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SIGNIFICANCE OF RESERVOIR INDUCED SEISMICITY PHENOMENON

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ABSTRACT

Studies on reservoir induced seismicity at various dam sites have been undertaken since last fifty years or so. The objectives of the studies are mainly to monitor the pre- and post-impoundment levels of seismicity and to assess the realistic seismic risk. Results of these studies could be more fruitfully utilized for two diverse purposes, viz., application to earthquake control and economic design of dams and appertenant structures. For this purpose it is necessary to widen the scope of the studies to include geological and geophysical aspects, rock properties and local hydrology.

INTRODUCTION

The phenomenon of reservoir induced seismicity (RIS) was first documented and reported in 1945 for the well known Lake Mead area in USA. The experimental support and explanation to this hypothesis were available much later in 1966 through the study of seismicity at Rocky Mountain Arsenal Well, Denver, USA, where fluid wastes were pumped down a 3.67 km deep borehole. These observations were further substantiated by the controlled experiments at the Rangeley Oil Fields in USA in 1968. To-date the number of reservoirs with which RIS could be associated has gone to over 100. A number of dam sites in India and elsewhere have been instrumented for monitoring seismicity at reservoir sites (Padale et al., 1989). However, it may be noted that in depth RIS studies involve multidisciplinary observations such as measurements of tectonic stresses, identification of susceptible natural faults, physical properties of crustal rocks, pore pressure measurements at depth, etc. Since these observations require substantial funds, there is hardly any site where intensive measurements of above mentioned parameters have been undertaken. Seismilogical observations are comparatively easy and hence primarily relied upon for monitoring, rather than for understanding the mechanism of RIS phenomenon.

SUMMARY OF RIS STUDY RESULTS

Analyses, by various researchers, of the data obtained from over a hundred documented case histories have led to the following general conclusions.

(i) Onset of RIS occurs from 'immediately after' to 'few years after' the first impoundment. Though the occurrence is commonly after 1 to 3 years, a delay as long as 18 years, has been reported in the case of Lake Nasser formed by the Aswan dam on River Nile in Egypt.

(ii) Most probable RIS maximum magnitudes are in the range 3.0 to 5.9 on Richter Scale. Events of magnitudes above 6.0 have been reported to-date only in four cases, viz. Hsinfengkiang, China (M:6.2); Kremasta, Greece (M:6.3); Kariba, Zimbabwe (M:6.1) and Koyna, India (M: 6.5).

(iii) No direct relationship has been observed between water volume or reservoir depth and maximum earthquake magnitude.

(iv) In a few cases, enhanced seismicity was observed following faster rate of loading and/or unloading.

(v) Most favourable tectonic regime seems to be that with moderate tectonic stress (moderate seismicity) and in the vicinity of active normal or strike-slip faulting. Thus, reservoirs located over geologically older formations seem to be more prone to RIS than those located over younger geological formations.

Incidentally, all these characteristics cannot be associated with each case.

The basic causes of RIS associated failure have been identified as follows:

(1) Reservoir load effect as postulated by Westergaard and Adkins (1934) and Gough (1969);

(2) Pore pressure effect which reduces the effective stresses required for yielding of crust rocks (Healy et al., 1968 ; Evans, 1970);

(3) Failure of rocks due to weakening caused by chemical interaction with water (Griggs, 1967). . This phenomenon was identified in laboratory experiments and has been recently reported in the case of Srinagarind reservoir site in the Western Thailand by Ghose and Oike (1987).

It is likely that a combiantion of these factors is effective in any particular case. Reported presence of water at depths of upto 20 km has strengthened the pore pressure hypothesis.

Model studies on the basis of pore pressure effect suggest that, for occurrence of RIS, the following conditions must exist (Simpson, 1986) :

(a) Tectonic stress level at the site should be close to critical;

(b) Geological formations must be favourable for seepage of water to depths for increasing pore pressure or for weakening the rocks.

The above mentioned observations suggest the following feasible applications.

APPLICATION TO EARTHQUAKE CONTROL

Intensive efforts to predict earthquakes have been made since the 60's with the aim of predicting location, magnitude and the likely duration of occurrence of the impending event. It has been possible to identify areas of future events by methods such as seismic gap, b-value, etc. Precise prediction which is of public utility for mitigation of seismic disaster, is still not possible. The observation that the fluid injection at high pressures in deep boreholes located over favourable geology leads to release of tectonic stresses suggests that the method could be deployed for controlled release of crustal stresses in the form of weaker earthquakes. However, both these branches of study-earthquake prediction and earthquake control are in preliminary stages, and intensive observations, model studies and experimental work would have to continue towards attaining satisfactory levels. Intensive RIS studies would be helpful in understaning the mechanism of RIS phenomenon and in identifying the geotectonic situations which are susceptible to RIS, and hence to earthquake control. For this purpose, the seismic monitoring at dam sites must be intensified to yield precise focal parameters, faulting mechanism, migration of strain foci, triggering reservoir levels or rates of loading/unloading, etc. These studies should be supplemented by geological and geophysical investigations related to properties of crustal rocks and local subterranean hydrology.

APPLICATION TO EARTHQUAKE ENGINEERING

The seismic design of engineering structures basically requires knowledge of maximum size of earthquake likely to occur during the economic life of the structure, the distance to the seismogenic geological feature in the vicinity and the attenuation laws. Importance of RIS in aseismic design could be attributed to the following related effects.

- RIS is likely to occur during the economic/useful life of the structure, although longer recurrence periods might have been indicated by the historical earthquake data.
- RIS events occur at shallow depths and in close proximity to the engineering structures, and thus could subject the structures to higher ground accelerations than normally anticipated.
- On account of increased pore pressures, enhanced fault dimension may undergo seismogenic rupture resulting in higher magnitude seismic events.

Although these possibilities are generally accepted, design engineers have preferred to ignore RIS effect in aseismic design for the following reasons :

(i) Very low percentage of world reservoirs has experienced RIS.

(ii) Noticeable damage due to RIS events has been reported only for two sites, viz. Hsinfengkiang and Koyna, whereas, the damage due to natural earthquake has been reported for more sites (Table 1).

(iii) As yet, it has not been possible to clearly identify RIS prone areas. In this context, a statement by Dr. G.W. Housner (1990) the leading Earthquake Engineer may be mentioned. He says, "Engineers designing structures must rely on proven principles; in contrast, seismologists investigating geologic processes have the privilege of posing, testing and discarding hypothesis". This summarizes the basic difference in the outlooks of these two specialists. All the same, there could be no disagreement over the fact that in order to arrive at the proven principles, one must pose and test all feasible hypotheses.

CONCLUSIONS

The understanding of the mechanism and conditions associated with RIS is important for the purpose of controlling earthquakes as well as for realistic assessment of seismic risk at dam sites. Both these aspects of RIS have the potential to contribute substantially to earthquake hazard mitigation. In view of this, it is suggested that the RIS studies should not be restricted to seismic monitoring only, but should be intensified to include detail evaluation of seismic parameters and geological and geophysical investigations to assess tectonic stresses, subterranean hydrology, porosity and physical properties of rocks, etc.

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TABLE 1

DAMS SUBJECTED TO NATURAL AND RESERVOIR INDUCED EARTHQUAKES

Dam	Country	Description of Dam	Height m	Completed or first impoundment in*	Earthquake M	Earthquake Date	Damage
Sheffield	USA	Embankment : Silty sand	8	1917	6.3	1925	Collapse
*Marathon	Greece	Gravity	63	1930	5.0	1938	Negligible
*Hoover	USA	Arch-gravity	221	1936	5.0	1939	Negligible
Hebgen	USA	Embankment	37	1915	7.1	1959	Severe
*Hsinfengkiang	China	Concrete buttress	105	1959	6.1	1962	Moderate
*Kariba	Zimbabwe	Arch	128	1959	6.3	1963	Negligible
Eklutna	Alaska	Embankment	6	1929	8.5	1964	Severe
El Soldado	Chile	Tailings dam	-	-	7.1	1965	Collapse
*Kremasta	Greece	Embankment	165	1965	6.3	1966	Negligible
*Koyna	India	Concrete gravity	103	1962	6.5	1967	Moderate
Baihe	Chine	Embankment	60	-	7.8	1976	Severe
On Izhu Peninsula	Japan	Tailings dam	-	-	5.7	1978	Failure

*RIS events