ICOLD
INTERNATIONAL
COMMISSION ON
LARGE DAMS

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

Non-linear behavior of a concrete gravity dam during seismic excitation
A case study of the Pine Flat Dam

Enzell J., Malm R. and Ahmed L.

Numerical model

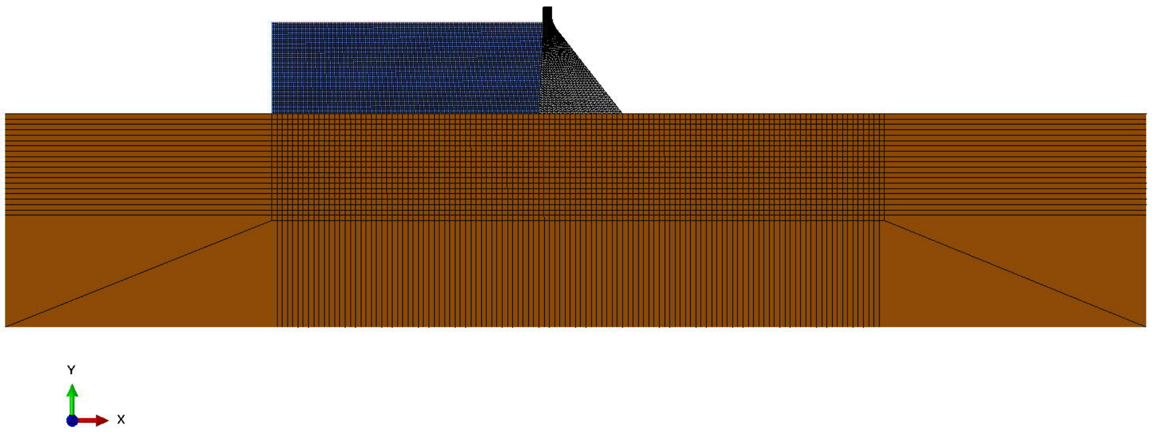
- Abaqus Standard ver. 2019 (implicit)
  - 2D plain strain model (out of plane thickness 15.24 m)
- Fluid-structure-interaction
  - Acoustic elements
  - Truss elements to describe displacements of the free water surface (with springs to ground)
  - Acoustic infinite elements to describe an infinite reservoir
- Rock boundary
  - Case A1 & A2; fixed at outer rock surfaces
  - All other cases; Infinite boundaries (Lysmer and Kuhlemeyer (1969) - both with and without free field (FF) boundaries tested the analyses
    - With out FF - Seismic excitation with shear forces (US/DS dir) at the base of the rock foundation
    - With FF - Seismic excitation with shear forces (US/DS dir) at the base of the rock foundation & simplified free field forces (lateral and vertical) on the vertical sides based on analytical 1D wave propagation.

Mesh

- Element length of the dam 1 m, to ensure that the length is sufficiently small to assure that the elastically stored energy can be absorbed by surrounding elements
- Element length of the rock 6 m, to ensure that it can describe the highest fundamental frequency of interest

$$L_{max} < \frac{E \cdot G_f}{{f_t}^2}$$

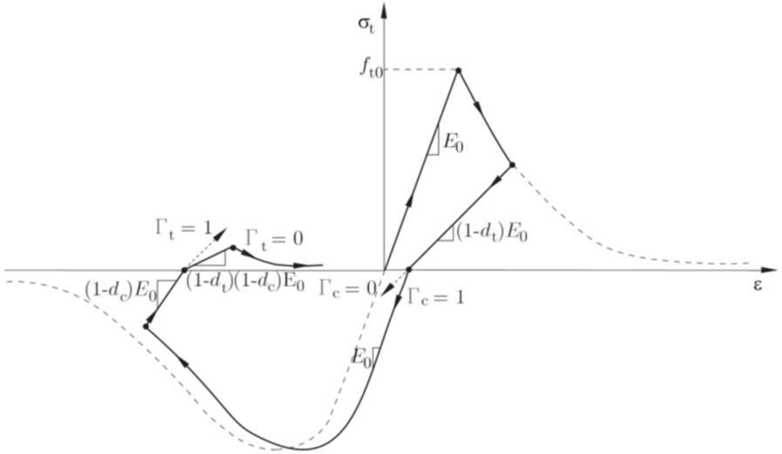
$$L_{max} = \frac{c}{n_{min} \cdot f_{max}}$$

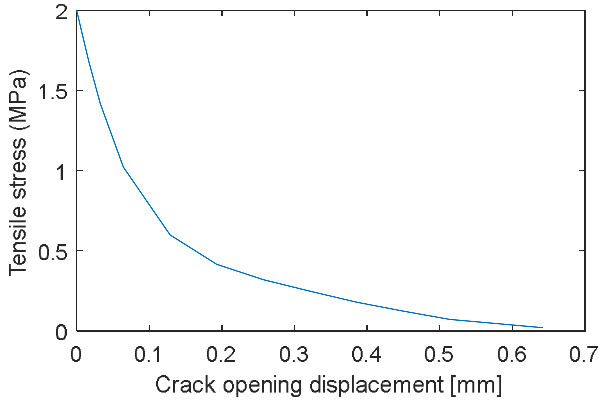


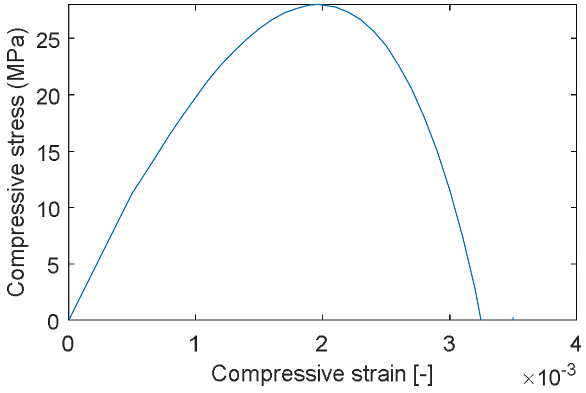
Parameter	Element type	Element name	No. Elements
Concrete	3-node linear plain strain	CPE3	11 862
Foundation	4-node linear plain strain	CPE4R	2 340
Foundation (infinite)	4-node linear, one-way infinite	CINPE4	157
Water	4-node linear acoustic	AC2D4	28 858
Water (infinite)	2-node acoustic infinite	ACIN2D2	94
Water surface	2-node linear truss	T2D2	124
Water surface (connection)	linear axial spring to ground	SPRING1	125

Non-linear material model

- Concrete damaged plasticity
  - Lubliner et al. (1989) & Lee and Fenves (1998)
  - Plasticity theory combined with isotropic damage theory (damage variables for tension and compression respectively)
  - Intended for cyclic damage
- Tensile behavior
  - Exponential curve, Cornelissen (1986)
  - One simplification; linear up to the tensile strength
  - $D_{max} = 0.9$
- Compressive curve
  - Eurocode 2







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ICOLD-BW 2019
9th-11th September
MILANO
Numerical analysis of dams

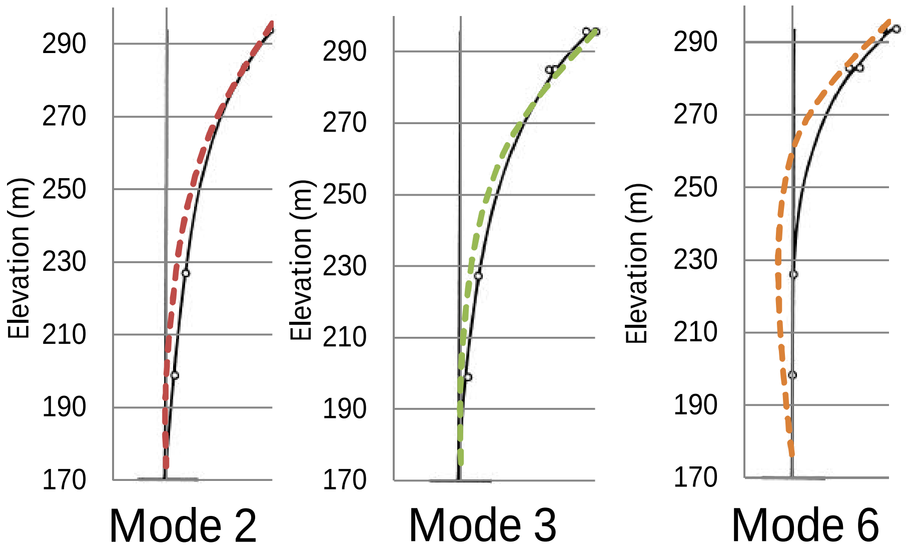
Case A1 & A3

- Natural frequencies
  - Both mass and massless approach
  - Massless approach is suitable to identify relevant structural modes, with relatively small difference in results.

Analysis	Season	W.L	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Mass	W	268.2 m	2.31	3.48	3.95	4.40	4.91	5.38
Massless	W	268.2 m	2.35	3.58	4.18	-	5.07	5.70
Exp.[1]	W	268.2 m	-	3.47	4.13	-	-	5.40

Analysis	Season	W.L	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Mass	S	287.6 m	2.20	3.38	4.07	4.59	4.99	5.46
Massless	S	287.6 m	2.24	3.47	-	4.49	5.29	5.79
Exp.[1]	S	278.9 m	-	3.27	4.07	-	-	5.65

Measured (black) vs calculated (dashed coloured line) mode shapes



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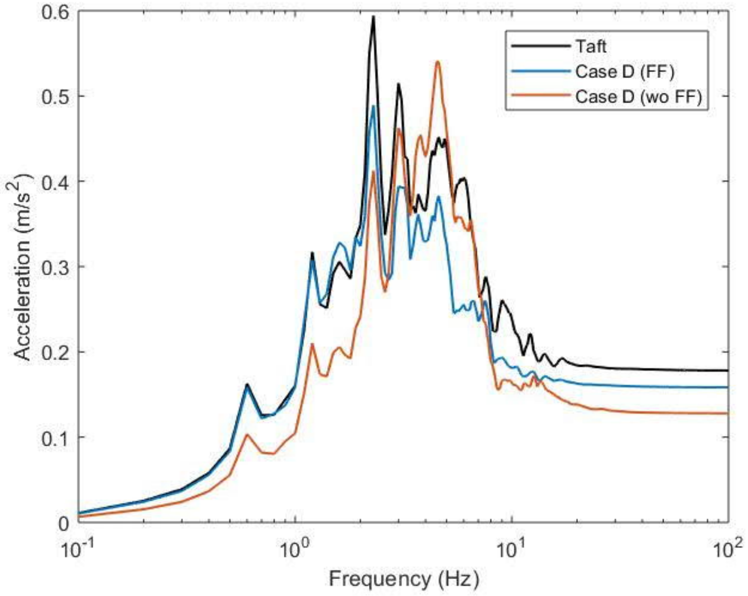
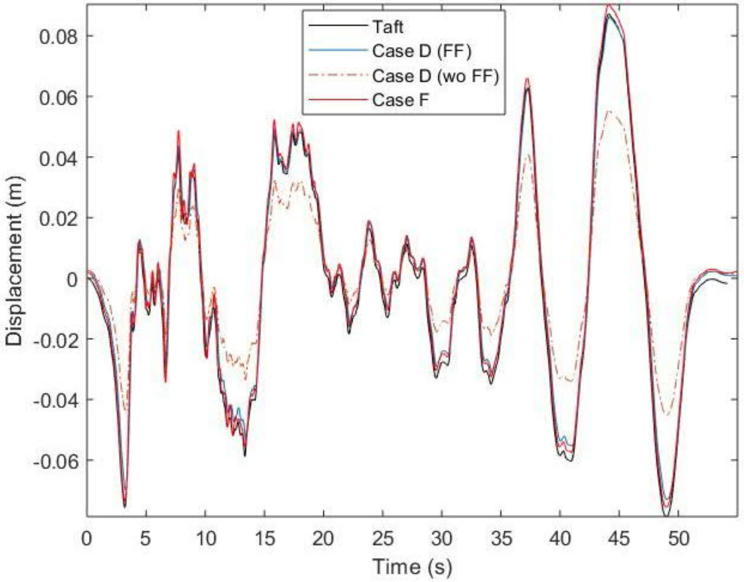
Case D1, E1 and F1

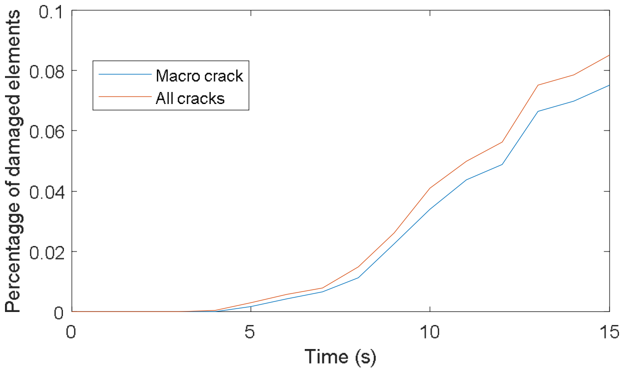
- Without free field boundary conditions (Case D1 wo FF), the acceleration at the upstream heel (point A) is significant lower than the Taft free-field for low frequencies.
- With free field boundary conditions (Case D1 FF), the acceleration is almost identical to the Taft free-field acceleration for lower frequencies, but lower for the zero period acceleration.
- Displacements from mass foundation with FF and massless (Case F) is almost identical to Taft.
- Case D1 shows local area in upstream heal subjected to tensile stresses > tensile strength.

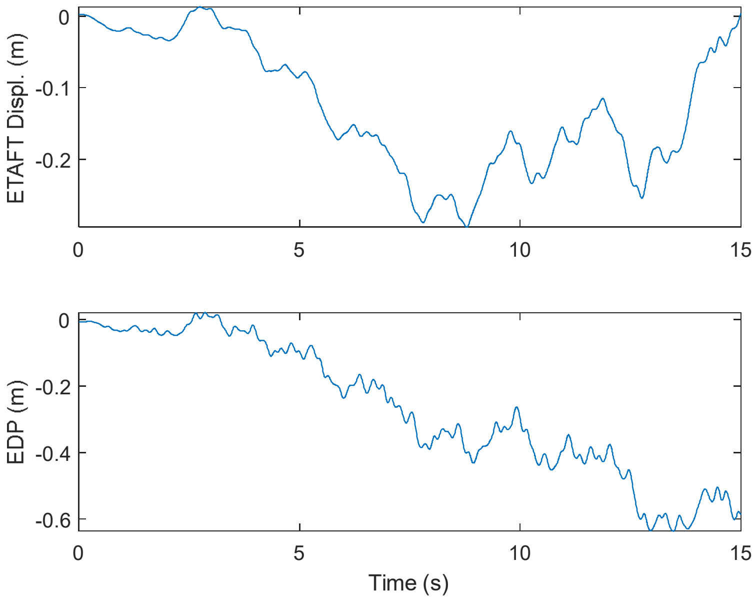


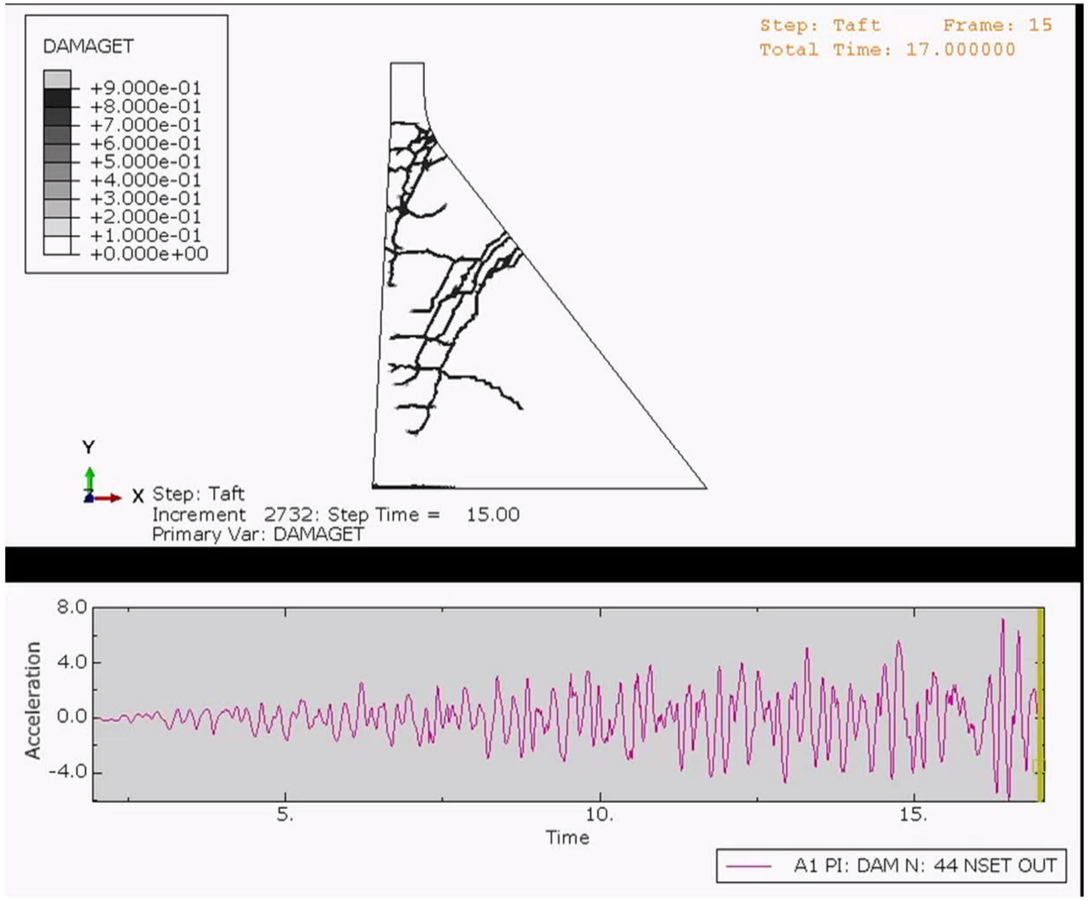


Case E2

- Completed the full 15 sec duration
  - However, crest becomes unstable after about 8 – 9 s
  - Significant cracking







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Summary and conclusions

- Good agreement between obtained natural frequencies and mode shapes compared to the results from EMVG test.
  - Massless foundation can be useful to identify structural modes
- Analyses with mass foundation showed that neglecting free field boundary conditions results in lower than expected accelerations and displacements (compared to the free field).
- Analyses with massless foundation gave accurate displacements but significantly higher accelerations.
- Small risk of cracking due to TAFT earthquake
- Significant cracking in ETAFT, where the crest becomes unstable.
  - Stable material model for concrete cracking that can capture the significant cracking and find a converging solution.

Thank you for your attention!

Jonas Enzell
Sweco
jonas.enzell@sweco.se

Richard Malm
KTH Royal Institute of Technology / Sweco
richard.malm@byv.kth.se

Lamis Ahmed
Vattenfall
lamis.ahmed@vattenfall.com