# EARTHQUAKES AND DAMS IN AUSTRALIA

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Gary wrote his first earthquake location computer program in 1971, and has been trying to learn more about earthquakes since then. He is particularly interested in earthquake hazard analysis, seismic instrumentation and the relationship between earthquakes and dams.

## SUMMARY

Large new reservoirs can trigger earthquakes. This is due to either a change in stress because of the weight of water, or more commonly due to weakening of fractures and faults under the reservoir by increased water pore pressure. The energy released in a reservoir induced earthquake is normal tectonic strain energy, released prematurely. Study of induced earthquakes provides useful insight into the mechanism of earthquakes in general, because of the effects of pore pressure and because they are likely to be well recorded.

Several Australian reservoirs have experienced reservoir induced seismicity (Talbingo, Thomson and Pindari), and there are several cases of probable induced seismicity (Eucumbene, Warragamba, Gordon and Argyle). The proportion of reservoirs which experience induced seismicity in Australia is much higher than the world average.

## KEYWORDS

reservoir induced seismicity, earthquake cycle

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## 1. EARTHQUAKES AND THE EARTHQUAKE CYCLE

An earthquake is the motion produced when stress within the earth builds up over a long period until it exceeds the strength of the rock, which then fails by breaking along a fault. Earthquake motion includes both transient vibrations and permanent rupture displacement.

The stress is associated with strain, or deformation, and it is convenient to think of the earthquake in terms of strain energy. It may take tens or thousands of years for the elastic strain energy to accumulate, and most of this energy may be released in seconds.

The earthquake cycle at a location may be considered in the following phases:

- quiescence, a period of build up of strain energy that may take tens of years in tectonically active regions, or very much longer in areas of low tectonic movement.
- precursory activity, with increasing seismicity in the highly stressed rocks, perhaps over a period of months or years. These events are sometimes called pre-shocks.
- foreshocks may occur minutes, hours or days before the major energy release.
- a main shock is the largest event in the cycle. In some cases almost all energy is released in a single main shock, or there may be multiple large shocks, or the energy may be released in a swarm of small events.
- aftershocks occur during the days following the main shock in numbers varying from few to many. The difference in magnitude between the mainshock and the largest aftershock can vary widely.
- adjustment activity occurs within the area for years after the main shock. This may occur at increasing distances from the main shock, and decreasing rates with time. It decays much slower than the aftershock activity.
- the next quiescence begins, lasting much longer than the total of the other periods.

The magnitude of an earthquake depends primarily on the volume of rock that is under stress, or on the area of fault plane that ruptures in the earthquake. The area of rupture in an earthquake of magnitude 4 is about 1 $km^2$ (1 x 1 km), magnitude 5 is 10 $km^2$ (3 x 3 km), magnitude 6 is 100 $km^2$ (10 x 10 km) and so on. The size of the stress volume or fault rupture area considered in a seismic cycle is not clearly defined, and for a particular point must be considered on a range of scales. The granularity of the volume must account for the observed variation in earthquake magnitudes.

The earthquake activity at a particular location is complicated by the surrounding area. The stress will be affected by surrounding earthquake activity. The average period for the earthquake cycle at particular locations will vary depending on local geological conditions. The effect of activity in the surrounding area will introduce considerable scatter into the actual interval between main shocks, so the earthquake cycle will not display periodicity. If adjacent areas approach high stress together, a single large main shock may result.

Reservoirs may induce, or trigger, seismicity by two mechanisms. Either the weight of the water may change the stress field under the reservoir, or the increased ground water pore pressure may decrease the stress required to cause an earthquake. In either case, **reservoir induced seismicity** (RIS) will only occur if the area under the reservoir is in the precursory activity phase of the cycle, or perhaps late in the quiescence phase. If the stress has been relieved by a recent large earthquake, say in the last few hundred years for low seismicity areas like Australia, then RIS is unlikely to occur.

## 2. STRESS DIRECTION AND WATER WEIGHT

Tectonic stress is considered in three orthogonal principal stress directions, ranked as maximum, middle and minimum. These may be oriented in any direction, but geological processes and the free surface of the earth often constrain one or other to be near vertical.

It is the difference between maximum and minimum principal stress that causes an earthquake. The fault plane will usually be at right angles to the plane containing the maximum and minimum principal stresses, and at an angle less than 45° (often 30° to 35°) to the maximum principal stress, depending on friction properties of the fault material.

If the minimum principal stress is vertical then horizontal compression gives reverse faulting. If the middle principal stress is vertical then, with both minimum and maximum stresses horizontal, strike slip faulting results. If the maximum principal stress is vertical, the resulting normal fault motion is equivalent to that from horizontal tension.

The effect of the weight of water on the stress field about the reservoir is quite complex. There will be compression under the reservoir with an increase in the vertical principal stress. The magnitude and direction of the change in stress in the area around the reservoir can be estimated using finite element methods or other techniques. The changes decrease rapidly with distance from the reservoir.

For reverse faulting the stress change increases the minimum principal stress under the reservoir, reduces the difference between maximum and minimum, and will tend to repress an imminent earthquake. This has been called reservoir induced aseismicity. In some cases earthquakes could then be induced by later releasing water from the reservoir.

For strike-slip faulting, the weight of the water will primarily affect the middle principal stress, so should neither repress nor trigger activity.

For normal faulting the weight of water will increase the vertical maximum principal stress, the difference between maximum and minimum may exceed the strength of the rocks, and a reservoir induced earthquake may be triggered.

It was originally thought that RIS occurs with normal faulting or strike-slip faulting, but rarely with reverse faulting. This is contrary to Australian experience, where the clear cases of RIS (Talbingo, Thomson and Pindari) and all cases of suspected RIS (Eucumbene, Warragamba, Gordon, and Argyle) are in areas where reverse faulting dominates.

## 3. GROUND WATER PORE PRESSURE

Ground water plays a large part in earthquake activity. Fluid injection into wells in USA, Japan and elsewhere has triggered earthquakes. Water pore pressure reduces the normal stress within a rock while not changing the shear stress. Increased pore pressure is due to:

1. the decrease in pore volume caused by compaction under the weight of a reservoir.
2. diffusion of reservoir water through porous rock under the reservoir. The rate of flow depends on the permeability of the rock, so this effect is not instantaneous but takes increasing time with distance from the reservoir. It may take years for the pore pressure to increase at depths of kilometres beneath a reservoir.

These occur under any reservoir, whether there is reverse, strike-slip or normal faulting. The first occurs near instantly, while the second is delayed depending on permeability. Any increase in water pore pressure means that a failure is more likely. The critical value of the shearing stress may be made arbitrarily low by increasing the pore pressure. It is now believed that for RIS, increased pore pressure is more important than stress changes.

## 4. CHARACTERISTICS OF RESERVOIR INDUCED EARTHQUAKES

If there is a **major fault** near the reservoir, RIS can produce earthquakes exceeding magnitude 6.0 (Xinfengjiang, China, 1962, M 6.1; Koyna, India, 1967, M 6.3). Several reservoirs have triggered earthquakes exceeding magnitude 5.0 (Eucumbene, 1959, M 5.0; Warragamba, 1973, M 5.4; Thomson, 1996, M 5.0). A larger magnitude RIS event only occurs if there is an existing nearby fault of sufficient dimension that is late in its earthquake cycle (the stress is already approaching the strength of the fault).

A **series of small shallow earthquakes** is a more common form of RIS (Talbingo, 1973 to 1975; Thomson, 1986 to 1995). These events possibly occur on joints rather than established faults, so are limited in size, with magnitudes up to ML 3 or 4. There is little or no hazard from such small earthquakes, even if they occur in large numbers. They are much smaller than the maximum credible magnitude for normal tectonic earthquakes, which may vary from 6.0 to over 8.0 depending on the local geological situation. It seems that RIS with many small events is more likely in areas with near-surface jointed crystalline rocks like granite, rather than sedimentary rocks.

RIS has been observed for over 100 reservoirs throughout the world, and small shallow induced events have probably occurred under many others. With limited knowledge of background seismicity, in space or in time, it can be very difficult to determine whether earthquakes near a reservoir have been induced. A high proportion of reservoirs with RIS seismograph networks record such activity.

A high proportion of RIS occurs in low-seismicity intraplate areas, especially regions that are close to an active plate boundary. Above average rates of RIS are found in China, Australia, Africa, Brazil and India.

The **onset** of RIS may be **immediate** after filling **or delayed** a few years, depending on whether it is due to stress or pore pressure. Any delay depends on the permeability of the rock. All large or moderate magnitude induced earthquakes have occurred within ten years of the first filling of the reservoir. Aswan Reservoir began filling in 1964, filled in 1975, and experienced a relatively deep induced earthquake in 1981. It is unlikely that reservoir induced seismicity will start beyond twenty years after first filling.

RIS activity usually **decays** within a few years of first occurrence. As years pass after first filling, pore pressure increases permeate to greater depths and distances, and the events may occur further from the reservoir.

In most cases RIS is a **transient** phenomenon which will cease once the stress and pore pressure fields have stabilised at new values. Earthquake hazard will then revert to similar levels that would have existed if the reservoir had not been filled. The Koyna earthquakes in India have continued for over 30 years. Even for those reservoirs showing a correlation between earthquakes and water level, RIS probably does not continue indefinitely.

The **depth** of RIS events, especially those occurring immediately after filling, is usually very shallow under or near the reservoir, within a few kilometres of the surface. Their shallow depth means that they may often be felt or heard. Induced earthquakes at reservoirs experiencing delayed triggering may be deeper, perhaps ten to fifteen km. These may occur from ten to twenty years after filling of the reservoir. Examples include Aswan in Egypt, Thomson in Victoria and possibly Warragamba in NSW. These suggest a diffusion rate of something like one kilometre per year.

It is not easy to **predict** whether a future reservoir will experience RIS, because the state of stress and the rock strength at earthquake depths are not easily measured. For the same reason, prediction of normal non-RIS earthquakes has usually been unsuccessful.

## 5. RESERVOIR INDUCED SEISMICITY IN AUSTRALIA

**Eucumbene Reservoir** began filling in 1958, with a capacity of 4.8 $km^3$ and height of 116 m. An earthquake of magnitude **ML 5.0** occurred about 10 kilometres south of the dam on 1959 May 18. Over 270 events occurred between Eucumbene Reservoir and Jindabyne Reservoir over the next 40 years.

**Warragamba Dam** was completed in 1960, with a capacity of 2.06 $km^3$ and height of 137 m. The dam is about 3 km west of the Lapstone Fault outcrop, and the reservoir extends to about 30 km further west. This is probably a reverse fault, dipping to the west under the reservoir at about 35°. On 1973 March 9, an earthquake of magnitude **ML 5.5** occurred at the south end of the reservoir, about 18 km west of the Lapstone Fault at a poorly constrained depth possibly about 12 km. It was followed by over 300 aftershocks.

**Talbingo Dam** was completed in 1971 with a capacity of 0.92 $km^3$ and depth of 162 m. Over 200 small shallow events occurred under the reservoir over the next four years, the largest of magnitude **ML 3.5** in 1973. Many of these were felt or heard in the town. This is regarded as a classic example of a swarm of shallow induced earthquakes.

**Lake Argyle** in the north of Western Australia was completed in 1971. It has a capacity of 5.72 $km^3$ and a depth of 99 m. To 1984, about 30 events occurred under or near the reservoir from about ML 2.0 to **ML 3.5**, well above the activity of the surrounding area. Seismograph coverage is poor, both before and since impounding. A seismograph installed nearby from 1995 to 1996 recorded several small events under the reservoir.

**Lake Gordon** in Tasmania began filling in 1972. This reservoir and Lake Pedder are connected by a short canal, and have a total capacity of 13.5 $km^3$ with a maximum depth of 140 m at Gordon Dam. A three to four-fold increase in earthquake activity under the two lakes was detected from July 1974. The increased level of activity ended about 1984 after some 120 events, the largest being only of magnitude **ML 2.5**.

**Thomson Reservoir** began filling in July 1983, with a capacity of 1.1 $km^3$ and depth of 166 m. It is about 25 km northwest of the outcrop of the Yallourn Fault. A swarm of very small events occurred at a depth of 11 km under the reservoir in November 1983. There was no significant activity until February 1986, when a series of events began under the reservoir at depths to about 3 km. For the next couple of years there were about 2 to 5 events per week up to ML 2.5. Activity from 1988 to 1996 spread away from the reservoir, north, south and deeper, with maximum magnitude of ML 3.1, and at a decreasing rate. An earthquake of **ML 5.0** occurred on the Yallourn Fault on 1996 September 25, with epicentre about 2 km from the dam, at a depth of 11 km, and at the nearest slant distance from the reservoir to the fault.

**Pindari Dam** in northeast NSW was built in 1969, doubled in height to 85 m in 1994, and began to re-fill in early 1995. In March 1995, a swarm of over 30 very shallow earthquakes occurred under the reservoir. The largest was of magnitude **ML 2.3** on March 27, within 3 km of the seismograph at the dam, giving a peak acceleration of 0.09 g. None of these events was reported felt. Further activity occurred in the Pindari area over the next two years.

## 6. CONCLUSIONS

Reservoir induced earthquakes are normal earthquakes that have been triggered prematurely. Their study provides useful insight into the mechanism of earthquakes in general, because of the effects of pore pressure and because they are likely to be well recorded. Relating induced seismicity to the earthquake cycle suggests that the problems of predicting induced events are similar to those for predicting normal earthquakes.