levels, earthquakes greater than M5, which are locally damaging, could perhaps be avoided. Recent detailed studies of Koyna aftershocks (Gupta and Iyer, 1984) have shown that each of the earthquakes of $M \geq 5$ on September 13, 1967, December 10, 1967, and October 17, 1973 were preceded by two M$\geqslant$4 earthquakes within two weeks of the main shock. On the other hand, three earthquakes of M$\geqslant$5 occurred in September 1980 without being preceded by a pair of M$\geqslant$4 events. Hopefully such studies may reveal premonitory patterns which could serve as warnings for impending larger events. To broaden such studies to other regions will require a considerable improvement of local seismic networks, which are far from adequate at most sites.

Hsingfengkiang Dam. Another widely studied reservoir induced seismic event was the M6.0 earthquake at Hsingfengkiang Reservoir near Canton, China (Chang-kang, et al, 1974). This 105 meter high dam was completed in 1959, and increasing numbers of local earthquakes were noted from the time of impoundment to the main shock on March 19, 1962. Before the main shock had occurred, the large number of small events had alerted engineers, and the dam had been strengthened. The M6.1 main shock caused some structural damage to the dam, which was then repaired and received a second stage strengthening. After the main event a number of accelerographs were installed at various elevations in the dam, and several earthquakes as large as M4.5 have been recorded which have provided much valuable information on ground motions and on structural response. Focal mechanism studies of the main shock indicated strike-slip faulting in directions compatible with existing fault structures. Although there is no record of destructive earthquakes in the region before impoundment, several small felt earthquakes had been noted. One month after initial filling, many small earthquakes in the immediate vicinity of the reservoir were recorded, with the numbers increasing rapidly as the water level was raised. There has since been a close correlation between reservoir levels and earthquakes, and a rapid rise of water level to a high value was often followed by increased seismicity. The foreshock-aftershock sequence displayed all of the classic features often associated with reservoir induced seismicity. The b-values for the foreshocks were greater than for the aftershocks, and both were greater than for normal tectonic earthquakes in the region. The ratio of the largest aftershock magnitude to the main shock magnitude was high, and the aftershocks attenuated very slowly.

Aswan Dam. An especially interesting case of reservoir induced seismicity is that of the Aswan Dam, which impounds the second largest reservoir in the world (Kebeasy, et al, 1987). Filling of the lake began in 1964, and it was seventeen years later on November 14, 1981, that a M5.5 earthquake occurred which caused some local structural damage but did not damage the dam. For a number of years Aswan was considered to be a notable case of an aseismic reservoir, but it is now generally accepted that a typical pattern of reservoir induced events has been triggered by Lake Nasser, after an unusually long time delay. Previous to the impoundment the region had been considered to be aseismic, with no significant earthquakes having been reported within 100km of the reservoir. In 1975, eleven years after impoundment, when the lake reached its maximum depth, two seismic stations were installed which detected infrequent low level seismicity. In 1982 after the main shock an eight-station telemetered array of seismometers was deployed, and accurately located events clearly delineated known existing faults which had been submerged since the 1975 high water level. The foreshock-aftershock sequence followed the typical pattern for reservoir induced seismicity. The water level in the region where the earthquakes occurred is only of the order of 10 meters deep, and the sandstone surrounding the reservoir is highly porous and relatively permeable compared to the underlying granite. The total load of the reservoir consists not only of the water in the lake, but also a significant amount of water stored in the sandstone, which also results in an increased pressure at the base of the sandstone. The delay in the appearance of the seismicity is probably connected with the time required for water to diffuse into the sandstone.

Nurek Reservoir. Whereas the Aswan Reservoir may serve as the most striking example of a delayed response, the Nurek Reservoir in the Tadjik Republic of the USSR is an excellent example of a very rapid response. In addition it is an example of a rare case in which very thorough seismic studies were made of the region before the impoundment of the reservoir. The region was known to be of complex tectonics with a high level of natural seismicity. In 1956 a M5.3 earthquake occurred approximately 10 km from the proposed dam site. A network of seismic stations has been operating since 1955, some twelve years before the impoundment which did not begin until 1967. The first phase of major filling occurred in 1972 when the water level attained 100 meters. A strong increase in seismicity occurred immediately, including earthquakes of M4.3 and M4.5. A second stage of filling took place in 1976 which raised the water level from 120 meters to 200 meters, accompanied by an intense burst of seismic activity (Simpson and Negmatullaev, 1981). Although the water level has since reached 250 meters, no induced earthquake larger than M4.1 has occurred since November 1972. In 1975 the original seismic network was supplemented by a 10-station telemetered network which permits a detailed study of local conditions. The distribution of epicenters for the induced earthquakes form a pattern quite distinct from that formed by natural events. The region of the Nurek Reservoir is in a broad zone of horizontal compression, and the focal mechanisms for the region are usually of a thrust type. This is an apparent exception to the general conclusion that reservoir induced seismicity does not occur in such compressional tectonic regions. This can perhaps be accounted for by a balance of opposing effects of load and pore pressure in such regions of horizontal compression. Detailed studies have shown that raising the water level above a previous maximum value seems to increase the potential for increased seismicity. The occurrence of subsequent seismic activity appears to be controlled by changes in the rate of filling of the reservoir, with decreases in the filling rate causing an increase in seismicity. A similar phenomenon was mentioned above in connection with Koyna Dam. It appears that a control of filling rate may influence the release of seismic energy, and that an artificial manipulation of rates of filling may be a feasible way in some cases to avoid triggering such activity. The pattern of foreshock and aftershock activity shows many of the same features noted in other cases of induced seismicity. The fault zones indicated by the induced seismicity do not, however, correspond to geologically mapped fault zones, which are more characteristic of the naturally occurring seismicity. The long term studies of the Nurek Reservoir confirm the generally noted fact that reservoir induced seismicity appears to be a transient phenomenon. In most cases, such induced seismicity gradaully decreases, and one would expect that the region would achieve a new equilibrium and the reservoir should eventually have no more effect than a large lake.

The Oroville Earthquake. The M5.7 Oroville, California earthquake of August 1, 1975 is of special interest because of the fact that although it has been very extensively studied, there is still no general agreement as to whether or not it represents a case of reservoir induced seismicity. The 236 meter high Oroville Dam is the largest dam in North America. The filling of the reservoir began in November 1967 and was completed in September 1968. The main shock, which was about 12 km from the dam, thus occurred some eight years after impoundment, and this time delay raised questions about the relationship between the reservoir and the earthquake. Since we now have a clear case at Aswan Dam of reservoir induced seismicity after 17 years, the delay question is not quite as critical, but other features introduce further doubts. As pointed out in a recent study of the event (Toppozada and Morrison, 1982), there are at least two factors indicating a direct connection between the dam and the earthquake: (1) the earthquake was quite near the dam, and the extension of the causative fault to the lake is indicated by gelogic, seismologic, and geodetic data; and (2) the earthquake occurred after an unprecedented seasonal change in reservoir level. During the winter of 1974-75 the reservoir was drawn down to its lowest level since filling to repair intakes to the power plant, and the earthquake sequence followed shortly after the refilling. This suggests a situation similar to that at Koyna Dam in 1967. In both cases the earthquakes did not occur upon initial filling, but rather several years later following unprecedented seasonal refilling. The region of the Oroville Resevoir was generally considered to be of relatively low seismicity although three other earthquakes in the M5-5.9 range have occurred since 1900 within 60 km of the site. In 1977 reservoir level fluctuations of an even greater amount than in 1975 were not accompanied by significant seismic activity (Rajendran and Gupta, 1985). There is thus no general agreement as to the degree of correlation between the fluctuation of reservoir levels and the seismic activity - for some intervals of several years, a correlation seems indicated, for others, unlikely. As discussed above it has been shown that for most cases of reservoir induced seismicity the b-values in the recurrence-magnitude relationships are higher than those for natural earthquakes in the region. At Oroville, the b-values for both foreshocks and aftershocks are definitely lower than the regional values, again suggesting that Oroville is not a typical case of reservoir induced seismicity. On the other hand the rate of decay of aftershocks at Oroville is similar to values for reservoirs which are definitely considered to show induced seismicity. As the years go by and new data become available, we may hope that the situation at Oroville will become clearer.

<u>Monticello Dam.</u> The situation at Monticello Reservoir in South Carolina is of special importance because of the comprehensive studies that have been made there. These include in situ tectonic stress measurements, and direct measurements of pore pressure, permeability, and the distribution of faults, fractures, and joints in two 1.1 km deep wells drilled into the hypocentral zone of the induced earthquakes (Gupta, 1985). The induced seismicity at the Montebello site is an example of the rapid response type. The 52 meter dam with a small reservoir volume of 0.5 km was filled rapidly, and swarms of small earthquakes (M_{max} = 2.8) occurred within weeks of impounding. The induced seismicity [illegible]red as the water level remained constant, although the seismic activity is still somewhat higher than the very low pre-impoundment values.

This is an example of induced seismicity which might never have been noticed, except for an unusual amount of investigative work at the site, including pre-impounding seismicity studies, which were motivated by the existance of a nearby nuclear power plant site, and by the hopes that such studies might throw some additional light on basic problems of earthquake prediction. A similar situation exists at the Grančarevo Dam in Yugoslavia, which was seismically monitored some seven years before impoundment. A clear pattern of reservoir induced seismicity developed, but all at a very low instrumental level. Without the pre-impounding measurements it would no doubt have been concluded that there were no seismic effects caused by the reservoir. It may well be that many dams which have had apparently no seismic effects could have involved considerable seismic activity at microseismic levels (Božović, 1974). The direct measurements made in the deep wells at Monticello were performed specifically to test the theory that increased pore pressures caused by fluid diffusion were an important factor in induced seismicity (Zoback and Hickman, 1982). Hydraulic fracturing stress measurements were made at different levels in the wells, and it was determined that near-critical stress differences for reverse-type fault motions existed at depths less than 200-300 meters. Tests with an ultrasonic borehole televiewer revealed fault planes with orientations similar to these calculated from seismic focal mechanism studies. Direct pore pressure measurements indicated that pore pressures were increased compared to pre-impoundment conditions, and permeability measurements produced data reasonably consistent with the time history of the induced seismicity. These direct measurements were compared with stress parameters determined from a network of five digital seismographs recording over 300 induced events (Fletcher, 1982). Estimates of shear stress from the in situ measurements agreed with the seismically determined stress drops for the larger $M \approx 3$ events, but were much larger than those for smaller events. These comprehensive investigations at Monticello Reservoir have confirmed the hypothesis that the near surface pore pressure changes caused by the reservoir were sufficient to trigger earthquakes.

Tarbela Dam. The Tarbela Dam in Pakistan has a height of 143 meters and impounds a reservoir of maximum depth 130 meters and a capacity of 13.7 km (Jacob, et al, 1979). It is located in a seismically active region in the lesser Himalayas. About one year before first impounding a telemetered seismic array was established at the site and detailed studies of local seismicity were carried out. Fault plane solutions indicated a pattern of thrusting and strike-slip motions consistent with a horizontal N.S. compression typical of Himalayan tectonics. Two initial reservoir fillings resulted in only a minor effect on seismicity. Small temporary decreases in local seismicity were observed, which disappeared after a few weeks, with seismicity then returning to pre-impounding levels. This pattern of decreased seismicity is compatible with a compressive stress environment with a delayed increase in pore pressure at depth. In this case the reduced seismicity is consistent with basic theories on the balance between pore pressure and loading effects in a compressional setting, and thus enhances the generally accepted picture of the mechanics of reservoir induced seismicity. Since Tarbela Dam is located in a highly seismic region, it is clear that the dominant seismic risk at the site is established more by natural earthquakes than by the possibilities of reservoir induced events.

SUMMARY OF RESERVOIR CHARACTERISTICS. To set the above special cases within a more general framework, it will be useful to refer to Table I, which presents basic data for a selected group of reservoirs which have been involved in notable investigations of reservoir induced seismicity. Many others could be included, which, however, would add no new features to the picture. Fig. 1 shows one way in which some of this basic information can be organized in the hopes that some general pattern will emerge. It is clear from Fig. 1 that many additional factors would have to be included before any general conclusions could be reached. From Fig. 1, however, it can be seen that depth of water appears to be a more important factor than reservoir volume, and that the size

TABLE I. RESERVOIR INDUCED SEISMICITY

Name	Country	Height of Dam (m)	Reservoir Volume ($\times 10^6 m^3$)	Year of Impounding	Year of Max. Eq.	Magnitude of Max. Eq.	References
Koyna	India	103	2,780	1962	1967	6.5	13,14,15,16
Kremesta	Greece	160	4,750	1965	1966	6.3	16
Kariba	Africa	128	175,000	1958	1963	6.2	9,10,11,16
Hsinfengkiang	China	105	13,896	1959	1962	6.0	7,16
Marathon	Greece	67	41	1929	1938	5.7	16
Oroville	USA	236	4,400	1967	1975	5.7	3,23,26,32
Aswan	Egypt	111	164,000	1964	1981	5.5	13,22
Benmore	New Zealand	110	2,040	1964	1966	5.0	16
Hoover	USA	221	36,703	1935	1939	5.0	5,16
Monteynard	France	155	275	1962	1963	4.9	4,16,25
Kurobe	Japan	186	149	1960	1961	4.9	16,19
Nurek	USSR	317	11,000	1972	1972	4.5	16,29
Grančarevo	Yugoslavia	123	1,280	1967	1967	3.0	4
Monticello	USA	129	500	1977	1979	2.8	13,33

of the maximum earthquake does not increase with either depth or volume. Many other factors such as tectonic setting, the permeability of rocks, the presence and pattern of faulting, etc., are also of key importance, and it is clear that each site requires a detailed individual investigation before any opinion as to future behavior can be formed.

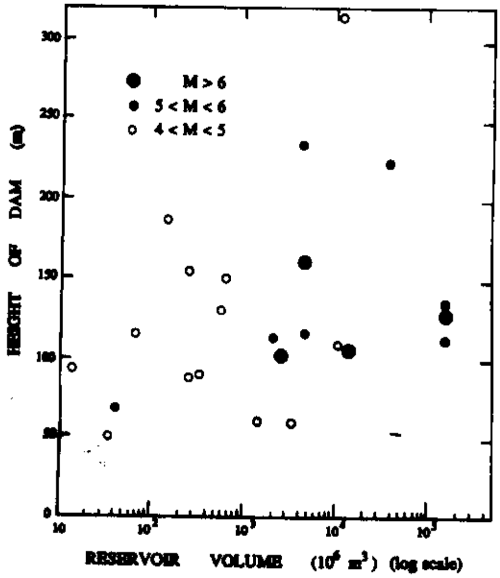

Fig. 1. Height of dam, reservoir volume, and maximum magnitude of induced earthquake (data from Ref. 13).

This same diversity of behavior will also be noted in Figs. 2a,b, which give the water depth versus time from impoundment for several of the reservoirs discussed above, along with an indication of when the maximum induced earthquake occurred.

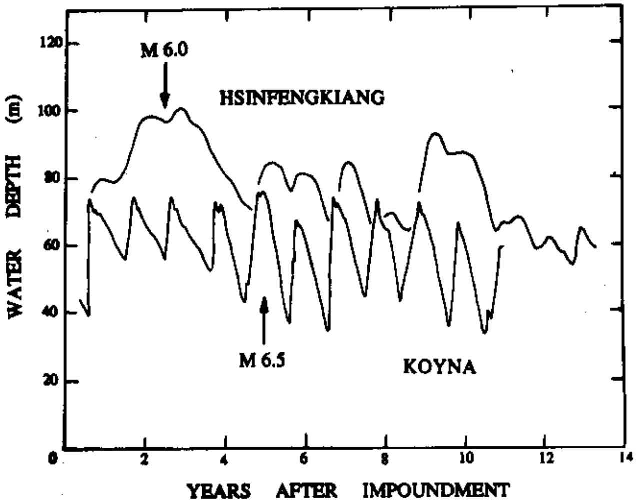

Fig. 2a. Depth of water versus time from impoundment for Hsingfengkiang Reservoir (data from Ref. 7) and for the Koyna Reservoir (data from Ref. 31). Time of occurrence of maximum induced earthquake is also indicated.

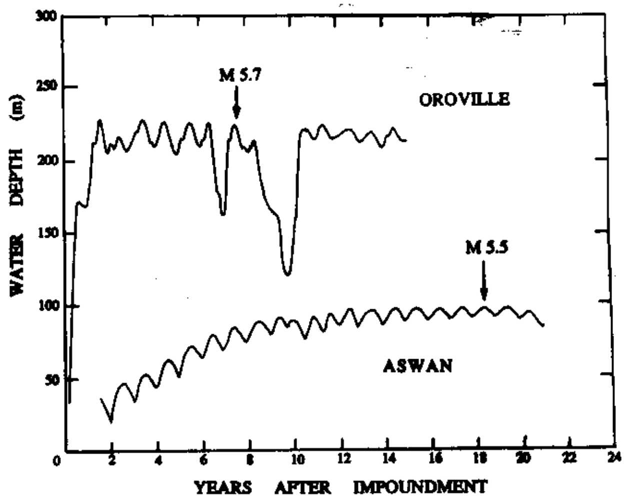

Fig. 2b. Depth of water versus time from impoundment for Oroville Reservoir (data from Ref. 23) and for the Aswan Reservoir (data from Ref. 22). Time of occurrence of maximum induced earthquake is also indicated.

A recent statistical investigation (Baecher and Keeney, 1982) has analyzed data from 29 reservoirs associated with reservoir induced seismicity and 205 reservoirs not showing this behavior, selected from some 11,000 reservoirs in the world. Three subsets of these 234 reservoirs were defined - very deep reservoirs, very large reservoirs, and reservoirs with reported cases of induced seismicity. Five attributes were used to describe each reservoir - depth, volume, stress state, presence of active faulting, and geology. The tentative conclusions from this relatively small and limited sample are: depth is the attribute which best discriminates circumstances which may or may not result in induced seismicity, and the next best is volume. The complete set of attributes most likely to produce induced seismicity would be a very deep, very large reservoir in a shear stress zone with active faulting prior to the reservoir, in sedimentary formations. After due warnings concerning the inadequacies of the present data set, the authors of the above statistical study concluded that "There is no method or methodology, nor could there be one, which is completely objective for developing a model of the likelihood of reservoir induced seismicity."

Another recent study which helps to achieve a broader perspective is an investigation of large reservoirs in the Himalayan foothills (Gupta and Rajendran, 1986). Nine large reservoirs (height > 100 meters, volume > 1 km^3) were studied, and in no case was reservoir induced seismicity reported. At Mangla Dam, among the largest reservoirs in the world, seismicity did not increase, but may in fact have decreased. We have already noted a similar situation for Tarbela Dam, and it has also been concluded that there is no relation between seismic activity and the reservoir created at Bhakra Dam. The predominant factor which seems to be inhibiting induced seismicity in this region is the thrust-fault environment, generally prevalent in the Himalayan foothills, which as has been discussed above is not usually conducive to reservoir induced seismicity. All of these Himalayan dams are located in regions of high natural seismicity, and all of the sites have in the past experienced many large earthquakes nearby. Naturally occurring earthquakes thus represent a much more severe threat to dams in this region than reservoir induced seismicity, and this is probably true for a very large fraction of the world's dams.

The relative importance of reservoir induced seismicity in the overall problem of seismic hazard assessment for dams has been widely discussed (Simpson, 1986). Some have felt that the small fraction of dams subject to this phenomenon indicates a minor role in the whole risk picture. Others point out that even though the numbers are small, the fact that such events often occur in regions of very low seismicity, where earthquake effects were perhaps not considered to be an important factor in the design process, and that such induced earthquakes are very close to the dam, means that careful consideration to such problems is always advisable (Allen, 1982). It seems clear, however, that there have already been enough induced earthquakes of damaging size, so that it would be prudent to give careful thought to such possibilities in the design of any significant reservoir project.

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