ALTER
Alliance for Disaster Risk Reduction

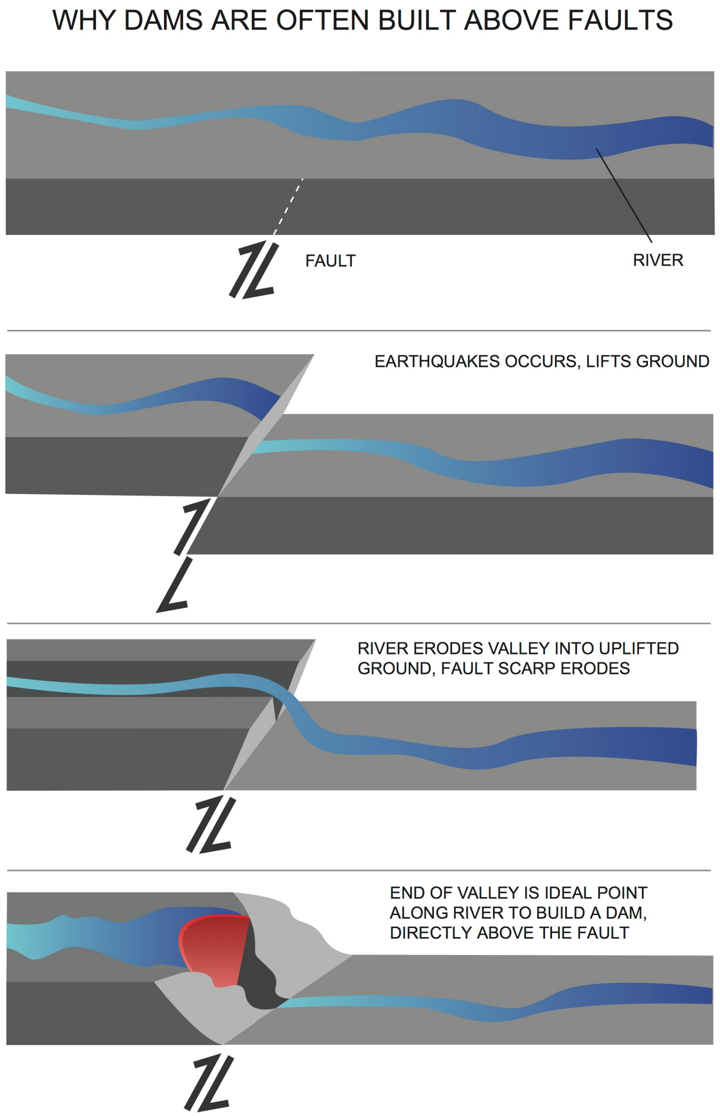
Seismic Monitoring of Large Dams

Dr. Christos Evangelidis

Funded by European Union Civil Protection

Large dams are particularly sensitive to earthquakes.

- Dams are often built in active earthquake areas
- Reservoirs can trigger earthquakes
- Some water supply structures are susceptible to earthquake motion.
- Embankments and outlet towers respond to earthquake vibrations. Shaking an unstable slope that has been weakened after saturation by rises in ground water levels may produce a landslide into the reservoir.



Why are Dams Often Built in Active Earthquake Areas?

- Dams are usually built in valleys
- Valleys exist because active erosion is taking place
- Active erosion implies there has been recent uplift
- Under compressional tectonic force, reverse or thrust faults produce uplift
- Reverse or thrust faults dip under the upthrown block
- Therefore, many dams have an active fault dipping under them
- Large dams are particularly sensitive to earthquakes.

Reservoir Triggered Earthquakes (RTS)

Large new reservoirs can trigger earthquakes. Due to:

- change in stress because of the weight of water
- increased groundwater pore pressure decreasing the effective strength of the rock under the reservoir.

ALTER
Alliance for Disaster Risk Reduction

Reservoir Triggered Earthquakes

For triggered earthquakes to occur, both mechanisms require that the area is already under considerable tectonic stress.

Reservoir triggered earthquakes are often referred to as reservoir induced seismicity (RIS)

The energy released in a reservoir triggered earthquake is normal tectonic strain energy that has been prematurely released because of the reservoir.

Funded by European Union Civil Protection

Water Pore Pressure

Ground water plays a large part in earthquake activity

Water pore pressure reduces the normal stress within a rock while not changing the shear stress. Under any circumstances, an increase in water pore pressure means that a failure is more likely. The critical value of shearing stress may be made arbitrarily low by increasing the pore pressure.

Water Pore Pressure

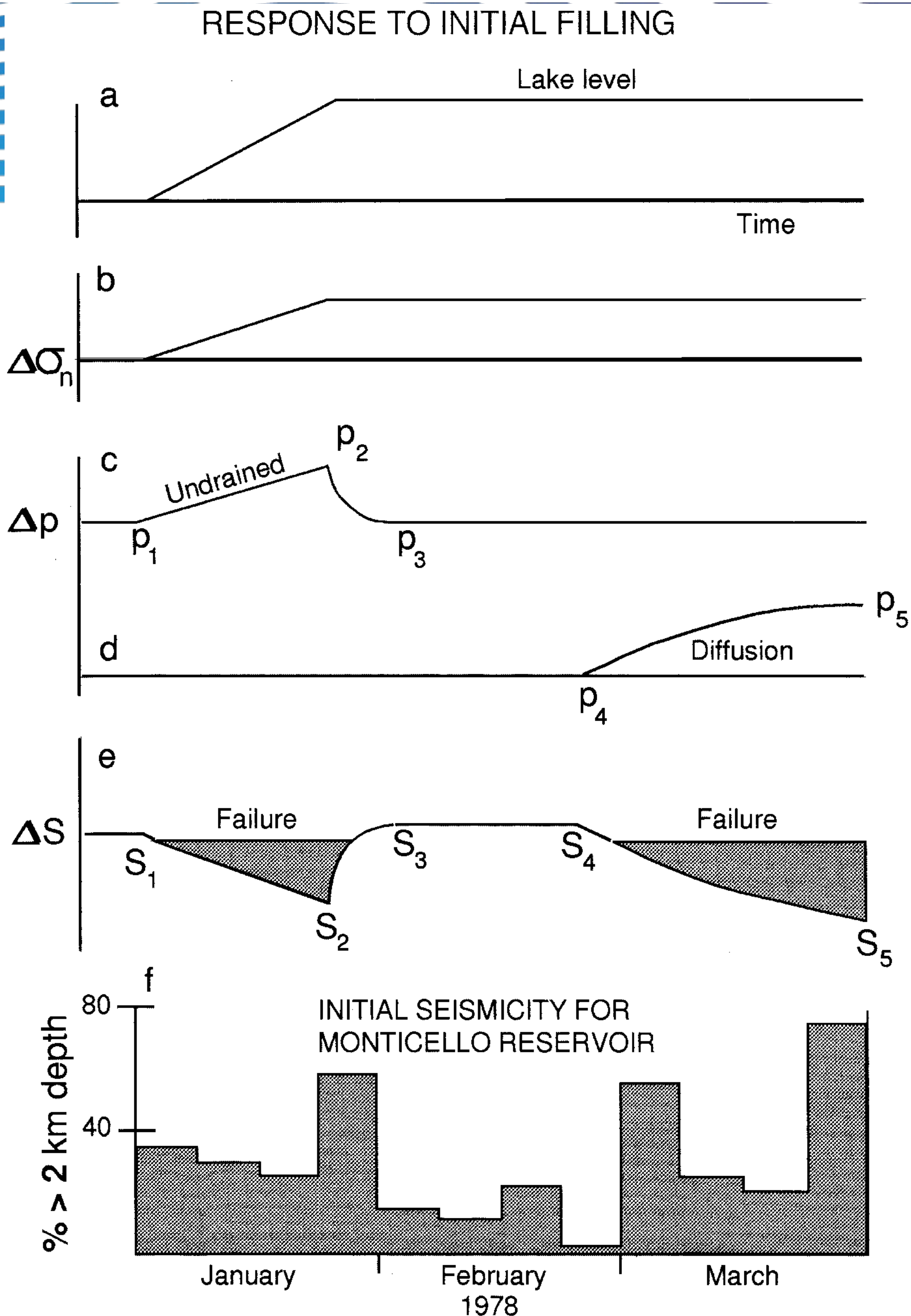
Pore pressure increases in two ways:

1. Decrease in pore volume caused by compaction under the weight of the reservoir. This occurs while the reservoir is being filled.
2. Diffusion of reservoir water through permeable rock under the reservoir. The rate of flow depends on the permeability of the rock, so this effect is not instantaneous. The increase in pore pressure takes more time depending on the distance from the reservoir. It may take years for the pore pressure to increase at depths of kilometres beneath a reservoir.

Alliance for Disaster Risk Reduction

Talwani 1997

(a) shows the filling curve of the reservoir, it is associated with an increase in Dsn (b) due to the load. The undrained response in a clogged pore causes an increase in the pore pressure (p1 to p2) (c) and a corresponding decrease in strength (S1 to S2) (e). When the pore is unclogged, the increased pore pressure dissipates (p2 to p3) and the strength increases (S2 to S3). When the pore pressure front due to reservoir loading arrives, there is an increase in pore pressure (p4 to p5, (d)) and a corresponding decrease in strength (S4 to S5, (e)). When the strength decreases below a critical threshold (marked FAILURE) seismicity occurs (shaded pattern). Panel (f) shows the percentage of ‘‘deep’’ events associated with the initial filling of Monticello Reservoir.

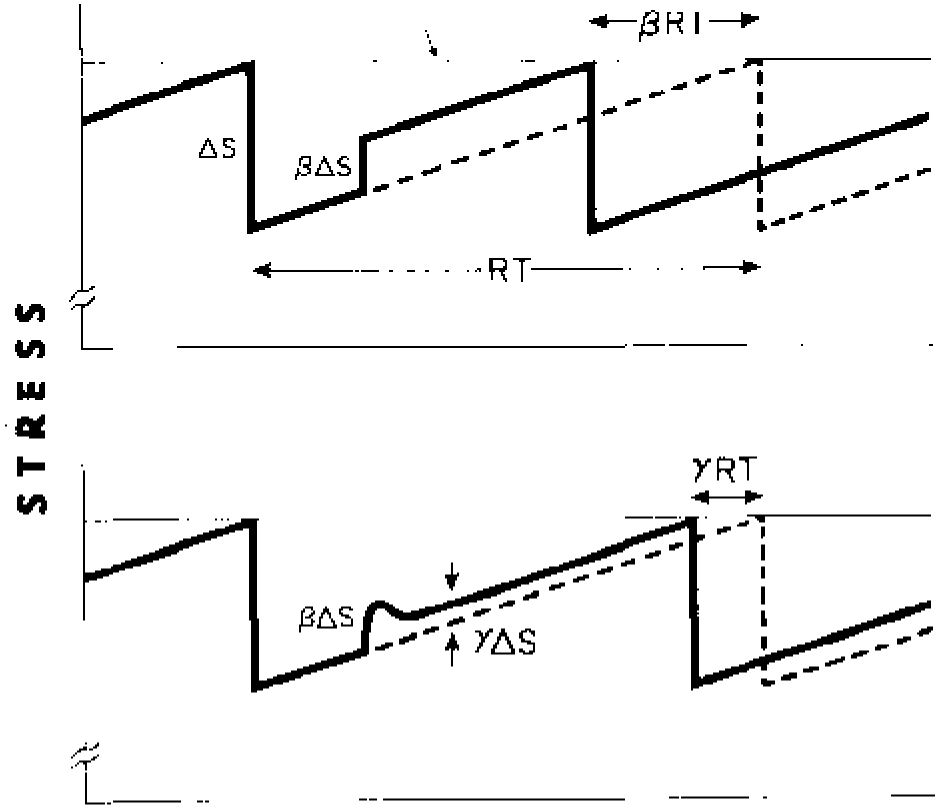


–

STRESS CYCLES AND TRIGGERED EARTHQUAKES

Stress on a fault zone. The normal earthquake cycle is shown as the dashed line. The stress drop (dS) in an earthquake is recovered during an interseismic period with repeat time RT. When the failure level is reached, rupture occurs and the cycle repeats.

If an induced stress change of fJdS occurs, the repeat time is shortened by fJRT. In the lower diagram, the induced stress change includes a transient component. Note that in both cases the induced stress change will trigger rupture if it occurs during the last fJRT yr of the cycle.



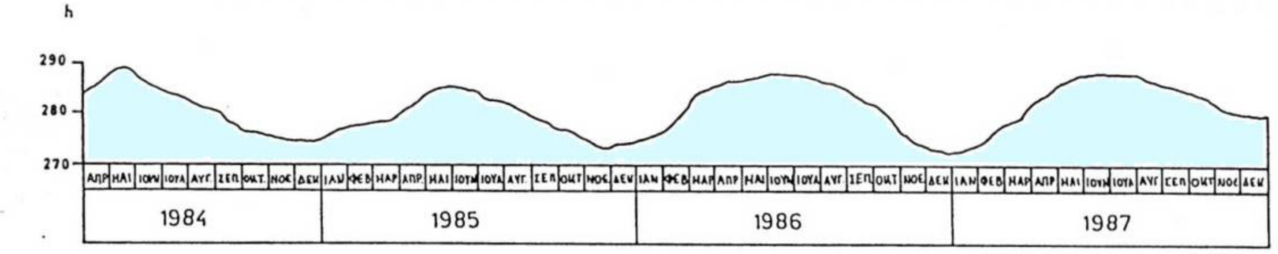
from Simpson 1986

Koyna, India, 1967, M 6.7

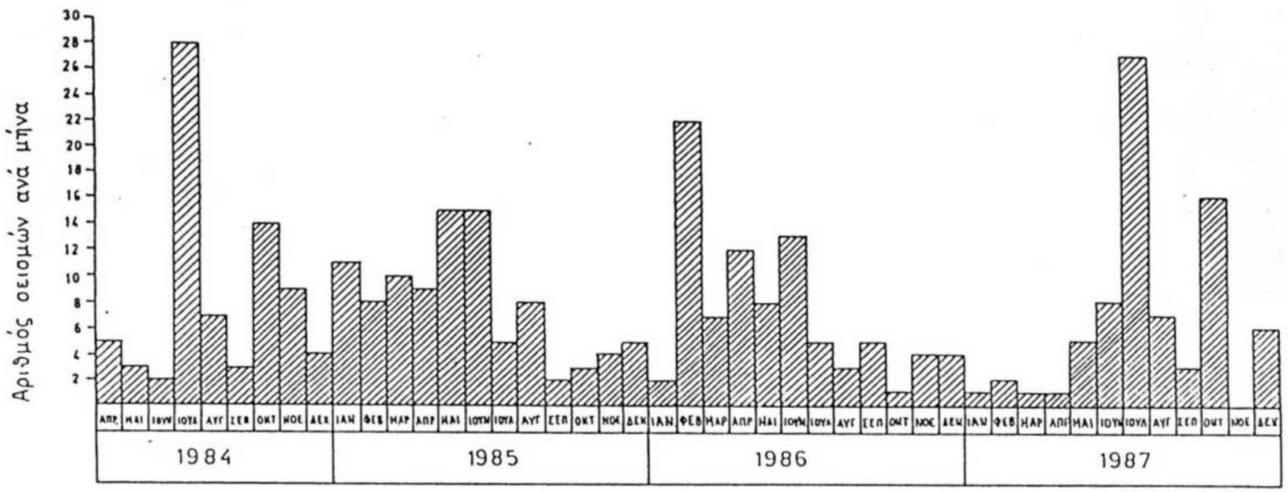
Centered in the vicinity of Koynanagar, about 160 miles southeast of Bombay, this shock killed 177 people, injured over 2,000, and left 50,000 homeless.

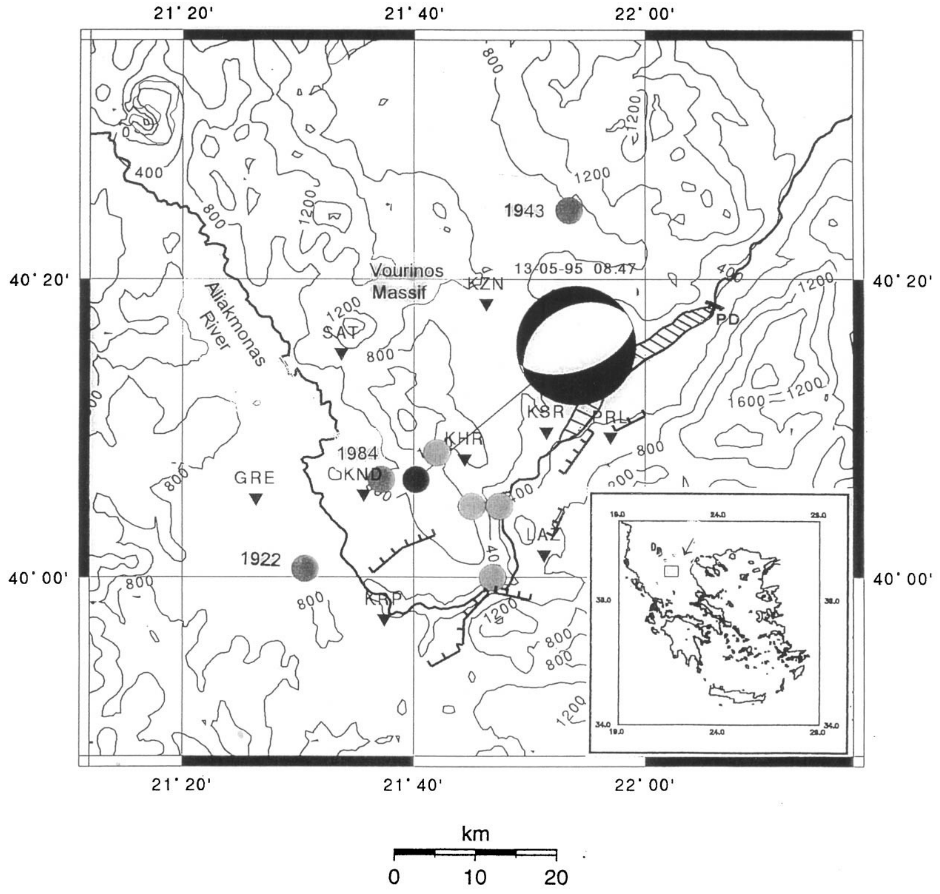
Polyfyto Lake (Greece)

- RIS correlated with water level changes
- Kozani 1995 Ms 6.6 event was NOT triggered from the impoundment of the lake (Drakatos et. al. 1998)



Διακύμανση της στάθμης της λίμνης Πολυφύτου



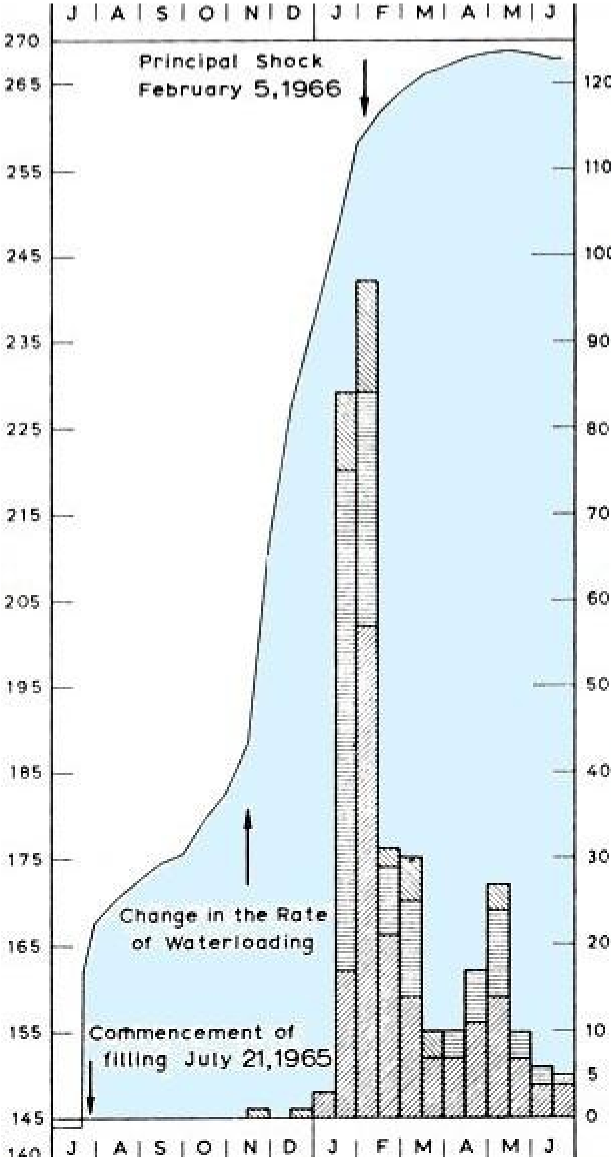


Vajont Dam Megatsunami 1963

50 million cubic metres of water overtopped the dam in a wave 250 metres high, leading to 1,910 deaths and the complete destruction of several villages and towns.

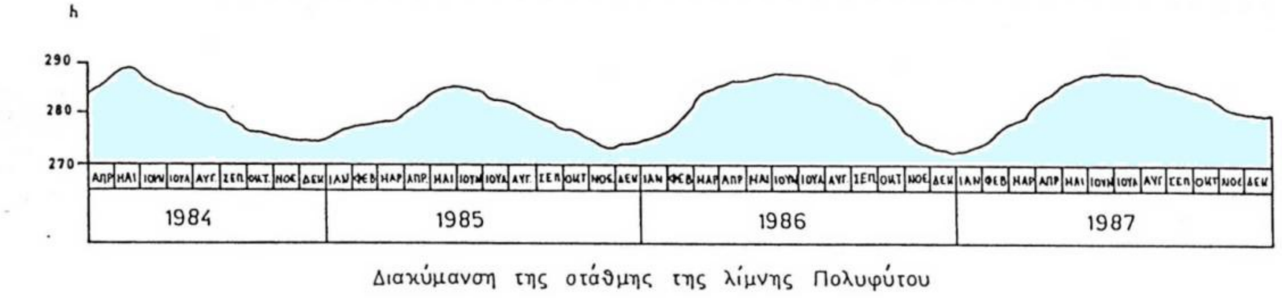
Kremasta Dam 1965-1966

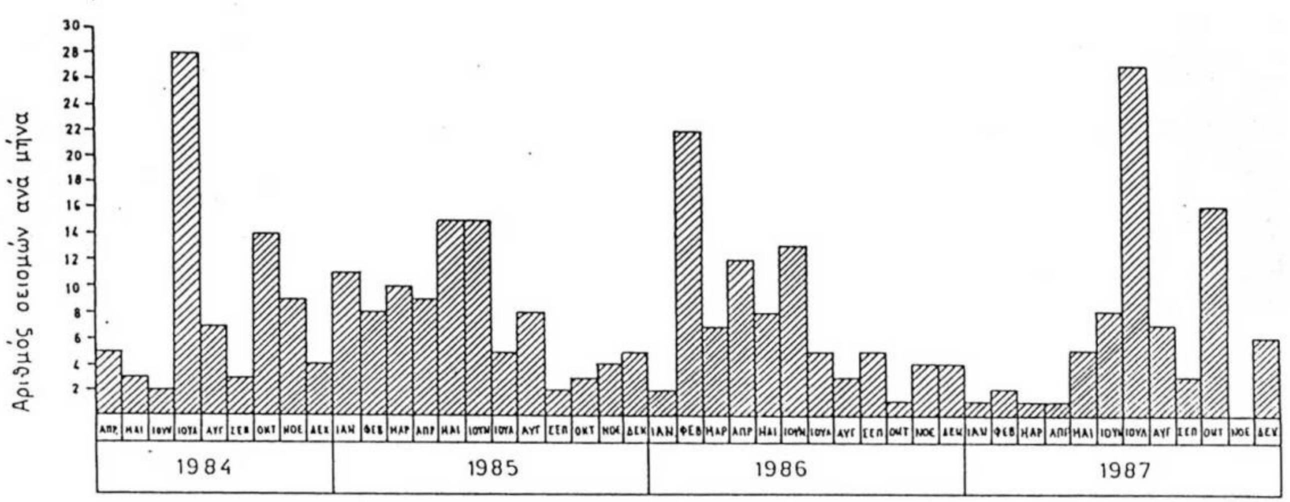
Shortly after the beginning of the impoundment of the Kremasta Dam in 1965, two Ms ≥ 6:0 events and numerous small shocks spread over a 120-km-wide region

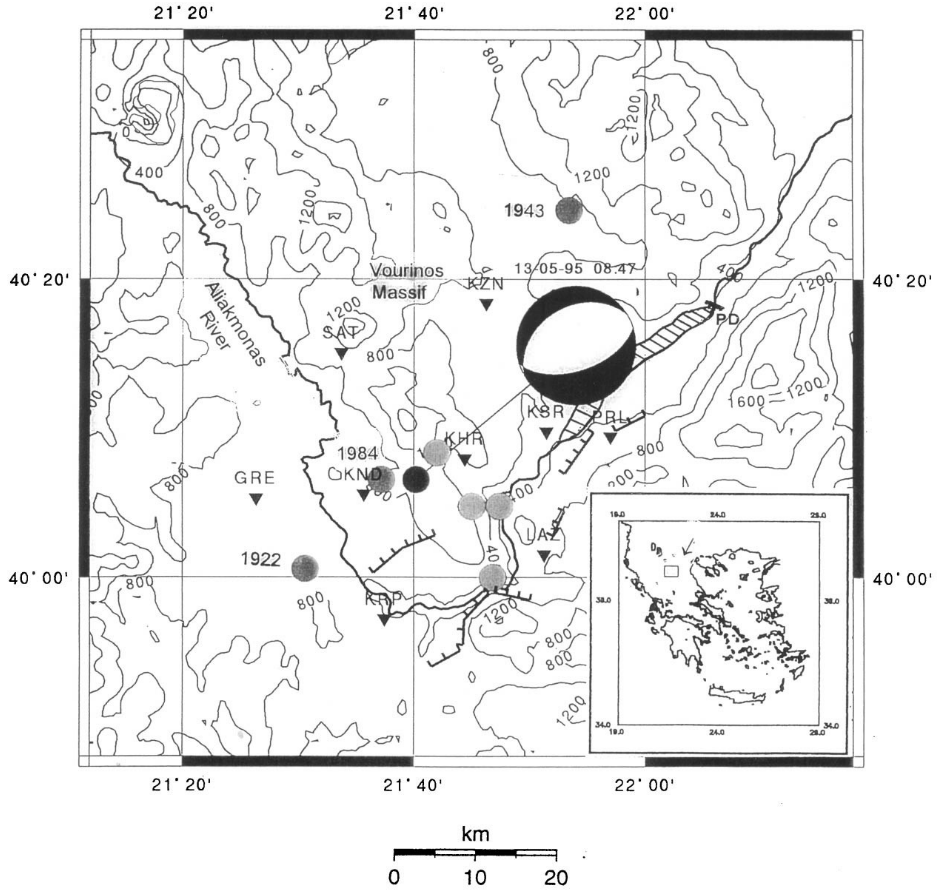


Polyfyto Lake (Greece)

- RIS correlated with water level changes
- Kozani 1995 Ms 6.6 event was NOT triggered from the impoundment of the lake (Drakatos et. al. 1998)







Vajont Dam Megatsunami 1963

50 million cubic metres of water overtopped the dam in a wave 250 metres high, leading to 1,910 deaths and the complete destruction of several villages and towns.

Duration of Reservoir Triggered Seismicity

Reservoir induced seismicity is a phenomenon which will occur either immediately after filling of the reservoir, or after a delay of a few years. If there is a delay, this depends on the permeability of the rock beneath the reservoir.

Once stress and pore pressure fields have stabilised at new values, reservoir induced seismicity will cease. Earthquake hazard will then revert to similar levels that would have existed if the reservoir had not been filled.

Even for those reservoirs that show a correlation between earthquake activity and water level, reservoir induced seismicity does not continue indefinitely as it is limited by the available tectonic energy.

Depth of Reservoir Triggered Seismicity

Depths of reservoir induced earthquakes, especially those occurring immediately after filling of the reservoir, are normally very shallow (1-3 km)

Induced earthquakes at reservoirs that have experienced delayed triggering may be much deeper (up to 10-20 km). These may occur ten to twenty years after filling of the reservoir.

Prediction of Reservoir Triggered Seismicity?

It is not easy to predict whether a new reservoir will experience reservoir induced seismicity, because the two most important factors – the state of stress and the rock strength at earthquake depths – cannot be measured directly.

This is the same reason why prediction of normal (non-induced) earthquakes is normally unsuccessful.

Seismic Instrumentation and Monitoring of Dams

Deploy strong motion accelerometers and associated data acquisition / analysis systems in a dam to detect exceedance of allowed performance criteria as well as identify and verify structural behaviour.

Utilising seismic instrumentation and monitoring systems, timely notifications about any potential problems can be generated and behaviour of the dam can be monitored

Seismic Instrumentation and Monitoring of Dams

Despite the progress in the dynamic analysis of dams, it is still not possible to reliably predict the behaviour of dams during very strong ground shaking due to the difficulty in modelling the inelastic behaviour of dams, the insufficient information on the spatial variation of ground motion and other factors.

The factors that eventually lead to failure as well as their severity and effect on the structure can be measured and monitored with Seismic Instrumentation and Monitoring systems.

ALTER

Alliance for Disaster Risk Reduction

Seismic Instrumentation and Monitoring of Dams

Fundamental features of a dam may be identified such as the damping within the large dam structure, amplification of the ground motion along the path from the foundation or abutments to the crest, wave propagation within the structure, differential motions between abutments, natural frequencies, mode shapes etc

Recommended Dam Seismic Instrumentation

- CREST
- ABUTMENT
- FOUNDATION
- FREE-FIELD