100 days after the Sichuan earthquake (Photo: Li Zheng/IFRC)

A Faultline Runs Through It

EXPOSING THE HIDDEN DANGERS OF DAM-INDUCED EARTHQUAKES

Besides posing a major risk to dams, scientists are increasingly certain that earthquakes can be triggered by the dams themselves. Globally, scientists believe that there are over 100 instances, strewn over six continents, of dam reservoirs inducing earthquakes. The most serious case could be the magnitude-7.9 Sichuan earthquake in China in May 2008, which some experts believe may have been induced by the Zipingpu Dam.

WHAT CAUSES RESERVOIRS TO TRIGGER EARTHQUAKES?

Reservoir-Induced Seismicity, or RIS, is thought to occur in two ways: (1) by the added weight of a reservoir and (2) by the water that seeps into cracks underground or along a fault. In the first case, the filling of a reservoir with millions, even billions, of tons of water can add stress to faults, causing them to rupture. In the second case, water seeps into the rock and changes the fluid pressure in micro-cracks and fissures in the ground under and near a reservoir. The load effect of the first case is immediate, while the pore pressure effect is delayed because it requires the flow of the water through rock. This delay can cause some reservoirs to begin triggering earthquakes years after the first impounding.

While it is well established within the scientific community that large dams can trigger earthquakes, attention to this problem has stagnated since the 1960s and 1970s, when interest in RIS was at its peak. Only with the news coverage in 2009 that linked the filling of the Zipingpu Dam to the devastating Sichuan earthquake in May of the previous year has the topic once more gained public and scientific attention.

Despite years of research on both specific and global RIS cases, the scientific explanation for RIS is still not certain. No single model can explain all the earthquakes that occur across diverse geological settings or predict when and where RIS may occur, especially given the lack of seismological data—or lack of access to the data if it does exist. Seismologists do agree, however, on the following:

- Depth of the water in the reservoir is the most important factor in RIS.
- The volume of the water also plays a significant role in triggering an earthquake. Other factors include the type of local geology and the region's historic seismic stress patterns.
- Reservoirs can increase the frequency of earthquakes in areas with a previously low occurrence of seismic activity.
- An increased rate of activity in RIS cases occurs within 10-15 kilometers of impounded reservoirs.
- The effect of RIS can be rapid (following the initial filling of the reservoir) or delayed (occurring later in the life of the reservoir). Minor cases of RIS can occur immediately during the filling periods.

DEBUNKING COMMON RIS MYTHS

Despite the uncertainties, seismologists already know enough about the impact of reservoirs on underground rocks to produce probabilities of earthquake risk. Many who study RIS also recommend abiding by the precautionary principle rather than risking a major catastrophe. One of the world's top experts on RIS, Leonardo Seeber, a seismologist with Columbia University's Lamont-Doherty Earth Observatory, stated soon after the news coverage of Zipingpu Dam, "My position is that earthquake hazard needs to be put on the table for a comprehensive evaluation and informed public decision. My experience, however, is that it is often minimized or neglected when public support for a project is sought." What follows is a set of common arguments usually made by RIS skeptics, with responses in light of recent scientific research:

No convincing correlation has yet been demonstrated between earthquakes and reservoirs.
In a number of cases, such as Koyna in India (1967) and Xinfengjiang Dam in China (1962), careful RIS studies show a strong cause-and-effect relationship. While most scientists agree that reservoirs cannot in themselves produce enough seismic energy to generate an earthquake, many areas of the earth's crust are already close to the breaking point, and a reservoir could bring forward an earthquake by hundreds or even thousands of years. Despite some resistance in the engineering community to accept the significance of RIS, groups like the International Commission on Large Dams (considered the most important trade organization of dam builders) recommend that RIS should be considered for reservoirs deeper than 100 meters.

If the natural seismicity is low, the danger of RIS is also low.
While historically unstable regions are more likely to experience RIS, previously inactive areas have also experienced RIS. One example is the Killari reservoir in India, which may have triggered the magnitude 6.1 (or M6.1 on the Richter scale) Latur earthquake that leveled 20 villages and killed 10,000 people. It is important to not only pay attention to earthquake-prone regions that lack adequate earthquake preparedness, but also to non-earthquake prone regions, which often lack any sort of earthquake preparedness guidelines.

No dam has yet failed disastrously because of RIS, so the danger is grossly exaggerated.
Both Koyna and Xinfengjiang came close to failure during RIS events, and both would have unleashed large fatal flood waves. However, while dams may (or may not) be built to withstand RIS, the surrounding cities and villages often are not. As the Killari and Sichuan earthquakes have shown, dam-induced tremors may have killed thousands of people even if the dams did not break.

Clarence Allen, a seismologist from the California Institute of Technology, wrote back in 1982, "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." He called for any new dam that would impound water to depths exceeding 80-100 meters to be designed with the assumption that a M6.5 earthquake could occur nearby. Since this statement, many new cases may be proving his prediction true, including the M7.9 Sichuan earthquake.

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THE NEXT BIG ONE

Many of the high dams planned and under construction around the world are in areas of significant RIS risk. For instance, hundreds of new large dams are planned for the Himalayas, one of the most seismically active areas on earth. Other seismic hotspots with major dam-building programs include Iran, Turkey, Mozambique, Patagonia, Mexico, and Central America. In southwest China, despite the strong link between the reservoir activity at Zipingpu Dam and the sub-

Major Dam-Triggered Earthquakes

Kariba Dam on the Zambezi, 2007 (Photo: Rhys Jones)

SICHUAN, CHINA: ZIPINGPU DAM, 2008, M7.9

The Sichuan earthquake in May 2008 killed an estimated 80,000 people, ruptured almost 300 kilometers of fault, and damaged as many as 2,380 dams, including the 156-meter-high Zipingpu Dam. Zipingpu was filled in 2004 to a weight of 315 million metric tons. According to Christian Klose of Columbia University's Lamont-Doherty Earth Observatory, the added weight of the reservoir both weakened the fault and increased the stress tending to rupture the fault. The effect was 25 times that of a year's worth of natural stress loading from plate tectonic motions.

Fan Xiao, a chief engineer with the Sichuan Geology and Mineral Bureau, had warned about Zipingpu's seismic risks since before the dam was completed. After the disaster, he stated, "We cannot rule out the possibility that building the Zipingpu Dam induced the earthquake because the epicenter is so close to the dam." In addition, the greatest danger of triggering an earthquake is when the water level is rapidly falling, which is exactly what had happened at Zipingpu a week before the earthquake. Given the strong link between the dam and the earthquake, Fan says, "The main lesson is that in building these kinds of projects we need to give more consideration to scientific planning and not simply consider the electricity or water or the economic interests."

KOYNA, INDIA: WARNA RESERVOIR, 1967, M6.3

Prior to the Sichuan earthquake, one of the largest and most damaging earthquakes with strong evidence of reservoir triggering was in 1967 in Koynanagar, India. The M6.3 quake killed around 180 people and injured 1,500 more. Following its impoundment in 1962, some 35,000 tremors were recorded in the reservoir area. As at the Zipingpu and Oroville dams, the major burst of seismicity did not occur upon initial filling at Koyna, but several years later following rapid seasonal refilling. The 103-meter dam and its powerhouse were seriously damaged by the quake.

KARIBA, ZIMBABWE/ZAMBIA: KARIBA DAM, 1963, M6.2

The 128-meter-high Kariba Dam is one of Africa's biggest. Operated by the Zambezi River Authority on behalf of Zimbabwe and Zambia, it has from its earliest days been a cause for concern on a number of safety issues, including RIS. The reservoir is located in a seismically active area, at the southern end of the Rift Valley. The total mass of Kariba's reservoir is 180 billion metric tons. The filling in the 1960s of what was then the world's largest reservoir was followed by considerable seismic activity, 20 of the quakes larger than M5 and one that was M6.2 during the year that the reservoir was filled.

OROVILLE, US: OROVILLE DAM, 1975, M5.7

The earthquakes at Oroville Dam may be the best studied RIS sequence in the world. Oroville, the tallest earthen dam in the US, was built on an active fault line in the 1950s. In the 1970s, the area experienced an unusual series of earthquakes, including the biggest one (M5.7) in 1975, which occurred 12 kilometers south of the reservoir. The dam impounds 4,364 cubic kilometers of water, and was built on a fault previously thought inactive. Prior to the earthquake, the reservoir level was drawn down to its lowest level since filling. The US Geological Survey (USGS) subsequently a found strong link between the quakes and the refilling of the reservoir.

Major RIS Cases Worldwide

Region	Name of Dam	Country	Height (m)	Year of Impounding	Year of Largest Quake	Magnitude
Asia/ Pacific	Koyna	India	103	1962	1967	6.3
	Xinfengjiang	China	105	1959	1962	6.1
	Killari	India	75	1991	1993	6.1
	Srinagarind	Thailand	140	1977	1983	5.9
	Charvak	Uzbekistan	148	1971	1977	5.3
	Nurek	Tajikistan	317	1963	1972	4.6
	Karun III	Iran	205	2005	2006	4.3
Africa	Kariba	Zambia/Zimbabwe	128	1958	1963	6.2
	Aswan	Egypt	111	1964	1981	5.6
	Akosombo	Ghana	134	1964	1964	4.7
North America	Oroville	USA	236	1967	1975	5.7
	Hoover	USA	221	1935	1939	5.0
	Manicouagan 3	Canada	108	1975	1975	4.1
South America	Porto Colombia/Volta Grande	Brazil	40/56	1973-74	1974	4.2
	Capivara	Brazil	59	1976	1976	3.7
	Carmo do Cajura	Brazil	22	1954	1972	3.7
Europe	Kremasta	Greece	160	1965	1966	6.2
	Monteynard	France	155	1962	1963	4.9
	Canelles	Spain	150	1960	1962	4.7

sequent earthquake, new dams are continuously being built in seismically active areas to the west and northwest of the quake zone. After the Sichuan quake, 62 experts in geology, water management and environmental protection appealed to the Chinese authorities to temporarily suspend the approval of large dams in geologically unstable areas in southwest China and assess the risks of RIS in this region.

INCREASING KNOWLEDGE AND IMPROVING SAFETY MEASURES

Currently, RIS is a neglected and under-funded field of research. However, in light of the potentially disastrous consequences of RIS, governments must increase their support for research and monitoring stations of dams worldwide. Under the precautionary principle, the onus is on developers to acknowledge that dam construction increases the probability of earthquakes. Prior to any dam construction, developers and governments must conduct open and transparent analyses of the RIS issue, including checking the local history of RIS in other regions with similar geologic environments as the proposed dam site. Earthquake hazard assessments done as part of the dam design process must also include the probability of RIS and recognize that RIS would raise the local earthquake hazard by many times.

Where dams are permitted to proceed, dam builders should monitor seismicity during impoundment, change or possibly reverse filling procedures if RIS starts, and model the changes in pore pressure and mechanics underground to understand why RIS is occurring. Throughout the entire dam-building process, full RIS disclosure must be made to stakeholders so that negotiations can take place on a fully informed basis.

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