DAMS AND EARTHQUAKES

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Introduction

About 2% of dam failures are said to be due to seismic activity (Foster, Fell and Spannagle, 2000). The vast majority of these are small, homogeneous earth dams many of which have been in China, India and Japan. In the following paragraphs comments are offered on the vulnerability of various types of dams to earthquakes.

Rockfill Dams with Clay Cores

Rockfill dams with clay cores have generally performed very well in earthquakes suffering only slight settlement. For example, the 102 m high **Yuvacik** dam in Western Turkey was only 10 km from the epicentre of a Magnitude 7.4 event on the North Anatolian Fault on 17 August 1999. The only permanent effect at the dam was crest settlement of 114 mm. There was no damage at appurtenant structures such as the intake to the gated spillway.

The average settlement suffered in earthquakes by 11 rockfill dams, for which figures are available, was only 195 mm with a maximum of 760 mm at the 156 m high **Zipingpu** concrete faced rockfill dam in China.

As one typically has more than 5 m freeboard at well-engineered large dams the conclusion is that settlement in earthquakes is unlikely to threaten the dam. However, there was a period when some rockfill dams were built without compaction. The 113.5 m high **Tikves** dam in Macedonia, which was built without compaction of the rockfill, has settled by 2.5 m without a nearby earthquake. Further significant settlement might be expected in an earthquake.

Concrete Faced Rockfill Dams

Concrete faced rockfill dams are often seen as particularly suitable for seismic areas. Even if the slab cracks substantial quantities of water can leak through the rockfill without endangering the dam.

The 156 m high **Zipingpu** CFRD in China suffered a foundation acceleration estimated at 0.51 g in the Magnitude 7.9 Wenchuan earthquake of 12 May 2008. The crest acceleration was about 2 g although the high accelerations were in high frequency peaks which may have been caused by falling rocks impacting the dam crest. There was some damage to the joints between the face slabs and some superficial damage to the slabs on the crest of the dam but the dam was not itself seriously threatened. Leakage increased from 10.4 l/s to 18.8 l/s and was turbid for a couple of days. There was 760 mm settlement including that in aftershocks.

The Longmenshan Fault, which was responsible for the earthquake, has the lowest long-term deformation rate compared with other major faults of the Qinghai-Tibetan plateau (Chen Houqun, 2009). With the exception of the M 7.5 Diexi earthquake of 1933, historic earthquakes within the Sichuan Province area have not exceeded Mw 6.5. The upper bound magnitude of the Yinxiu-Beichuan area has now been increased to 8.0.

The intensity of shaking in this case was dependent on the distance from the fault break rather than the epicentral distance. This will often be the case in large earthquakes where there is a long fault break – in this case 270 km long.

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Concrete Gravity Dams
Concrete gravity dams sometimes exhibit horizontal cracking towards the crest on the upstream and downstream faces. The **Platanovryssi** RCC Dam in northern Greece was designed for no cracking in the dam faces in an acceleration of 0.38 g. This was, perhaps, a bit conservative as some cracking is often accepted in an MCE.

The 103 m high **Koyna** Dam in India suffered such horizontal cracking in the Magnitude 6.5 earthquake of 10 December 1967. There are two interesting things about this:

1. Many people believe the earthquake was a case of reservoir triggered seismicity.
2. The cracking did not extend to the central spillway blocks where there was less weight at a high level in the dam.

Some have expressed the opinion that if the earthquake had been of slightly longer duration the dam would have failed. As it was about 180 people were killed by the earthquake.

Arch Dams
Arch dams have behaved well in earthquakes. The Ambiesta arch dam in northern Italy is 59 m high and was only 22 km from the epicentre of the Gemona-Friuli earthquake of 6 May 1976 (Magnitude 6.5). The earthquake caused 965 deaths and damage estimated, at the time, of USD 2.8 billion. A maximum acceleration of 0.33 g was measured at the right abutment.

Neither the Ambiesta dam nor 13 other concrete arch dams in the area suffered damage from the event; this includes the 136 m high Maina di Sauris dam some 43 km from the epicentre.

The 132 m high Shapai RCC arch dam in China suffered bedrock acceleration of about 0.5 g. The reservoir was almost full at the time but there was no damage to the dam.

The 113 m high Pacoima arch dam in California suffered cracking at the left abutment in a Magnitude 6.6 event in 1971.

Concrete Buttress Dams
Buttress dams do not have a particularly good reputation with regard to earthquakes. This is largely because of serious cracking at Sefid Rud dam in Iran and **Hsingfengkiang dam** in China.

Despite the concerns of analysts about out-of-plane vibrations of the monoliths both of these dams seem to have cracked in response to transverse (upstream/downstream) accelerations.

Hsingfengkiang dam is 105 m high and suffered horizontal cracking 16 m below the crest in an event of magnitude 6.1 in 1962. The Sefid Rud buttress dam in Iran is 106 m high and was affected by the earthquake of June 1990 which had a Magnitude of 7.3 to 7.7. It has been estimated that the PGA at the dam would have been about 0.71 g. Major cracks about 10 mm wide developed along horizontal construction joints near to the change of slope on the downstream profile. Unlike at Hsingfengkiang, the level of the cracks varied from monolith to monolith. At monolith 15 there was a 20 mm displacement of the crest of the dam towards the downstream side, with severe leakage through the crack. There was also some relative movement between buttresses.

Earthfill Dams
The first point about earthfill dams is that one must be very concerned about the risk of liquefaction in the dam or foundations.

It is often said that 'no well-built embankment dam has ever failed due to seismic action'. Of course it is all a matter of definition. What is the definition of failure and what is the definition of well built?

In fact a lot of embankment dams have failed as a result of earthquakes.

145 dams failed in Japan in the Nihon-kai-Chubu earthquake in 1983 the definition of failure was:

- Sliding of slope
- Longitudinal crack more than 50 mm wide
- Transverse crack
- Crest settlement more than 300 mm
- Leakage of water

Some of these 'failures' may not have involved a catastrophic release of water although they would probably have required reconstruction of the dam. In this it is worth noting that irrigation reservoirs may only be full for a short time at the start of the irrigation season each year and that 'failure' will often not lead to a catastrophic release of water.

Until March 11, 2011 no people have died from the failure or damage of a large water (rather than tailings) storage dam due to earthquake. However, during the magnitude 9.0 Tohoku earthquake in Japan in 2011 an 18.5 m high embankment dam failed and the flood wave created by the release of the reservoir caused the loss of eight lives 330 earthfill dams were damaged in China in an earthquake in 1976.

There are other dams that could be mentioned including the 245 damaged in the 1991 Gujarat earthquake in India. Damage at some of the dams was quite serious although the earthquake fortunately took place on 25 January when water levels were generally low.

Many of the dams damaged, in China and Japan, were of only modest height.

The reference to well-built dams not failing seems to go back to H. Bolton Seed's 1979 Rankine lecture but it is worth quoting his words in full. What he said was:
'Virtually any well-built dam on a firm foundation can withstand moderate earthquake shaking, say with a peak acceleration of about 0.2 g, with no detrimental effects'.

Many of the dams mentioned above probably suffered accelerations well in excess of 0.2 g but the reference to well-built dams is a bit dangerous. The time to decide whether a dam was well built may be after the earthquake rather than before it.

Well-designed dams with wide filters are generally considered good for earthquakes. Unfortunately the filters tend to be expensive and there is not a lot of published advice on the desirable thickness of filters.

It is worth mentioning that in the 1906 San Francisco earthquake, which had a magnitude of 8.25, there were 33 earth dams within 56 km of the fault and 15 within 8 km. It seems likely that all these dams were subjected to ground motions having peak ground accelerations greater than 0.25 g and that those within 8 km probably experienced accelerations greater than about 0.6 g. Yet none of these old dams suffered any significant damage. In his 1979 Rankine lecture Seed pointed out that the slopes were fairly steep (typically 1:2 to 1:3) and that the dams had generally been compacted by moving livestock or by teams and wagons. He added that they were all constructed of clayey soils on rock or clayey soil foundations. Two dams were built largely of sand but this was apparently not saturated.

The Sharredushk dam in Albania failed after a modest earthquake on 18 March 2009 (M=4.1) when freeboard was reduced from 1.5 or 2.0 metres to only 0.1 m. The contents of the reservoir were not, however, lost.

Finally the Earlsburn Dam in Scotland failed on the evening of 23 October 1839 some 8 hours after an earthquake thought to have had a magnitude of 4.8. The dam was an embankment of peat and earth with a narrow central core of silty clay. The core extended down to rock but most of the dam, which was 6 m high, was only founded on peat.

Liquefaction
Liquefaction is a serious potential problem for dams built on or with low density, saturated sands. The crest of the 40 m high Lower San Fernando Dam settled 8.5 metres in the 1971 earthquake which had a magnitude of 6.6. The dam was built of hydraulic fill, which is particularly vulnerable to liquefaction, because of the low density of the fill.

Fortunately the water level was about 10 m below the crest before the earthquake but only 1.5 m of badly cracked material remained after the event. 80,000 people living downstream of the dam had to be evacuated.

The 8 m high Sheffield dam failed completely in the magnitude 6.3 Santa Barbara event of 29 June 1925. The dam and its foundation were silty sand and some experts have blamed the failure on liquefaction of these materials.

Krasnodar Dam in Russia near to the Black Sea is 11.5 km long and built of hydraulic fill. It holds 2,914 Mm^3 in a reservoir with an area of 413 km^2. A seismic study was carried out by Swiss Experts who recommended improved drainage at a cost of USD 56 m. The cost of failure was estimated at USD 3 billion at the time (about 2000).

Tailings Dams have a particularly bad record with hundreds killed in various events in Chile. The 84 m high Las Mejitas Tailings Dam holds 48 million tonnes of very acidic tailings at the Pueblo Viejo gold mine in the Dominican Republic. It is only 35 km from the Septentrional Fault and the MCE at the site is estimated at 0.5 g. There is said to be a lack of adequate zoning in the dam and further studies were recommended for the dam in 2002. Liquefaction of the tailings, which would be denser than water, seems to be possible.

Reservoir Triggered Seismicity
Reservoir triggered seismicity (RTS) is really a separate subject but needs to be considered when contemplating construction of a reservoir holding hundreds of millions of cubic metres or involving a dam more than about 100 m high. RTS has been blamed on the Hoover Dam, Kariba, Kremasta in Greece, Koyna, Nurek, Hsingfengkiang and Aswan amongst others. The suspected mechanism involves high pressure water from the reservoir lubricating pre-existing fault planes at depth and triggering earthquakes which would otherwise have occurred at a later date.

Dams on Faults
Until a few years ago nobody would have thought of building a dam across an active fault but there are some very tempting sites where active faults run down the valley. The dangers are, of course, obvious as at the Shih Kang weir in Taiwan where the fault moved several metres beneath the barrage in 1999. Many houses were destroyed although this was directly due to the earthquake rather than to the failure of the dam.

The Rudbar Lorestan Dam is in the Zagros mountains in western Iran and is only 1.6 km from the Main Recent Fault system and in particular from the Saravand-Baznavid Fault which is a right lateral strike slip fault trending NW to SE. the Main Recent Fault is thought to have moved about 50 km in the last 3-5 million years implying a horizontal slip rate of 10-17 mm/yr and is the source of frequent earthquakes of M_s 6-7.

The Seylakhore earthquake on 23 January 1909 had a Magnitude of 7.4 and a focal depth of 33 km. The earthquake was on the Dorud fault at a distance of 76.2 km from the dam site. The Dorud fault is a northwest extension of the Main Recent Fault so it was considered necessary to design for an event of at least this magnitude with its epicentre on the Main Recent Fault 1.6 km from the site. This assumption is consistent with a rupture length of about 80 km according to the Novrouzi formula (1986) and also the Ambraseys and Melville formula (1982).

Peak ground accelerations at the dam site calculated using seven different attenuation formulae varied from 0.52 g to 0.7 g with a mean of 0.61 g

One of our biggest worries on this job was what we called Fault F46 at the left abutment. This is quite short and is not a seismogenic fault but there are fears that it might move a few hundred millimetres during an earthquake on the Main Recent Fault. Thermo-luminescence tests suggest that the last movement was 6,000 to 7,000 years ago. Estimates of the greatest possible movement on this fault vary from 10 – 200 mm to 500 mm.

The fault is vertical running upstream/downstream so a joint in the RCC dam was designed to permit some movement. A similar joint was incorporated into the Clyde Dam in New Zealand.

At Rudbar-Lorestan there followed several years of discussion as to whether a rockfill dam might be better able to resist fault movement than an RCC dam. Possibly it would but it would be much more expensive than an RCC dam because it would need spillway tunnels through the abutments whereas spilling water could have been routed over an RCC dam at little extra cost.

Eventually a fill dam was built.

Seiches

Seiches may be caused by resonances of water in a reservoir that has been disturbed by seismic activity. The fundamental period of these reservoir oscillations depends on the size of the reservoir and is usually very long.

A 131 m high dam in Japan settled 30 mm in a magnitude 7 earthquake in 1961. This is one of two dams for which preliminary risk analyses were recently prepared. The probability of failure of the dams as a direct result of an earthquake was considered negligible even though a seismogenic fault passed only 250 m from the right abutment of one of them. However, there was concern about seismic seiches overtopping the dams and about seismically induced landslides into the reservoir causing displacement waves which might overtop the dam.

Estimated annual probabilities for the principal modes of failure were as follows:

Failure Mode	Annual Probability	Return Period (years)
Internal erosion	11.3×10^{-6}	88,496
Overtopping in typhoon	50×10^{-6}	20,000
Seismic seiche	4.3×10^{-6}	232,558
Landslide	9.3×10^{-6}	107,527
M & E spillway gate	13.2×10^{-6}	75,758
TOTAL	88.1×10^{-6}	11,350

Table 1. Preliminary Failure Mode Analysis for dam in Japan.

Some quite sophisticated work on these modes of failure is being done at HR Wallingford but for this particular exercise reliance was placed on the simple formulae of Dr. Sato and the Russian SNIP 11-7-81 to predict the amplitude of possible seismic seiches. There was reasonable agreement between the two formulae which suggested that seismic seiches could overtop the dam if the reservoir was full at the time of the event.

There was a seiche at Yuvacik Reservoir in the 1999 earthquake in Turkey. The amplitude was about 5 m but the reservoir was not full at the time so there was no overtopping. If the reservoir had been full there could have been up to 1.68 m overtopping at the abutments and 0.25 m at the centre of the dam.

The 35 m high Hebgen dam in Montana suffered a seiche in 1959. The reservoir was full at the time. This seiche was caused by fault movements crossing the reservoir rather than by ground shaking.

A few minutes after the first shock, the caretaker had rushed to the dam and, in the moonlight observed the reservoir action from the high ground above the right abutment. The first waves had already overtopped the dam before he arrived. A few minutes later another wave struck the dam with such momentum that water 1 m deep ran uniformly over the crest for 10 minutes. Subsequently the wave receded and seemed to travel to the other end of the reservoir. After 10 minutes it returned and water flowed over the crest for another 10 minute period. This action was repeated and, although the estimates of depths and durations are approximate, there can be no doubt that the water flowed over the dam at least four times. The magnitude of the earthquake was 7.5 to 7.8 with one of the main faults passing within 215 m of the dam.

Landslides

A total of 30 large landslide dams were created by the 2008 Wenchan earthquake. Of these the largest was Tangjiashan which was 124 metres high and had a crest length of more than 300 metres. Its volume was more than 20 Mm^3.

The landslide impounded a 320 Mm^3 reservoir 6 km upstream of a town and 100 km upstream of Mianyang city.

There was no road access after the earthquake so initial information came from satellite photography. Access by helicopter was first obtained eight days after the earthquake. A channel had to be constructed to release the water which was flowing into the reservoir at a maximum rate of 170 m^3/s. It was therefore decided to bring in equipment using a large Russian helicopter with a lifting capacity of 13 tonnes. In this way 24 excavators were lifted in, 13 bulldozers and 8 tipper trucks. The necessary work was done in 10 days.

Appurtenant Structures

Some appurtenant structures are vital to the safe operation of a reservoir after strong earthquakes, e.g. fuel tanks needed to run the standby generators for opening the spillway gates. It is important that safety critical structures at dams and reservoirs are identified and designed accordingly.

Guides

There are two guides which are worth mentioning – the 1991 UK guide published by the Building Research Establishment and ICOLD Bulletin 148 approved in 2010. The latter is a rewrite of the earlier Bulletin 72. The crucial advice is that large dams, where failure would present a great social hazard, should be designed for the MCE or for ‘the earthquake ground motion with a return period of about 10,000 years’. There is much other good advice in the Bulletin.

The UK guide was not universally welcomed when it was first published because of fears that it would lead to very expensive works at many UK dams. Most of our dams have now been checked and only two have had to be strengthened to meet the guidelines. Concrete gravity dams Upper Glendevon and Argal and probably both would have required work anyway for other reasons.

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