Effects on earth dams of drawdown scenarios imposed after a strong earthquake

Stefania Sica, Federica Rotili
(University of Sannio, Italy)

Luca Pagano
(University of Naples Federico II, Italy)

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Lowering the water level of a reservoir may be critical for the stability of earth dams. In literature, several cases of slope failures caused by rapid drawdown were described (Sherard et al. 1963; Morgenstern 1963, etc.). An iconic case-history is San Luis Dam in California in 1981.

To date the combined effects of an earthquake first and a rapid drawdown later have never been investigated.
DRAWDOWN EFFECTS: HYDROSTATIC PRESSURES ALONG THE SLOPE SURFACE

Effects on earth dams of drawdown scenarios imposed after a strong earthquake

Sica et al.
The external stabilizing hydrostatic pressures reduce but the internal-to-slope pore water pressures could delay their decrease to the steady-state values associated to the new reservoir level.
**DRAWDOWN EFFECTS: CHANGES IN TOTAL STRESS AND PORE PRESSURE INSIDE THE SLOPE**

The change in hydrostatic pressures along the slope surface induces a change in total stress and pore water pressures inside the slope.

The resulting pore water pressures will not be in equilibrium with the new boundary conditions and a transient regime will develop.

\[ R/k = \text{Rate of drawdown/Hydraulic conductivity} \]

During the drawdown, the resulting pore pressures will be affected by:

- soil permeability
- rate of water level lowering
- initial pore pressures (and initial stress field),
- soil skeleton behavior (controlled by soil stiffness and change in saturation).
GLOBAL INSTABILITY – DRAWDOWN

Pore water Pressure ($u_w$) at steady state 1
Drawdown rate/Hydraulic conductivity

GLOBAL INSTABILITY – DRAWDOWN

$U_w1$ at steady state 1
$U^*_w1$

1

$U_w2$ at steady state 2
$U^*_w2$

$\Delta U_w2$

Drained drawdown
Partially drained drawdown
Undrained drawdown

Pore water Pressure ($u_w$)
GLOBAL INSTABILITY – DRAWDOWN AFTER AN EARTHQUAKE

Drawdown rate/Hydraulic conductivity

Pore water Pressure ($u_w$)

Drained drawdown

Partially drained drawdown

Undrained drawdown

Global Instability

$H$}

Earthquake effect

Pore water Pressure ($u_w$)
Coupled 2-phase formulation from construction up to the end of the seismic stage.

- Non-linear elastic soil behaviour combined to Mohr-Coulomb yield criterion.
- Cyclic soil behavior described through a hysteretic model combined to Masing (1926) rules.
- Excess pore water pressure model (Byrne, 1991) activated during the seismic loading.

**THE CAMPOLATTARO DAM (ITALY)**

- Rock outcrop
- Bedrock
- H = 63 m
- Built 1986 -1992
- Maximum water storage 125 Mm³

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<th>n</th>
<th>c’ [kPa]</th>
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<th>Date</th>
<th>M</th>
<th>Epicentral distance [km]</th>
<th>PGA [g]</th>
<th>$F_S$</th>
<th>Scaled PGA [g]</th>
<th>$D_{rms}$</th>
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- ID: Identification number.
- Earthquake: Location and date of the earthquake.
- M: Magnitude of the earthquake.
- PGA: Peak ground acceleration.
- $F_S$: Scaling factor.
- $D_{rms}$: Root mean square displacement.

**ID**    | **Earthquake** | **Date**       | **M** | **Epicentral distance [km]** | **PGA [g]** | **$F_S$** | **Scaled PGA [g]** | **$D_{rms}$** |
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Coupled unsaturated approach (3-phase formulation) during the drawdown stage.

Soil-water retention curves defined through the Van Genuchten (1980) model.
Pore water pressures at different stages of the dam lifetime

- **a)** end of the construction stage
- **b)** water level at +42.36 m
- **c)** water level +52.62 m
- **d)** steady-state at the maximum water level
- **e)** static drawdown
- **d)** end of the dynamic stage (4674xa input signal)
- **e)** post-seismic drawdown
The shear strength reduction technique proposed by Duncan (1996) was adopted following the specific procedure implemented in FLAC2D.

**SAFETY FACTOR vs Drawdown ratio (L/H)**

- **Drawdown rate**: 0.5 m/day
- **Post-seismic drawdown**
- **‘static’ drawdown**

The shear strength reduction technique proposed by Duncan (1996) was adopted following the specific procedure implemented in FLAC2D.
For $L/H<0.3$, the global instability phenomenon develops entirely within the upstream shell.

With increasing the drawdown ratio, the critical slip surface partly crosses the core where the excess pore water pressures are higher.
Different drawdown scenarios were simulated on a zoned earth dam considering the combined effects of a strong earthquake first and a drawdown later.

For the case-history considered in this study, the earthquake stage affected dam stability during the reservoir lowering.

The global safety factor (FOS) dropped to one when a very fast drawdown was superimposed to a previous severe seismic stage.

Dam managers should be aware of the risk of rapidly emptying the reservoir immediately after a major earthquake, in the unjustified belief that they are proceeding in the safest way.
Rapid drawdown on earth dam stability after a strong earthquake

Stefania Sica\textsuperscript{a}, Luca Pagano\textsuperscript{b}, Federica Rotili\textsuperscript{a}

\textsuperscript{a}Università degli Studi del Sannio, Italy
\textsuperscript{b}Università degli Studi di Napoli “Federico II”, Italy

\textbf{ARTICLE INFO}

\textbf{ABSTRACT}

The paper focuses on the rapid drawdown of earth dams in the hypothesis that a prompt reservoir lowering is needed soon after a strong earthquake. The interest on such a topic comes from the fact that in Italy and worldwide there are many large dams placed very close to active faults. In this case, the dam may be asked to face the earthquake first and the rapid drawdown later to face an emergency state. The problem has been numerically investigated with reference to a zoned earth dam (Campolattaro Dam) placed in a highly seismic area of Southern Italy. To solve the overall boundary value problem, encompassing several stages of the dam lifetime, a 2D finite difference model has been solved through the FLAC2D code, implementing a coupled transient seepage formulation, which accounts for partial saturation of the soil during the drawdown stage. Unlike past literature studies, in which the drawdown stage was modelled without accounting for the past loading history of the dam, in the performed simulation the drawdown stage was placed at the end of a quite real sequence of events, encompassing the embankment construction, the reservoir impounding, and earthquake scenarios compatible with the dam site seismic hazard. The performed analyses pointed out that a seismic stage previously experienced by the dam could further contribute to decreasing dam stability during the drawdown especially during the first stages of reservoir lowering. In addition, the faster the drawdown, the smaller the dam safety factor against stability (FOS) with more prominent effects of the initial (pre-drawdown) soil conditions.