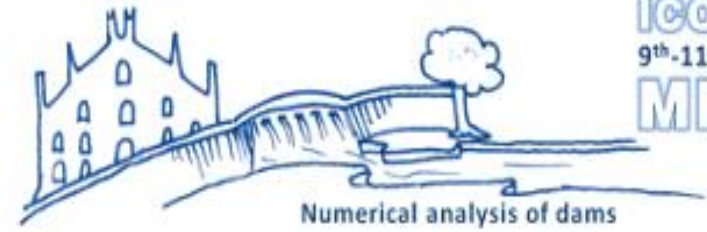




ICOLD
INTERNATIONAL
COMMISSION ON
LARGE DAMS



ICOLD-BW
9th-11th September 2019
MILANO

ICOLD COMMITTEE ON COMPUTATIONAL ASPECTS OF ANALYSIS AND DESIGN OF DAMS

15th INTERNATIONAL BENCHMARK WORKSHOP ON NUMERICAL ANALYSIS OF DAMS

Theme A - Formulation

SEISMIC ANALYSIS OF PINE FLAT CONCRETE DAM

9 September 2019, Milan, Italy

Numerical seismic analysis of Pine Flat Dam using explicit finite difference method

Numerical modelling



- Plane strain modelling / 10 m wide → FLAC3D 6.0, Itasca : 3D explicit finite difference program
- 3 meshing criteria
 - Elements size adapted to frequencies range of interest of each load case (Lysmer & Kuhlemeyer, 1973)
 - Case E (non-linear) refined mesh for better comparison with other contributors (similar mesh size) → Fracture energy approach despite perfectly fragile behavior law

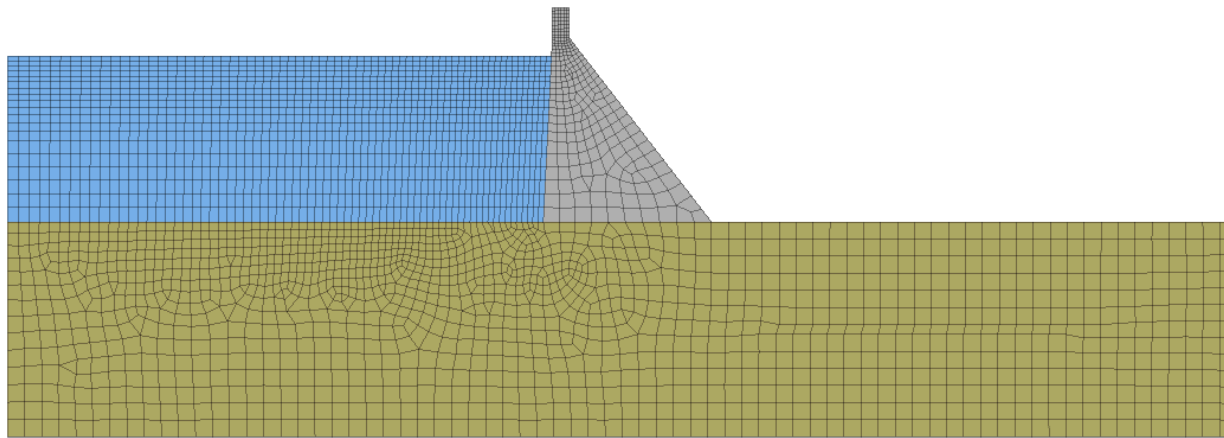
$$l_{cr} = \frac{E.G_f}{f_t^2} = 1.40m$$

- Foundation with/without mass

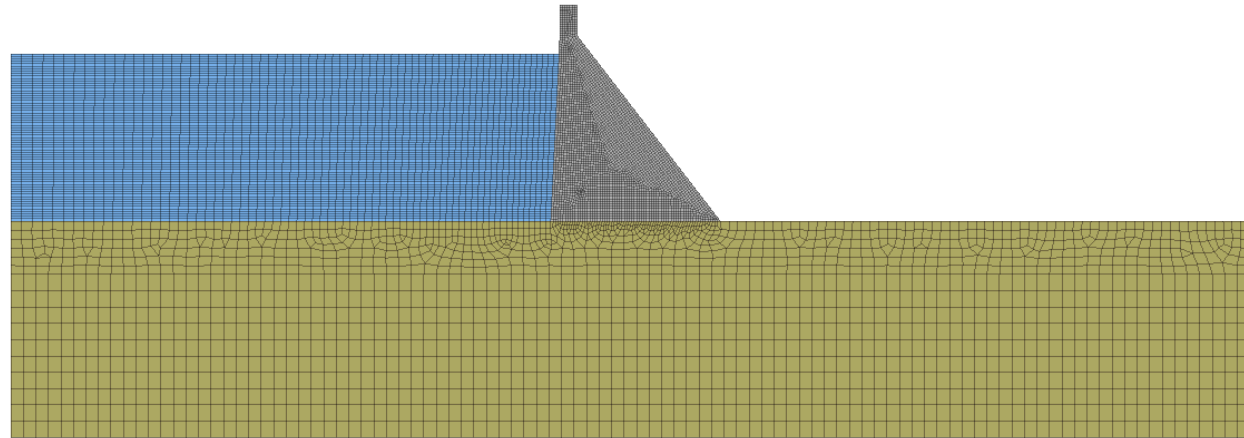
Total of 6 meshing layouts

Meshing layout

- Dam / foundation / reservoir → hexa-dominant mixed discretization scheme elements



Cases A & D (linear analysis)



Case E (non-linear analysis)

Constitutive laws

- All cases except case E : linear analysis → elastic constitutive laws

- Case E : non-linear behavior of dam concrete

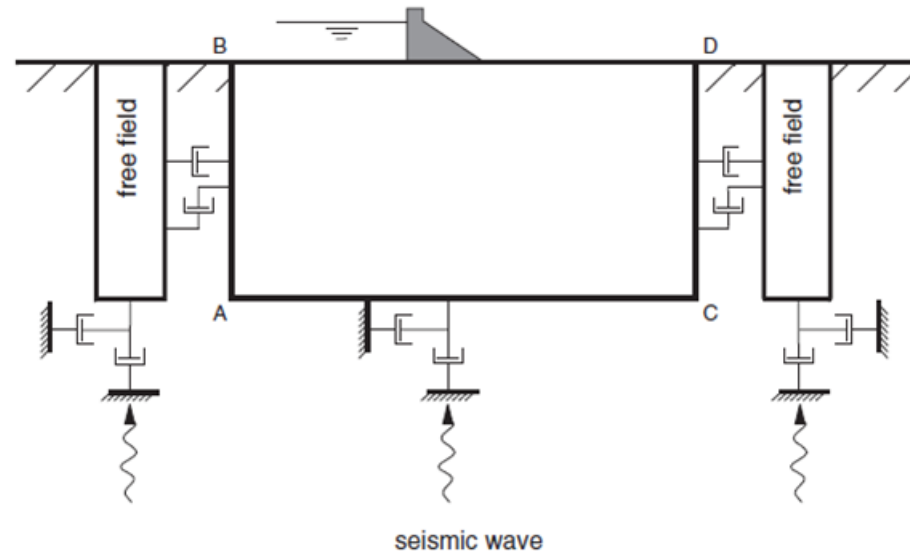
- Up to three mutually perpendicular cracks in each element



- Shear behavior (i.e. parallel to crack) → Elastic perfectly plastic constitutive law with Mohr Coulomb failure criterion. Partial shear strength recovery in case of crack closing, but $c = 0$ kPa
 - Tensile behavior (i.e. perpendicular to crack) → Elastic perfectly fragile constitutive law. $F_t = 0$ once crack has opened

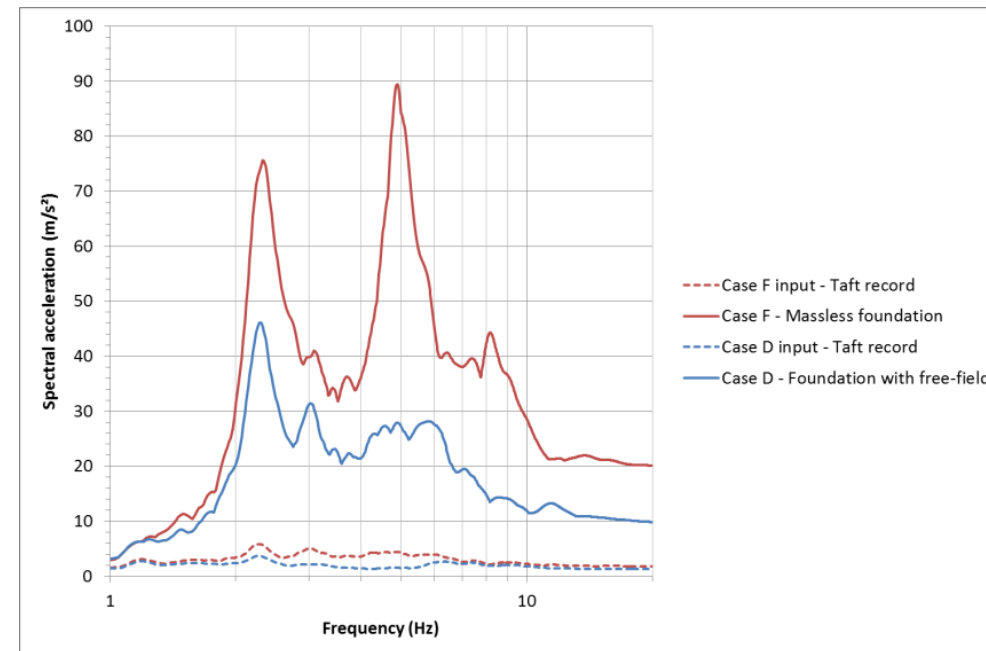
Dynamic features

- Dynamic viscous damping as per Rayleigh formulation (2% or 0% as requested by the Theme formulation)
- Bottom viscous boundary (Lysmer & Kuhlemeyer, 1969)
- Lateral free-field conditions → systematically used by ARTELIA's team since 2010



Radiation boundary condition effects

- Comparison between case D (linear + free field boundary condition) and F (linear + massless foundation) results
- Without free-field conditions
→ overestimation of dynamic response by a factor 2 to 3

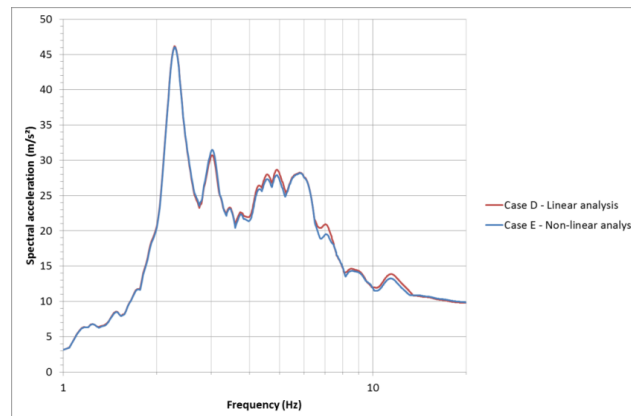


Horizontal spectral accelerations at dam crest

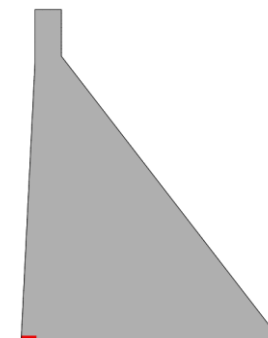
- Results in consistency with previous works (Chopra, 2008 / ICOLD CFBR collaboration, 2014-2017 / 14th International ICOLD Benchmark Theme B)

Taft time history analysis

- Comparison between linear (case D) and non-linear (case E) results
- Crest spectral accelerations almost similar → very low range of yielding
- Authors recommend to consider
 - Dam / foundation interface → irreversible displacements / rearrangements may be triggered
 - Pore-pressure distribution through material, or at least uplift distribution at the dam/foundation interface : 1.2MPa expected at upstream toe vs 2.0MPa concrete tensile strength



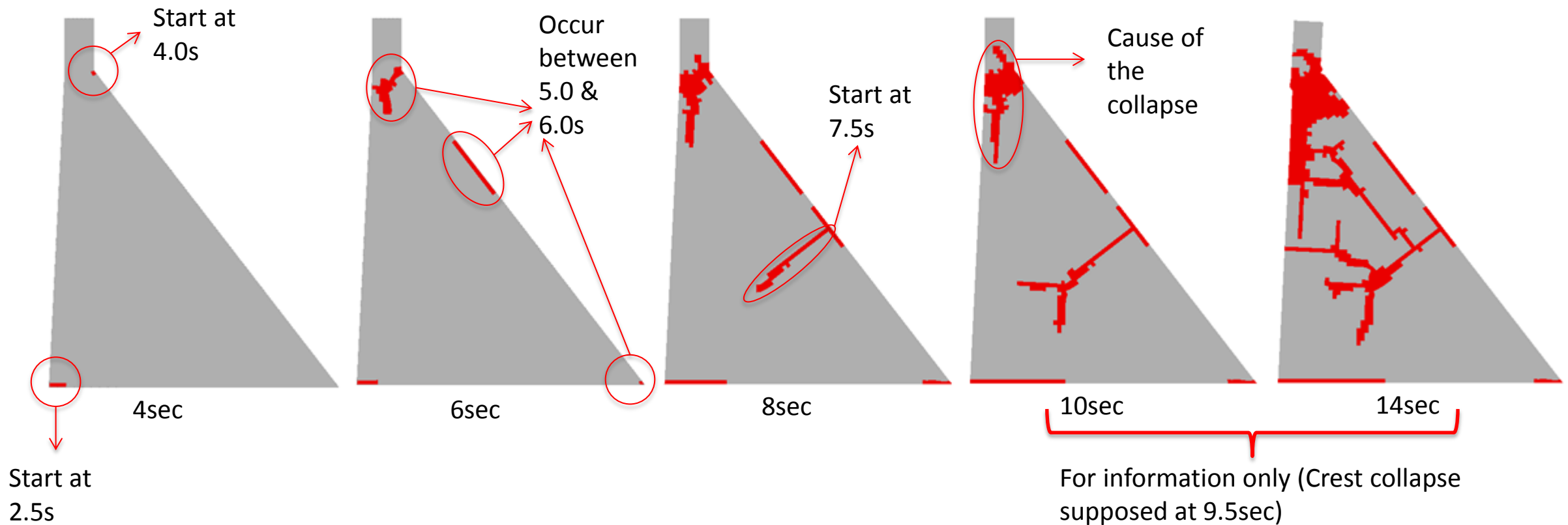
Horizontal spectral accelerations at dam crest

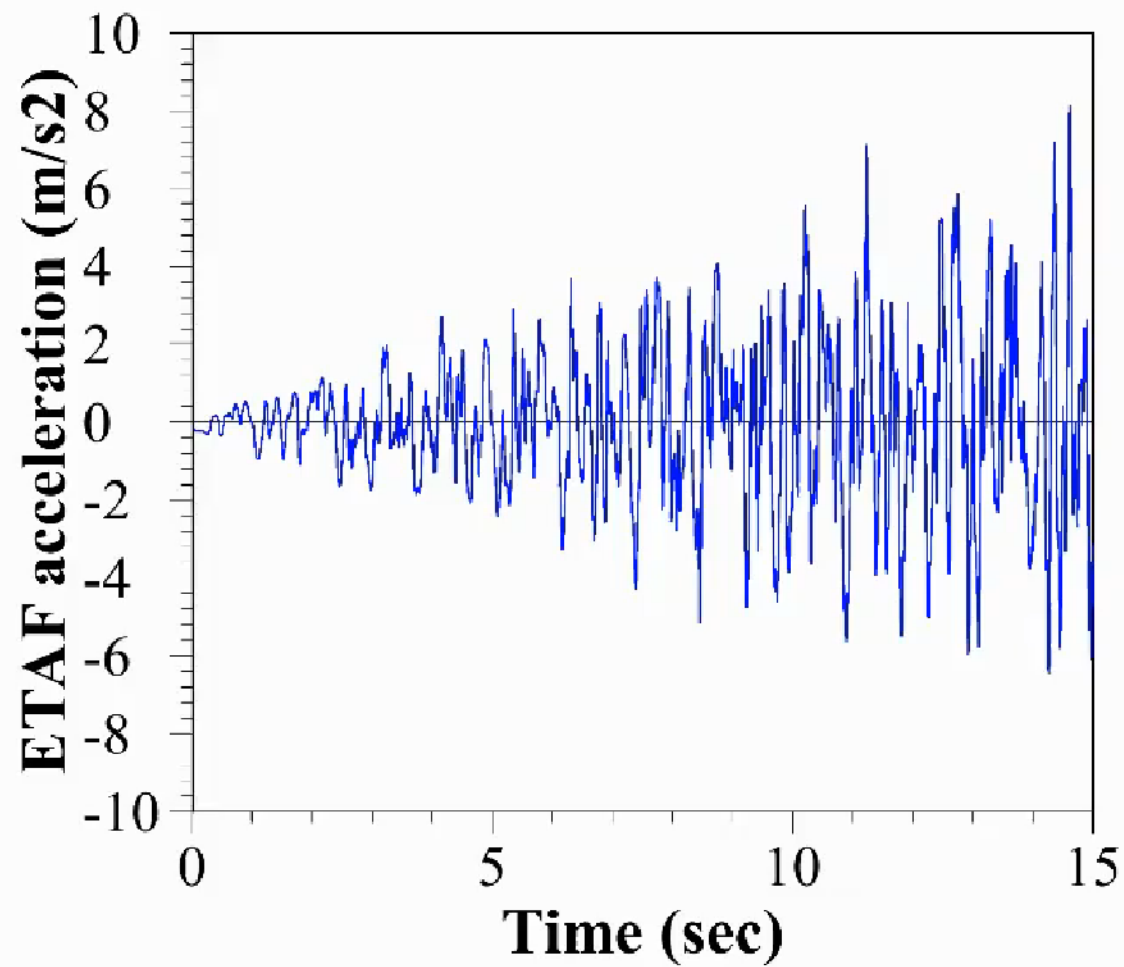
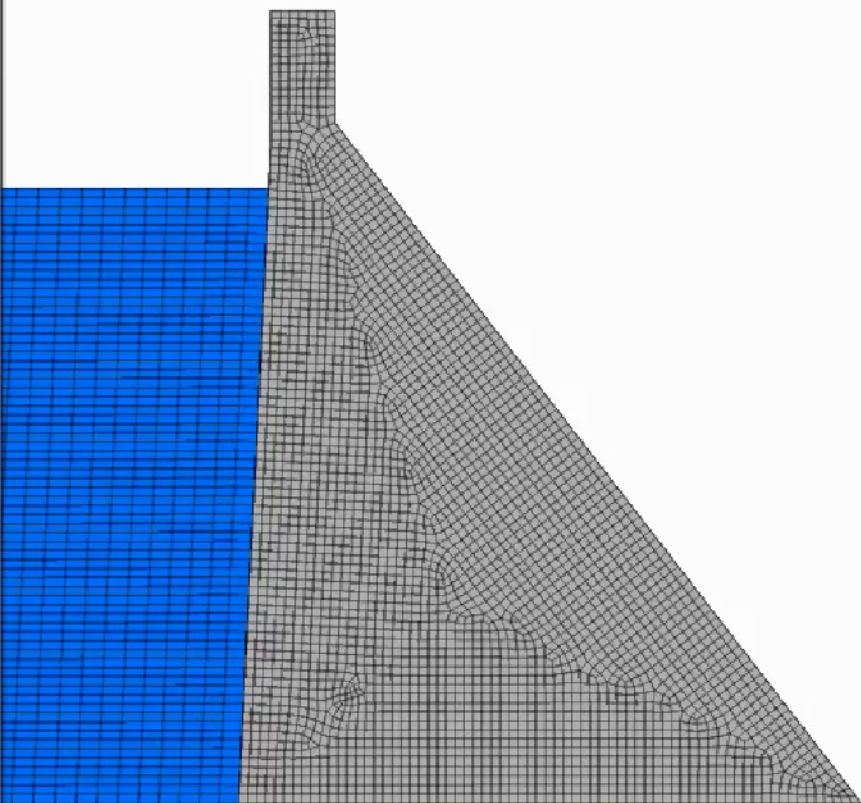


Tensile failure (in red)

ETAF time history analysis

- Large strain hypothesis
- Explicit integration scheme → calculation despite unstable mechanical state





FLAC3D 6.00

ETAF time history analysis



- ETAF record = Increasing acceleration time history → determination of the “ultimate” PGA
 - Saving time approach for linear analysis
 - May raise questions for non-linear analysis
 - Non-linear = path dependent calculation
 - When testing dam at high ETAF PGA, cracks are already implemented
- May unrealistically exaggerate the non-linear effects and lead to alarmist conclusions

Conclusions



- Comparison with/without radiation boundary condition → in consistency with previous studies : overestimation of the dynamic response by a factor 2 to 3
- ETAF signal is interesting for linear analyses but probably conservative for non-linear analyses
- Miscellaneous aspects
 - Vertical input may play a major part to get calculated results fitting recorded ones (JCOLD-CFBR collaboration, 2014)
 - Strength parameters increase during dynamic loading should be taken into account