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

RSE Ricerca Sistema Energetico

9th September 2019

Assessment of the dynamic response of Pine Flat concrete gravity dam

FEM simulation of dam-foundation interaction

Giorgia Faggiani, *Piero Masarati*, *Antonella Frigerio*

Contents

METHODS & APPROACHES

RESULTS

FINAL REMARKS

Performed analyses

FEM model, constitutive laws & FSI approach

SSI approaches, boundary conditions and loadings

Main results

Conclusions and lessons learned

Performed analyses

A — Modal Analysis & EMVG Test Simulation

A-1: Modal Analysis with WRWL
A-2: Modal Analysis with SRWL
A-3: EMVG Test Simulation with WRWL
A-4: EMVG Test Simulation with SRWL

D — Linear Dynamic Analysis with Taft earthquake

D-1: WRWL
D-2: SRWL
D-3: NRWL

E — Non-Linear Dynamic Analysis at WRWL

E-1: Taft earthquake
E-2: ETAf signal

F — Linear Dynamic Analysis with massless foundation

F-1: WRWL
F-2: SRWL
F-3: NRWL

INDIA

In-house FEM computer code for linear elastic analysis of dam-reservoir systems

DASSAULT SYSTEMES SIMULIA

Abaqus/standard

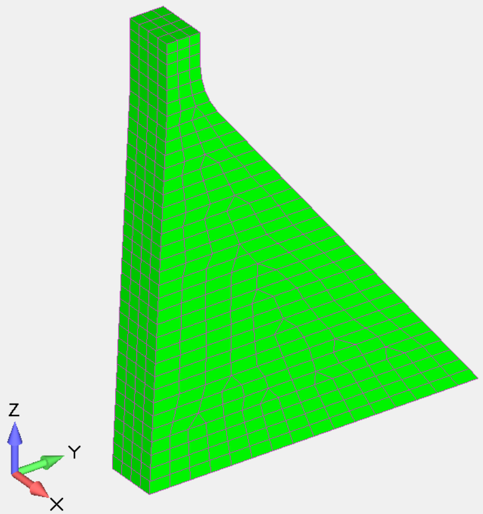
Time integration scheme: **HHT implicit** method with $\Delta T=0.005$ s

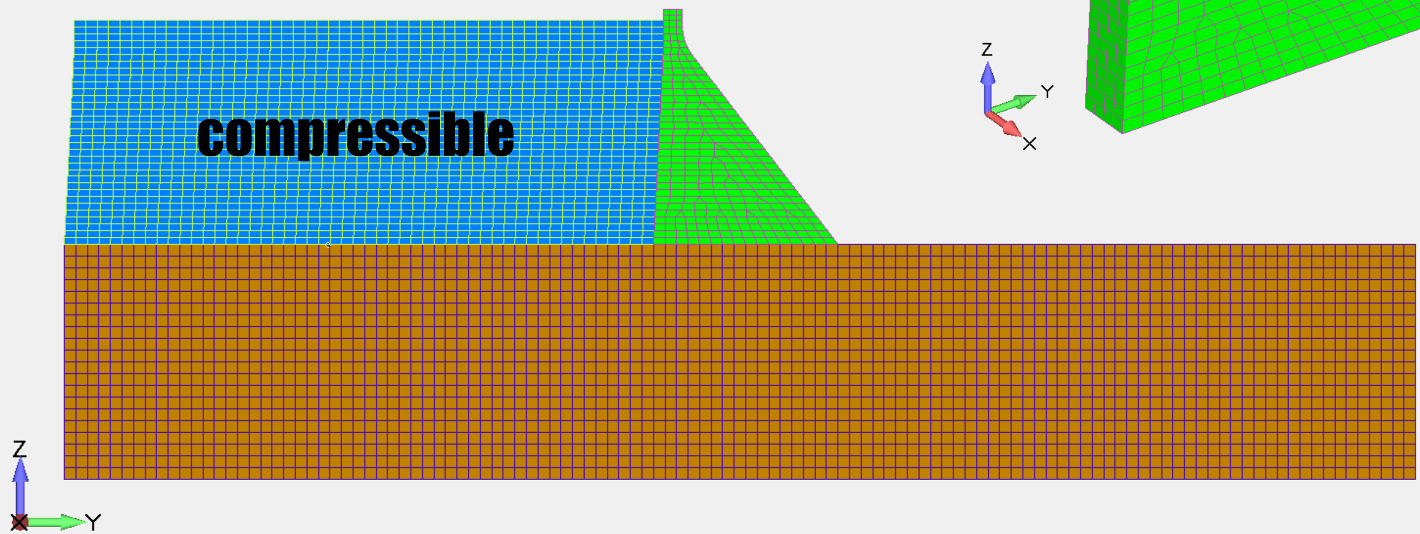
FEM model and main assumption

3D model

Foundation: 9360 solid linear elements (size 6 m)
Fluid: 6732 acoustic elements
Monolith 16: 1076 solid linear elements (size 3÷6 m)

Linear Cases A, D & F





Assumptions

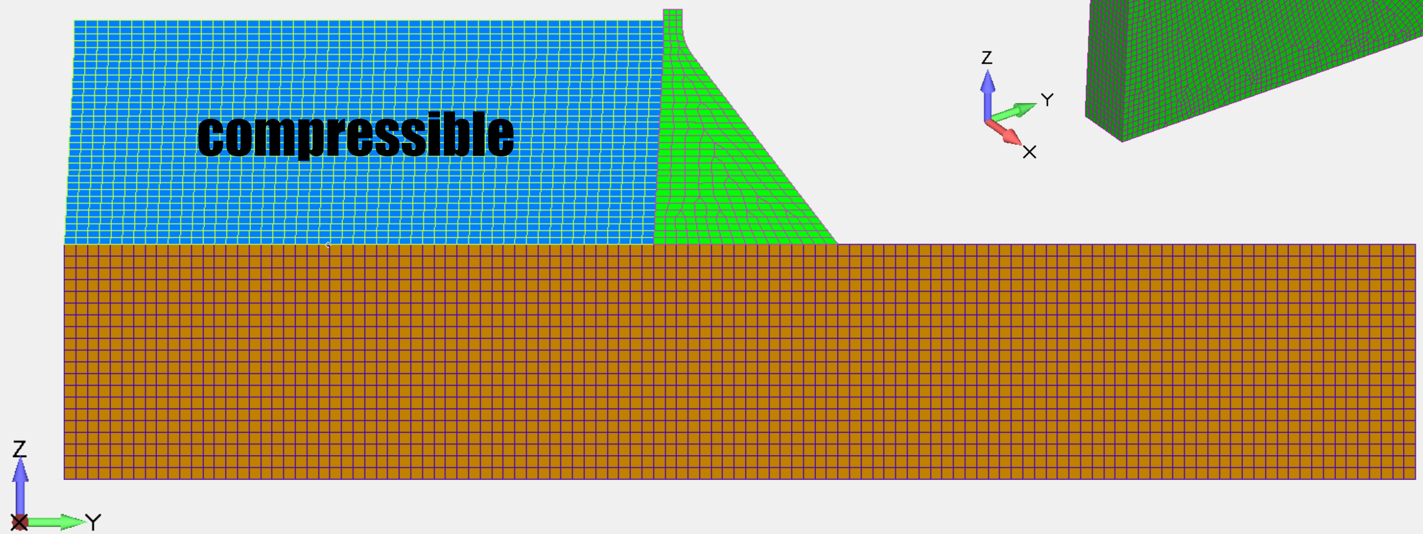
- foundation: linear-elastic model
- fluid-structure interaction: coupled mechanical-acoustic approach (Zienkiewicz, 1977)
- dam: linear-elastic model

3D model

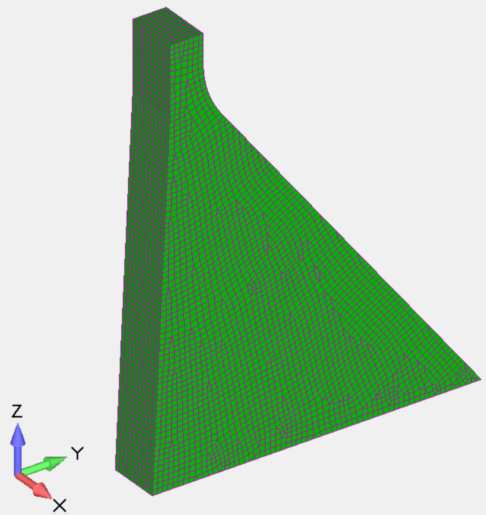
Foundation: 9360 solid linear elements (size 6 m)
Fluid: 6732 acoustic elements
Monolith 16: 1076 solid linear elements (size 3÷6 m)

Non-Linear Case E

Monolith 16: 25120 solid linear elements (size 1.5 m)

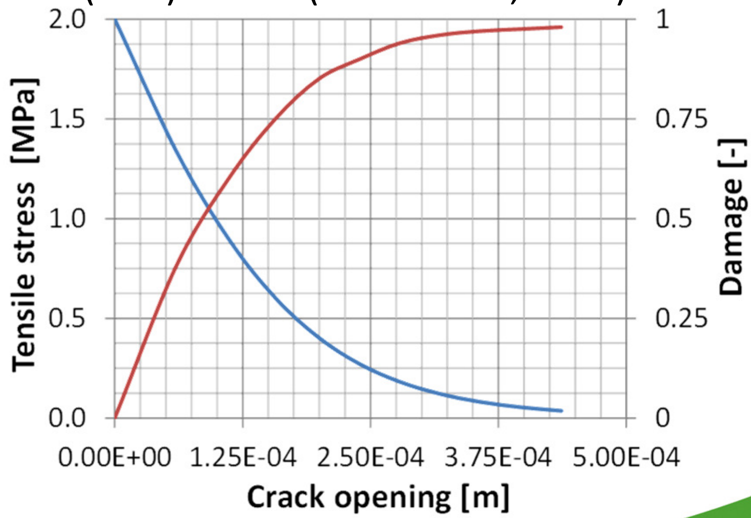


Non-Linear Case E



Assumptions

- foundation: **linear-elastic** model
- fluid-structure interaction: **coupled mechanical-acoustic** approach (Zienkiewicz, 1977)
- dam: **linear-elastic** model
- dam: **Concrete Damage Plasticity** (CDP) model (Lee-Fenves, 1998)

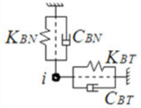


Soil-Structure Interaction approach

Approaches & loads

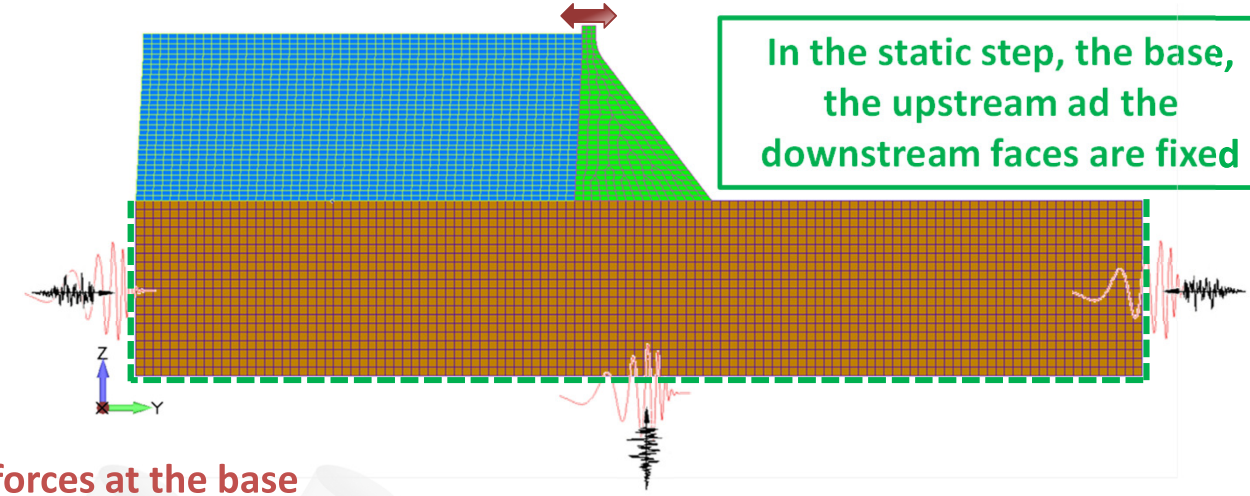
- seismic wave propagation achieved through the **viscous-spring artificial boundaries VSAB model** (Chuhan, 2009; Chen, 2012; Liu, 2013)
- spring & dashpot elements available in Abaqus: **absorbing artificial boundaries**
- homogeneous foundation with low damping: **effective earthquake forces** analytically computed basing on the theoretical solution of the elastic wave problem in a half-space
- EMVG applied as force to dam crest
- ETAf applied as total movement only to the base of the massed foundation
- Taft applied uniformly to the base and side boundaries using the **massless approach** (Clough, 1980)
- Static Loads: weight of dam and reservoir

Absorbing boundaries



$$\begin{cases} K_{BN} = \frac{1}{1+\alpha}\frac{\lambda+2G}{r_b}, C_{BN} = \beta\rho c_p \\ K_{BT} = \frac{1}{1+\alpha}\frac{G}{r_b}, C_{BT} = \beta\rho c_s \end{cases}$$

In the static step, the base, the upstream ad the downstream faces are fixed



forces at the base

$$\begin{bmatrix} F_{Bx} \\ F_{By} \\ F_{Bz} \end{bmatrix} = \begin{bmatrix} 0 \\ K_{BT}\left[v_0(t) + v_0\left(t - \frac{2L}{c_s}\right)\right] + C_{BT}\left[\dot{v}_0(t) + \dot{v}_0\left(t - \frac{2L}{c_s}\right)\right] + \rho c_s\left[\dot{v}_0(t) - \dot{v}_0\left(t - \frac{2L}{c_s}\right)\right] \\ 0 \end{bmatrix}$$

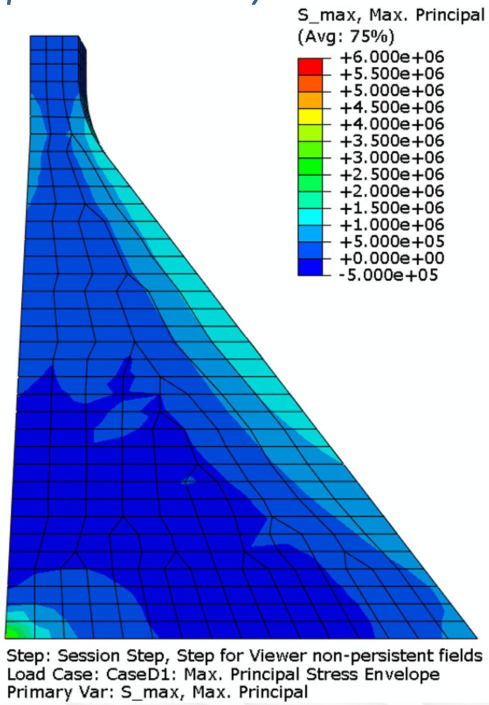
forces at side boundaries

$$\begin{bmatrix} F_{Bx} \\ F_{By} \\ F_{Bz} \end{bmatrix} = \begin{bmatrix} 0 \\ K_{BN}\left[v_0\left(t - \frac{l}{c_s}\right) + v_0\left(t - \frac{2L-l}{c_s}\right)\right] + C_{BN}\left[\dot{v}_0\left(t - \frac{l}{c_s}\right) + \dot{v}_0\left(t - \frac{2L-l}{c_s}\right)\right] \\ -\rho c_s\left[\dot{v}_0\left(t - \frac{l}{c_s}\right) - \dot{v}_0\left(t - \frac{2L-l}{c_s}\right)\right] \end{bmatrix}$$

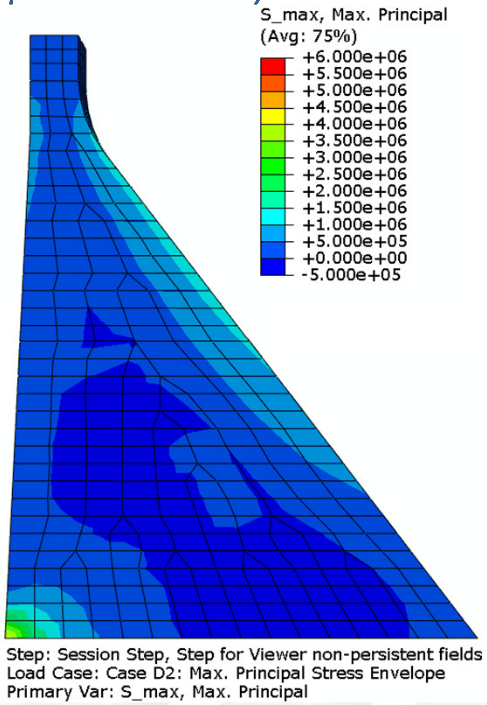
Linear Dynamic Analyses for different reservoir levels

Tensile Stress Envelope

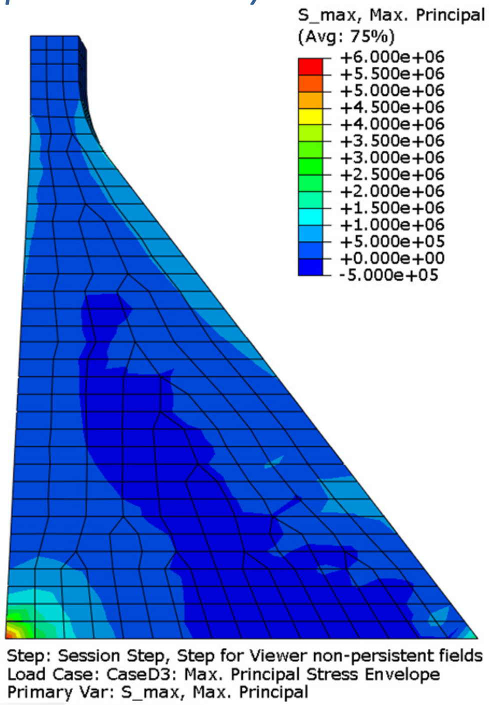
Case D-1
(268.21 m a.s.l.)

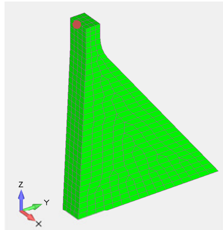


Case D-2
(278.57 m a.s.l.)

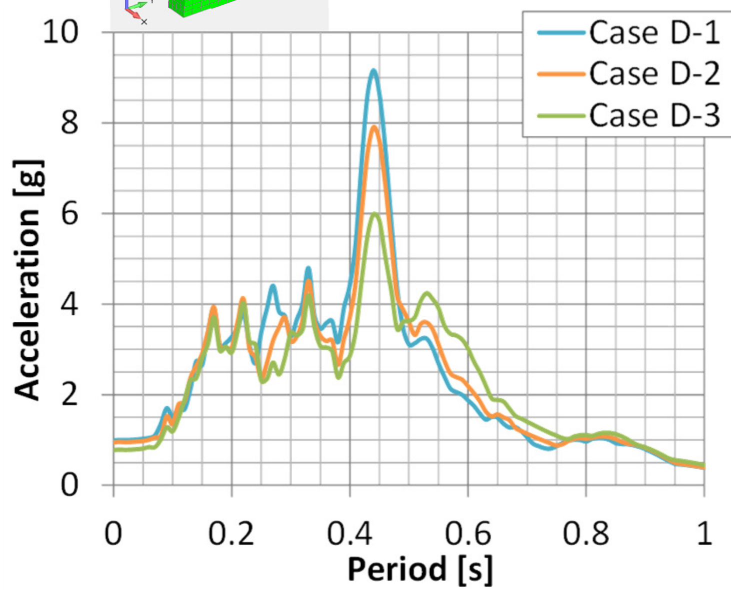


Case D-3
(290.00 m a.s.l.)





Acceleration
at point C



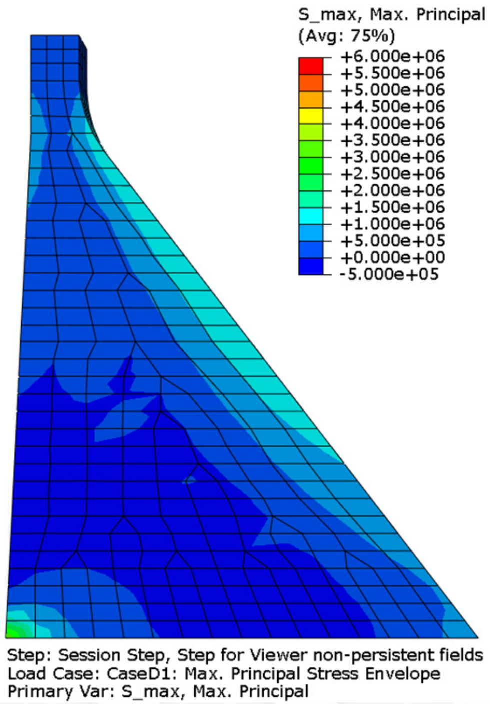
increasing the **water level** the **tensile stress state** decreases at **downstream face** and **becomes greater** in the nearest of **dam heel**

acceleration at dam crest **reduces growing up** the **water level**

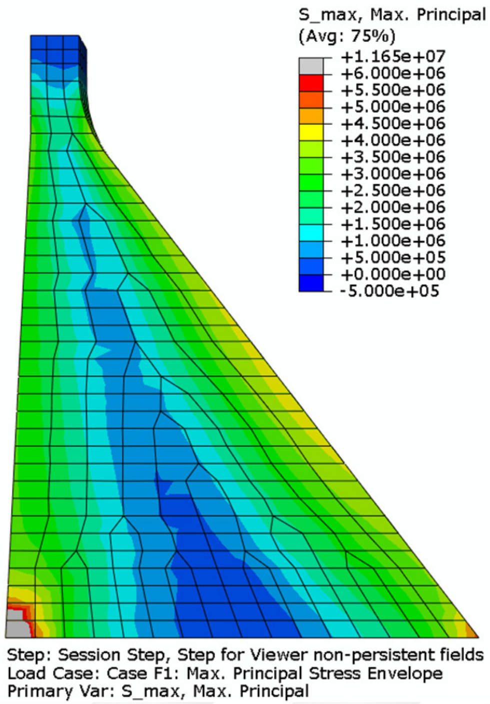
Linear Dynamic Analysis: VSAB model versus massless approach

Tensile Stress Envelope

Case D-1



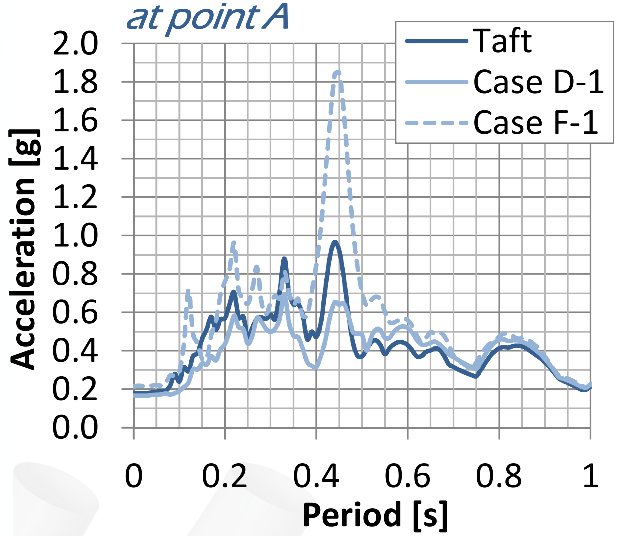
Case F-1



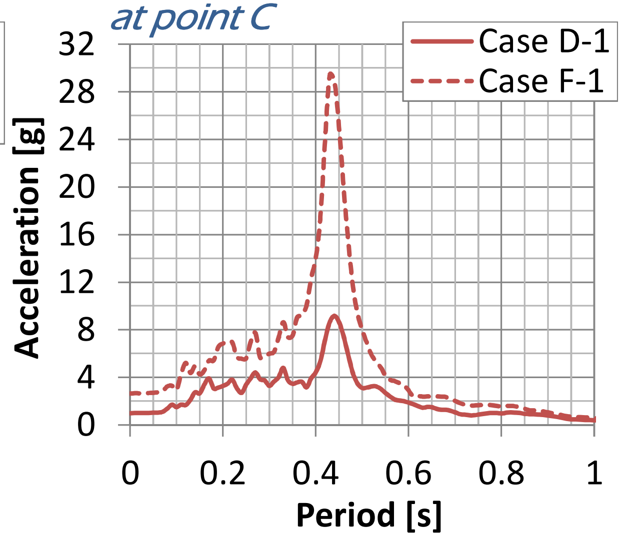
the **massless approach** leads to a **more demanding seismic response** of the system than the VSAB model (about the double). Nevertheless the **periods of the resonant peaks** are **comparable**

Acceleration

at point A



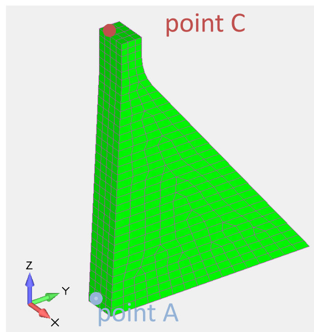
at point C



Modal Analysis

	Case A-1	Case A-1*
Mode [n]	Natural Frequency [Hz]	
1	2.28	2.33
2	3.75	3.78
3	4.08	4.37
4	4.60	5.26
5	4.87	5.79
6	5.56	6.31

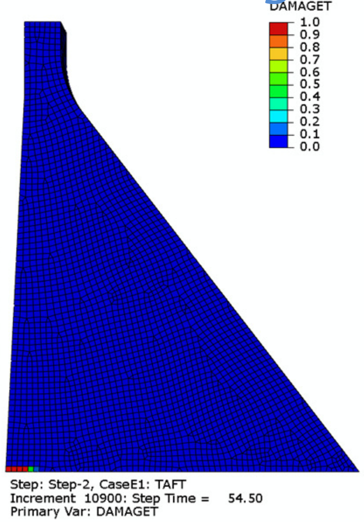
* massless



Non-linear Dynamic Analysis for different time-history signals

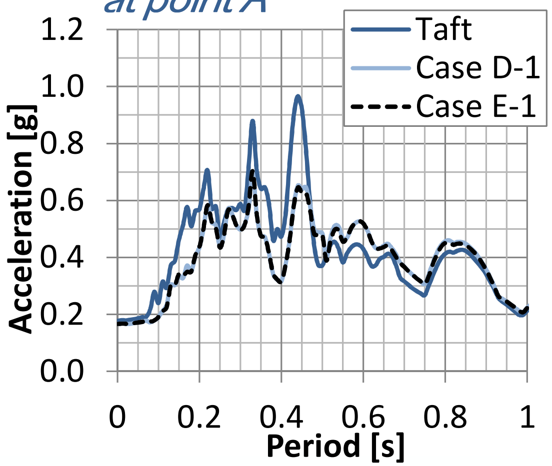
Tensile Damage

Case E-1

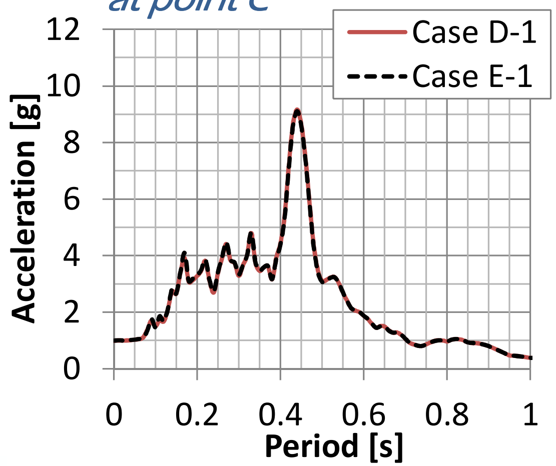


Acceleration

at point A

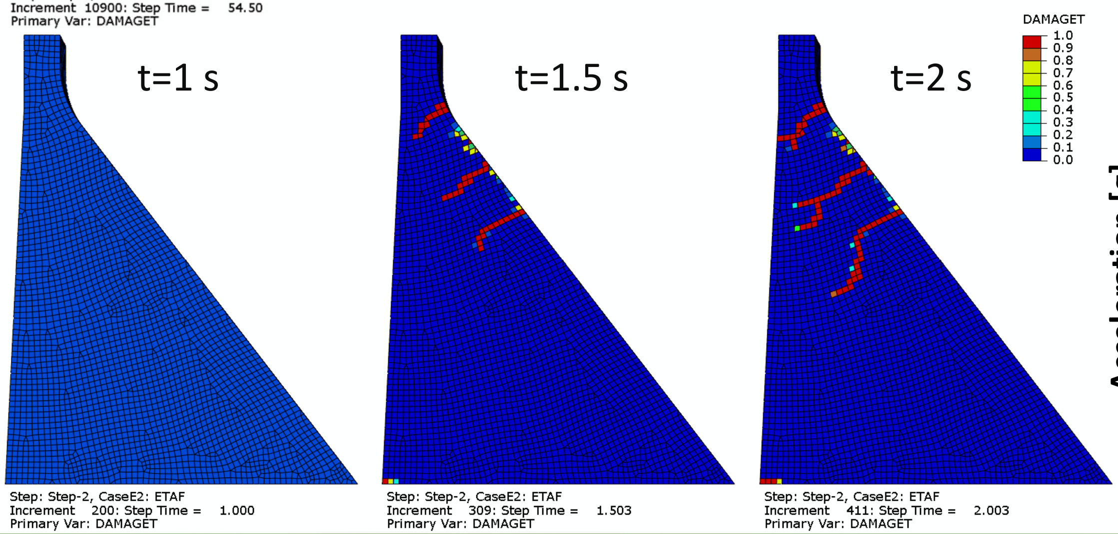


at point C



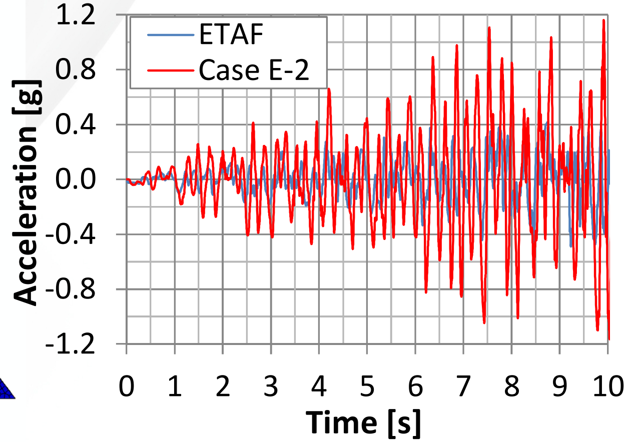
Taft earthquake is not severe enough to trigger significant non-linear effects. Only **a small damaged area** occurs at dam-foundation interface **near the dam heel**

Case E-2



Acceleration

at point A



ETAf signal allows to observe the **onset of increasing non-linear effects up to the failure** (assumed to occur when a single crack extends from the downstream to the upstream face)

Final remarks

- The models with the seismic wave propagation approach provide a less demanding seismic response of the system with respect to that achieved with the massless approach. Nevertheless, the periods of the resonant peaks resulting from the two approaches are rather comparable.

- Thanks to its conservativeness the massless approach is still widely used in the seismic safety assessment of dam-reservoir-foundation system.

- In many cases it may be important to reduce this excessive conservativeness that may lead to the non-fulfilment of the performances required by the regulations: consolidating and increasing the confidence in the use of models that carefully simulate soil-structure interaction represent a crucial issue.

- To enhance the reliability and the confidence in using these advanced FEM models, the comparison with earthquake records on dams should be needed.

- The results of non-linear dynamic analysis with Taft earthquake shows that no significant non-linear effect arises and the structural behaviour results pretty unchanged with respect to the correspondent linear case.

- The case carried out with the ETAF signal allows to observe the onset of increasing non-linear effects up to the failure.

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

9th September 2019

Assessment of the dynamic response of Pine Flat concrete gravity dam

FEM simulation of dam-foundation interaction

Giorgia Faggiani, *Piero Masarati*, *Antonella Frigerio*

Ricerca sul Sistema Energetico - RSE S.p.A.