reservoir-induced earthquakes and engineering policy

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In numerous parts of the world today, including some of the most highly developed countries, many dam designers and operators have tended to close their eyes to the engineering problems posed by reservoir-induced earthquakes. One sometimes hears these kinds of defensive arguments: 1) no convincing correlation has yet been demostrated between earthquakes and reservoirs; 2) since the natural seismicity at a given site is low, the danger of reservoir-inducement is therefore also low; 3) the geology at a given site is different from that at localities where major reservoir-induced events have occurred; 4) only 3 or 4 out of some 11 000 large dams worldwide have experienced significant induced earthquakes, and one should therefore not worry about a given site; and 5) no dam has yet failed disastrously because of a reservoir-induced earthquake, and the danger is thus grossly exaggerated. While many of these arguments have some elements of truth to them, they are essentially evading the primary issues: Virtually every careful study has concluded that there is indeed a cause-and-effect relationship between some earthquakes and some reservoirs, and two dams (Koyna, India, and Hsinfengkiang, China) have in fact come uncomfortably close to disastrous failure during such events. Furthermore, it is precisely in the regions of low natural seismicity where the major existing problems lie, because in areas of high seismicity dams are usually designed for substantial earthquake resistance anyway.

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The unhappy current state of affairs is that our degree of understanding of reservoir-induced earthquakes is so minimal that almost no new reservoir anywhere in the world can be declared free of this possible danger. In particular, we do not know why such earthquakes occur, and we cannot as yet recognize with confidence those areas where reservoir-induced earthquakes are more likely than at other localities. It is easy to say that the geology and seismo-tectonics of a given site are different from those at Koyna, for example, but until we understand what it is in the physical environment of Koyna that led to the triggering of earthquakes there, this is not a very meaningful statement. And one must recognize that the various sites where major induced events have occurred represent a wide variety of geologic environments; there is as yet no recognized geologic theme at these localities which marks them as particularly distinctive or dangerous as compared to the thousands of apparently similar sites where large events have not occurred. Even nearby reservoirs that seem to be in the same geologic environment have sometimes given rise to widely disparate degrees of activity, as has recently been demonstrated at Manic 3 Reservoir, Quebec (Leblanc and Anglin, 1978.)

Therefore, in estimating risk, we are to a large degree forced to utilize a statistical approach based on the total experience throughout the world. Out of some 11 000 worldwide "large" dams, only a small number have triggered known seismic activity. Packer et al. (1977) list 16 "accepted" and 35 "questionable" cases of reservoir-induced seismicity, and Simpson (1976) lists 32 cases of "changed" seismicity, including some where the filling of the reservoir caused the natural seismicity to decrease. Many other cases of changed micro-earthquake activity have probably escaped notice or report. But of more significance is the number of instances of induced earthquakes large enough to be potentially damaging, and only 4 induced events have exceeded magnitude 5.7. These are: Hsinfengkiang, China, 1962, M = 6.1 (Sheng *et al.*, 1973; Wang *et al.*, 1975); Kariba, Rhodesia-Zambia, 1963, M = 5.8 (Gough and Gough, 1970a, 1970b); Kremasta, Greece, 1966, M = 6.3 (Gupta and Rastogi, 1976; Drakopoulos, 1974); and Koyna, India, M = 6.5 (Gupta and Rastogi, 1976; Guha *et al.*, 1971). All of these earthquakes were associated with reservoirs with water depths exceeding 80 m., of which there are perhaps 200 worldwide. (Packer *et al.*, 1977, list 179 reservoirs with water depths exceeding 92 m.) Thus, for a deep reservoir, one might argue that the statistical chances of an earthquake exceeding magnitude 5.7 being triggered are perhaps 4 in 200. Although this probability might appear to be very low, assuredly it is not so low that engineers can dismiss the phenomenon of reservoir-induced earthquakes when designing large dams, almost all of which have truly catastrophic consequences of failure.

Therefore, it is the author's opinion that at this time, anywhere in the world, almost any new dam that will impound water to depths exceeding 80-100 m. must be designed with the assumption that a magnitude 6-1/2 earthquake could occur nearby. It should also be emphasized that the shaking associated with a local earthquake of this magnitude does not normally represent a terribly severe design restriction for either concrete or embankment dams, although the effects of heavy shaking on some critical auxilliary structures such as outlet towers and spillway gates may require very special attention.

One must keep in mind that this somewhat discouraging state of affairs could change very rapidly as the result of research currently underway. Particularly promising at the moment are studies of the subsurface hydrologic environments near reservoirs. Although the mechanism of reservoir-inducement is not understood, it is probably closely related to pore-pressure changes in underlying fault zones resulting from reservoir filling. And although we cannot as yet confidently recognize diagnostic geologic features associated with areas of reservoir-inducement, there is increasing evidence that large triggered events are most likely in areas of active (i. e., Holocene) faulting. It is particularly unfortunate that careful geologic field studies emphasizing the neotectonic environment have not yet been carried out in a number of areas where reservoir-induced earthquakes have been documented.

Several investigators (e. g., Simpson, 1976; Packer *et al.*, 1977) have pointed out that induced earthquakes during reservoir filling are most numerous in areas of normal and strike-slip faulting, as opposed to areas of thrust faulting. In at least one case (Tarbela Dam, Pakistan), moreover, minor seismicity in a thrust-faulted region has been observed to *decrease* during periods of reservoir filling, and a reasonable mechanical argument has been made for this phenomenon (Jacob *et al.*, 1979). Although these kinds of research studies have only limited engineering application at the moment, assuredly they represent the types of efforts that eventually will lead to a full understanding of the reservoir-inducement problem and to its engineering mitigation.

For the dam designer and operator, many significant questions remain in addition to that of the probability of reservoir-inducement. Among these are the following:

Is surface faulting possible in association with a reservoir-induced earthquake? Inasmuch as the largest reported reservoir-induced earthquakes are of the same magnitude as those often associated with surface faulting in natural events, there is no obvious reason why surface rupture should not accompany some triggered events. Indeed, the 1967 Koyna earthquake appears to have been associated with about 30 cm. of surface displacement on a Holocene fault that passed through an arm of the reservoir (Cluff, 1977). Of particular concern, of course, is the possibility that such a fault might pass through the dam itself, as was the subject of considerable debate and concern in the case of Auburn Dam, California (Allen, 1978).

Is it possible that triggered displacement might occur on a fault otherwise considered to be "inactive"? Under natural conditions, displacements on "inactive", faults are usually not considered credible from the point of view of engineering planning. In fact, this is often the basis for the definition of "active" vs. "inactive" faults. In the author's opinion, however, reservoir loading could conceivably cause displacement on a fault normally considered "inactive", in view of the fact that the reservoir may produce a stress distribution quite unlike that which the area has experienced for many thousands of years. This would seem like a particularly credible scenario where a fault zone was a major and continuous zone of weakness (e. g., a throughgoing massive shear zone), even though it had experienced no displacements within Holocene time. Packer *et al.*, (1977) present an opposing point of view.

Is magnitude 6-1/2 the maximum earthquake that can be expected by reservoir inducement? The largest generally accepted induced event to date is of magnitude 6.5 (Koyna, 1967), and there is no particular reason to assume that this is the largest event that is physically possible. Nevertheless, in view of the uniqueness of the Koyna event —and the thousands of dams that have not experienced similar earthquakes— it would appear still larger triggered earthquakes should be considered in the siting and design of most structures. In areas close to major active faults, larger design earthquakes are often stipulated, of course, as representative of possible naturally occurring events.

How long following the initial filling of a reservoir are induced earthquakes likely? The four largest reservoir-induced events had time intervals between the commencement of filling and the largest earthquakes of 1, 3, 4 and 5 years. In each of these cases, however, minor seismic activity started at the time of first filling and continued at least sporadically until the time of the largest shock. Time intervals of larger than 5 years are certainly not ruled out, although admittedly the cause-and-effect relationship becomes less convincing with longer elapsed time. One of the reasons why many scientists do not consider the 1975 earthquake near Oroville Dam, California, (M = 5.7) to be reservoir-induced is that the time delay was 8 years, and all but the last few months of this period was devoid of even small shocks in the reservoir area. Others have argued that the long delay was in fact closely related to the fact that the epicenter was as far as 11 km from the reservoir, albeit on a fault that extended into the reservoir (Bufe *et al.*, 1976).

Would not an earthquake similar to a reservoir-induced earthquake occur sooner or later in the area even in the absence of the reservoir? It is generally agreed that a reservoir, by whatever physical mechanism, is only *triggering* the release of natural tectonic strain, and is not in itself generating the principal seismic energy. Therefore one might argue that the presence of the reservoir has only hastened the arrival of an event that would have happened at a later time anyway. On the other hand, one can equally well argue that many areas of the earth's crust are very close to the breaking point on a more-or-less continuing basis, as might be envisaged from the concepts of plate tectonics; only when a perturbing phenomenon is introduced, such as a large reservoir, is the breaking strength locally exceeded. The author prefers this second point of view and therefore argues that the seismic history of a region, even if extending over many hundreds of years, is not an adequate guide to the maximum credible size of a reservoir-induced earthquake in the region.

What effect can the phenomenon of reservoir-induced seismicity have on dam design? Aside from the obvious wisdom of designing a structure to withstand the shaking associated with the largest credible local earthquake, the type of design of a dam may depend on whether surface fault displacements through the dam are considered credible. Dams have been designed with this assumption (Sherard *et al.*, 1974), and the proposed designs of other dams have been changed when this danger became accepted, as at Auburn Dam, California. The phenomenon of triggered earthquakes may also give added weight to the arguments for rapid-drawdpwm capability for a dam that is under design.

What effect can the phenomenon of reservoir-induced earthquakes have on dam operation? Simpson and Negmatullaev (1978) have suggested that reservoir-induced earthquakes might, in a sense, be controlled by the manner in which a reservoir is filled. They specifically suggest that such events can be held to a minimum if a reservoir is filled slowly and smoothly, based on experience at Nurek Dam, USSR. In at least one case (Hsinfengkiang Dam, China), the surprising presence of many small earthquakes during the initial stages of filling led to such concern that the dam was immediately strengthened, the wisdom of which became apparent shortly thereafter when a magnitude 6.1 event occurred almost beneath the structure (Sheng *et. al.*, 1973.)

It is generally recommended by seismologists that some sort of seismographic network be established around new large, deep reservoirs. But many dam owners have logically asked why such an investment is called for; certainly a network can not stop reservoir-induced events from happening. Some seismologists have seemed to reply that their seismographs are justified simply because their cost is so minuscule as compared to total project costs, but assuredly a more responsible justification is called for.

There are several valid reasons why a seismographic network should be established: 1) Particularly for low-magnitude earthquakes, only through instrumental recording can it be established whether or not reservoir-induced events are in fact occurring, and all accepted large triggered events have been preceded by numerous small ones. 2) If, as argued by Simpson and Negmatullaev (1978), reservoir-induced earthquakes can be partly controlled by the manner in which the reservoir is filled, a reasonably sophisticated network is mandatory to plan operations and to monitor progress. 3) The public living near and downstream from major dams will inevitably be concerned about earthquakes in the vicinity, whether or not reservoir-induced, and a seismographic network is the only realistic means for providing prompt, forthright, and accurate information.

What kinds of networks should dam owners be prepared to install and operate? A minimum of three stations is required for a hypocentral location, and the author suggests that for most reservoirs, 5 to 8 stations should represent an adequate network. Networks with as many as 18 stations have sometimes been installed, but these have usually been in conjunction with sophisticated research programs having broader objectives. Radio or telephone-line telemetry of seismic signals to a common recording point is now both scientifically advantageous and cost-effective, and in many cases seismic telemetry can be combined with telemetry that has been planned for other purposes, such as hydrologic monitoring. On the other hand, relatively simple recording and analysis techniques are much to be desired, particularly in remote areas, unless there is a large research element involved, with highly trained personnel. Drum recording, even on smoked paper, has many operational advantages over sophisticated schemes using magnetic tape and complex data-analysis techniques.

In view of the present degree of ignorance concerning reservoir-induced earthquakes, and recognizing the tremendous stakes involved, major dam-building agencies have a clear obligation to support those kinds of research that will enable us eventually to solve the problem. The argument is impelling: Literally millions if not billions of dollars are now being expended in designing and building dams for reservoir-induced earthquakes that will never occur, simply because we are as yet unable to recognize those areas where such events are more likely than others. Owners and builders of individual dams perhaps cannot be expected to support basic research studies of this type from project funds, but certainly the major dam-building agencies should. At least in the United States, this obligation seems not to have been generally accepted. From a purely economic point of view, not to speak of public safety, the problem of reservoir-induced earthquakes deserves far more attention than it currently is receiving in most parts of the world.

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