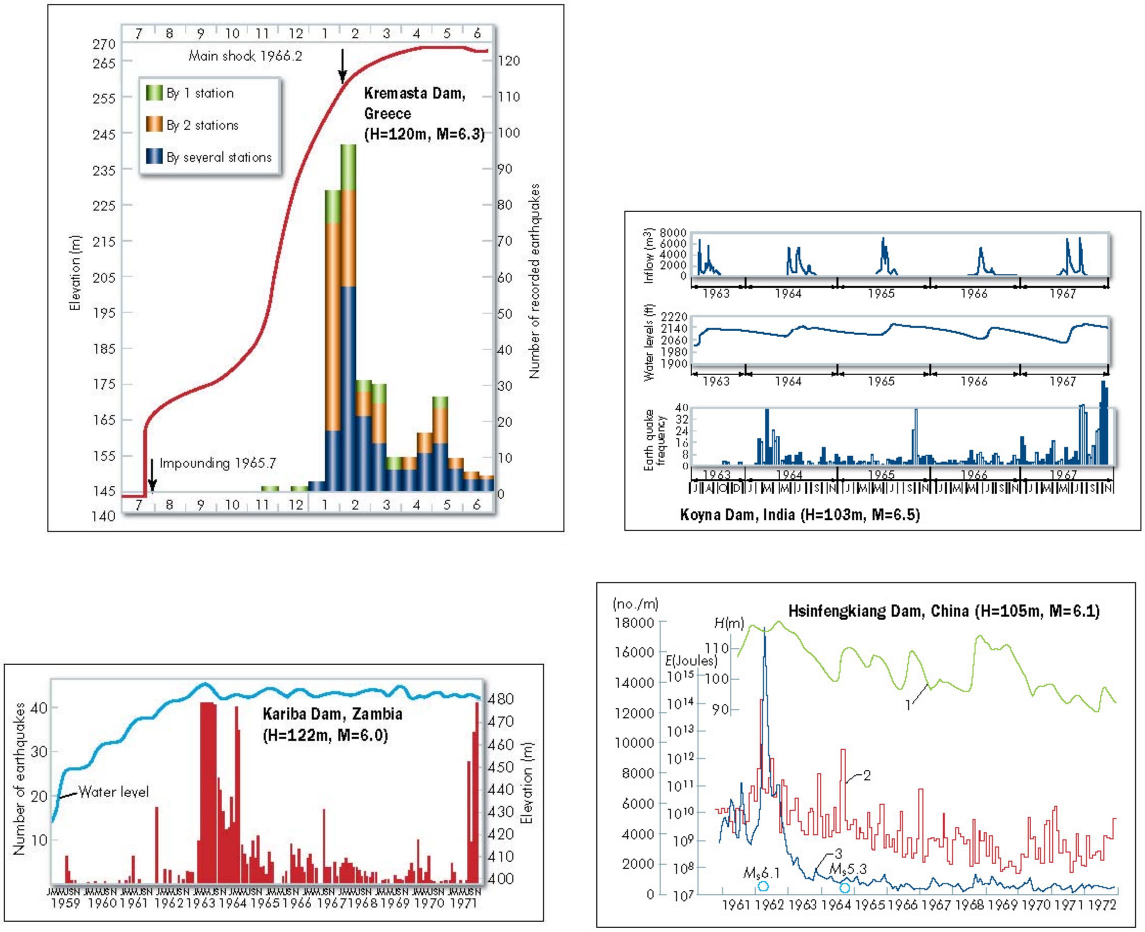
BRIEFING MEMO ON RESERVOIR TRIGGERED SEISMICITY (RTS)

1. General.

The issue of reservoir-triggered seismicity (RTS) has been controversial, and hotly debated, for many decades. There has been general recognition by the dam engineering community of an association between the impoundment of large reservoirs and seismicity since 1935, when it was observed that the filling of Lake Mead behind Hoover Dam was related to several small earthquakes in the surrounding area - the first documented case of RTS. Subsequent observations of apparent relationships between the occurrence of earthquakes and reservoir impoundments at different locations around the world precipitated increasing interest and research into the issue. However, although the engineering community acknowledges that RTS is a real phenomenon, much controversy surrounds various theories of causal mechanisms and likelihood of occurrence.

As of this time, reservoir-triggered seismicity is described as earthquake events that are triggered by the filling of a reservoir, or by water-level changes or fluctuations during operation of the reservoir. It is believed that RTS primarily represents the release of pre-existing tectonic strain, with the reservoir being only a perturbing influence (Yeats et al, 1997; USCOLD, 1997; ICOLD, 2008). Thus, the reservoir does not cause or induce the seismicity, it merely triggers the release of the accumulated, naturally occurring tectonic strain that already existed. In this regard, the term "triggered seismicity" is currently preferred over "induced seismicity" (the former terminology used until about the late 1980's). RTS events occur only as a result of the incremental effects of reservoir load and the build-up of pore water pressure to make them happen.

Throughout the world, several thousand dams have been constructed and are safely impounding reservoirs which are operating without any observed RTS. Compared to the substantial number of operating large reservoirs, there are only a very few instances of possible RTS cases. Out of some 11,000 worldwide "large" dams, only a small number have triggered known seismic activity (USCOLD, 1997). Packer and others (1977) list 45 "accepted" and 12 "questionable" cases of reservoir-induced seismicity.



The relation of reservoir earthquake activity and reservoir water level for the four strong tectonic reservoir earthquake cases: Kremasta, Kariba, Hsinfengkiang and Koyna.

At those reservoirs where RTS has been suspected, the maximum reported earthquake magnitudes for RTS events are primarily much less than M 6.0, and typically in the micro earthquake, or small macro earthquake range (i.e., < M 4.0). These are nearly all below the range felt by humans and are only detectable by special sensitive instruments.

The most significant aspect of the RTS record is the fact that of the verified RTS cases large enough to be potentially damaging, only 4 events have exceeded magnitude 6 and only 13 events were in the range M 5.0 to M 5.9 (USCOLD, 1997; Yeats et al, 1997). The largest reported RTS earthquake was the 1967, magnitude M 6.5, Koyna, India event. The other three events were: Hsinfengkiang (China, 1962) M=6.1; Kariba (Zambia, 1963) m=6.0; and Kremasta (Greece, 1966) M=6.3. The figures show time histories of seismicity and reservoir water level for these projects.

2. Causes of RTS.

Research into the causes of RTS, based on its nature, pattern, and geophysical and geomechanical characteristics - as well as statistical and empirical evaluations of the occurrence of RTS - have resulted in the identification of several physical, tectonic, and geologic characteristics that appear to be common to observed RTS cases, and contribute to the incidence of RTS (USCOLD, 1997). These characteristics include:

Reservoir Parameters. The filling history and the rate of filling appear to be important regarding the potential for, and triggering of, RTS. RTS appears to be more likely where a reservoir is filled rapidly. The maximum water depths, and the maximum reservoir volume, appear to be the most significant factors in the generation of RTS. RTS is more likely at deep reservoirs (i.e., greater than about 325 ft), than at shallower reservoirs, and it is more likely where the reservoir volume is greater than about 1.0E10 cubic meters. ICOLD guidelines recommend that RTS potential needs to be considered at the outset for large dams over 325ft in height.

Geologic and Hydro Geologic Parameters. RTS appears to be more probable where reservoirs are underlain by sedimentary rock sequences compared to metamorphic and igneous bedrock. In addition, more permeable lithologies appear to be more susceptible to RTS possibly because they may allow more effective pore-water pressure increases at depth.

Tectonic Parameters. The presence of pre-existing active tectonics is important. Most, if not all reported cases of RTS with earthquakes greater than magnitude M 5.0 had pre-existing active faults in the area of influence of the reservoir. In addition, areas with active extensional (e.g., normal-slip faults) or shear (e.g., strike-slip faults) stress/tectonics are more likely to have RTS than areas with active compressional (e.g., reverse-slip faults) stress/tectonics. RTS is not likely to occur in areas lacking active tectonics, and it is not likely to re-activate, faults that are inactive in their current tectonic regimes.

The temporal distribution of RTS following impoundment of the reservoir has shown two types of response. At some reservoirs, seismicity has begun almost immediately on first filling, while at others, increases in seismicity are not observed until several seasonal filling cycles have passed. These differences in response are postulated to correspond to two fundamental mechanisms by which a reservoir may influence the earth's crust. In the first case, that of rapid response, the reservoir water load is directly transmitted by the crustal material as it responds to increased loading. This additional load affects the tectonic stress regime causing triggering of earthquakes on existing seismogenic faults. In the second case - that of delayed response - the filling of the reservoir probably increases the pore pressure, which is slowly transmitted to the underlying crust. Transmission of pore pressure is a diffusion process controlled by the joints within the rock. Depending upon the continuity of the joints and their degree of openness, transmission of pore pressure may take some time. Although the pore pressure is uniform in all directions, it reduces the strength of the crustal material and so may also trigger earthquakes on seismogenic sources.

The current consensus in the engineering community is that impoundment of a reservoir can cause triggering of seismic activity only if favorable pre-existing tectonic conditions have already developed and that the seismogenic fault that could produce the energy release is already near to failure. Another contributory factor is how the reservoir is operated. Rapid fluctuations in reservoir level are known to increase the occurrence of event triggering. In addition, the seismogenic source of the RTS has to be in the vicinity of the impoundment so that the influence of the reservoir can be transmitted either by direct loading or by pore pressure increase.

Evaluation of the potential for RTS at Watana and computation of the resulting ground motions is included in the approach and methodology for determination of the earthquake design parameters that will be derived for design of the dam and other project features.

3. Earthquake Resistant Design and Monitoring.

The Watana dam will be designed correctly - in accordance with current ICOLD and other internationally accepted practices - for the seismic hazards pertaining to the site, and will be able to withstand the maximum RTS event. Further, the largest RTS event will not exceed the maximum design earthquake for which the dam will be designed anyway. Therefore RTS is not a direct safety issue.

For projects where RTS is considered a possibility (e.g. large and/or deep reservoirs, location in an active tectonic environment), it is good practice to provide adequate monitoring prior to, during, and after impoundment. This will help distinguish naturally occurring events (background seismicity) from those that could be attributed to the filling and operation of the reservoir.

4. Evaluation of the Probability of RTS.

As described, the attributes that are considered in evaluating the probability of RTS include: reservoir depth, reservoir volume, the tectonic stress state, and the rock type underlying the reservoir. The probabilities that are considered are conditional and represent the total chance for RTS to occur as a result of reservoir filling and operation. Conditional probabilities are developed for each single attribute, as well as for all the attributes combined. For the multi-attribute analysis, they are considered independently, and also in a discrete-dependent model that focuses on the reservoir depth and volume attributes.

The Watana Dam Project reservoir has characteristics that make it somewhat susceptible to RTS:

- Its maximum reservoir depth is significant at 700+ ft (215 meters), although its total volume is relatively small at 4.3 million acre feet (5 billion cubic meters),
- It is within an active tectonic region.

The mean probability of RTS was previously estimated as 37% and 46% depending on the model used. As part of the investigation undertaken in future studies for this project, the probability of RTS will be estimated based upon the work performed for previous studies and updating with current research.

However, if RTS were to occur at the Watana Project, it would be on an active fault. Earthquake sources, magnitude and associated distance, which are under consideration for the seismic design of the dam are listed below.

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Source	Distance miles	Magnitude (M)
Denali Fault	45	7.9
Susitna Glacier Fault	40	7.2
Castle Mountain Fault	60	7.1
Mega thrust Zone	90	9.2
Wadati-Benioff Zone	30	7.5
Susitna Seismic Zone	25	7.4
Random Unknown Local Fault		6.2

The reservoir is anticipated to be 39 miles long (63 km) by two miles wide (3 km). The Denali Fault lies to the north and the Castle Mountain Fault to the south. The Wadati-Benioff Zone lies approximately 50 km below the site based upon the focal depth of recent earthquakes, and the megathrust zone lies to the south. With the exception of the “unknown” local faults, the earthquake sources do not lie within the zone potentially influenced by reservoir filling. Thus RTS can be precluded from occurring on the more distant larger faults, both by their being outside the zone of influence and by the observation that the largest earthquake associated with RTS is the Koyna 1967 M 6.5 earthquake.

This would be verified by further investigation. A thorough examination of remote sensing data (including photographs, geophysical surveys, LIDAR) and fieldwork should be performed to exclude the possibility of faults capable of generating strong or major earthquakes close to the site. The upcoming investigation will therefore verify that possible RTS earthquakes are encompassed by the dam seismic design parameters.

The increased frequency of moderate to strong earthquakes due to RTS will be incorporated into the probabilistic hazard assessment by assigning the RTS activity to the local earthquakes sources and including in the computation. The deterministic analysis will (by definition) incorporate the RTS effects as the earthquake magnitudes are based upon the physical capacity of the individual sources to generate earthquakes.

5. Conclusion.

RTS will be considered in the derivation of the seismic design parameters for all project features – including the Watana dam – and given the tectonic scenario at, and surrounding, the Watana site, will not be the governing seismic criteria. This is consistent with design practice worldwide.