Rapid Changes in Water Level and Reservoir-Induced Seismicity

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“Those Who Refuse to Learn”

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That way, if problems develop with the dam or abutments, or back along the reservoir itself - where rising water sometimes loosens rock and causes landslides, or causes the bedrock to shift under it weight, producing the same result - they can be dealt with.

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Mechanisms for triggered and induced seismicity

- Debate and some consensus concerning:
  - “Diagnostic” criteria
  - Probability of triggered earthquakes and maximum magnitude

- Significance of:
  - Elastic load, pore pressure and coupled response
  - Water level history - “Kaiser effect” (Nurek and Koyna)
  - Rapid and delayed response
  - “Triggered” and “induced” seismicity

**Induced seismicity** - “the causative activity can account for either most of the stress change or most of the energy required to produce the earthquake.”

**Triggered seismicity** - “the causative activity can account for only a small fraction of the stress change or energy associated with the earthquake - in this case, tectonic loading plays the primary role.”

McGarr and Simpson, 1997
Mechanisms for triggered and induced Earthquakes

• Debate and some consensus concerning:
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• Significance of:
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  • Water level history - “Kaiser effect” (Nurek and Koyna)
  • Rapid and delayed response
  • “Triggered” and “induced” seismicity

• Enigmatic issues
  – Why are triggered earthquakes relatively rare in the United States?
  – Why does Koyna continue to trigger earthquakes after 40+ years?
  – Why do most maximum earthquakes occur soon after a maximum in water level?
  – Why are changes in rate of filling important in triggering?
Two types of Reservoir Induced Seismicity

Rapid Response

Delayed Response
Rapid
Coupled response
Diffusion time constant related to internal fault scales

Simpson, Leith and Scholz, 1988

Simpson and Narasimhan, 1990
Rapid
Coupled response
Diffusion time constant related to internal fault scales

Delayed
Diffusion dominant
Diffusion time constant related to distance from reservoir

Simpson, Leith and Scholz, 1988

Simpson and Narasimhan, 1990
Nurek Reservoir, Tadjikistan

Increases in seismicity related to rapid changes in water level and changes in water level gradient

Simpson and Negmatullaev, 1981
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Increases in seismicity related to rapid changes in water level and changes in water level gradient

Filling rate $> 1$ m/day
Annual cycles $> 20$ m
$m_{\text{max}} = 4.6$
$V = 10 \text{ km}^3$

Simpson and Negmatullaev, 1981
Delayed Response

Aswan reservoir, Egypt
Triggered seismicity related to flooding of Nubian sandstone

Simpson, Gharib and Kebeasy, 1990
Delayed Response

Aswan reservoir, Egypt
Triggereed seismicity related to flooding of Nubian sandstone

Filling rate < 0.1 m/day
Annual cycles < 10 m
m_{\text{max}} = 5.6
V = 160 \text{ km}^3

Simpson, Gharib and Kebeasy, 1990
Kariba

Filling rate ~ .05 m/day
Annual cycle < 10 m?

\( m_{\text{max}} = 5.8 \)

\( V = 160 \text{ km}^3 \)

Simpson, Leith and Scholz, 1988
Kariba

Filling rate $\sim 0.05$ m/day
Annual cycle $< 10$ m
$m_{\text{max}} = 5.8$
$V = 160 \text{ km}^3$

Oroville

Filling rate $\sim 0.2$ m/day
Annual cycle $\sim 20$ m

1975
Filling rate $\sim 0.3$ m/day
Annual Cycle $\sim 50$ m
$m_{\text{max}} = 5.7$
$V = 4 \text{ km}^3$

Simpson, Leith and Scholz, 1988
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1975
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Annual Cycle ~ 50 m
\[ m_{\text{max}} = 5.7 \]
\[ V = 4 \text{ km}^3 \]

Koyna
Filling rate ~1.5 m/day
Annual cycle ~ 40 m
\[ m_{\text{max}} = 6.5 \]
\[ V = 3 \text{ km}^3 \]

Simpson, Leith and Scholz, 1988
Simpson, Leith and Scholz, 1988 - Two types of Reservoir Induced Seismicity
Conclusions

Rate of filling of large reservoirs is an important factor in controlling the timing of triggered and induced earthquakes.

Rapid filling can enhance the development of excess pore pressure, weaken faults and lead to triggering.

“At a slow rate of fill, such problems are less likely to develop in the first place” (Reiser, 1986)
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Timing of maximum earthquake following maximum in water level is related to change in rate of filling, rather than absolute water depth.

(Slow and smooth filling can decrease the likelihood of triggering)

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Paucity of triggered earthquakes in the US may result from slower filling – either from engineering practice or climatic controls.

Koyna – with rapid and large amplitude annual loading cycles – may simply represent a continuously refreshed case of large-scale “induced” seismicity.

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Recommendations

Systematic review of filling history at large reservoirs - both seismic and aseismic.
Collect accurate and frequent (daily) water level data in all future reservoir studies.

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