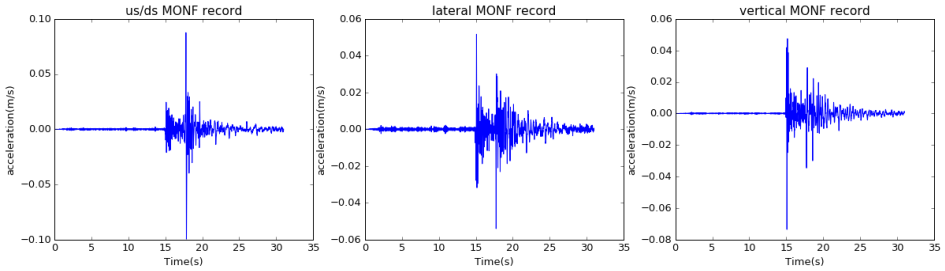
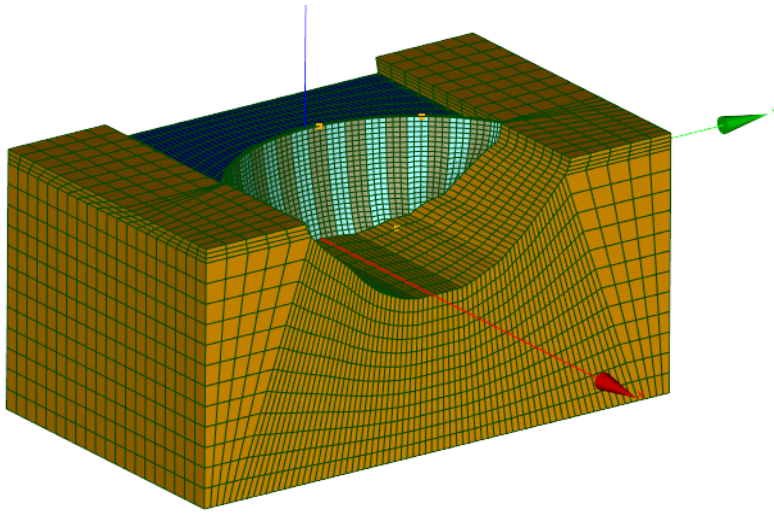
Hydro Engineering Center

BACK ANALYSES OF MONTICELLO ARCH DAM:

interest of earthquake records on dams to improve the reliability of safety assessments on concrete dams

Emmanuel ROBBE – 06/02/2017





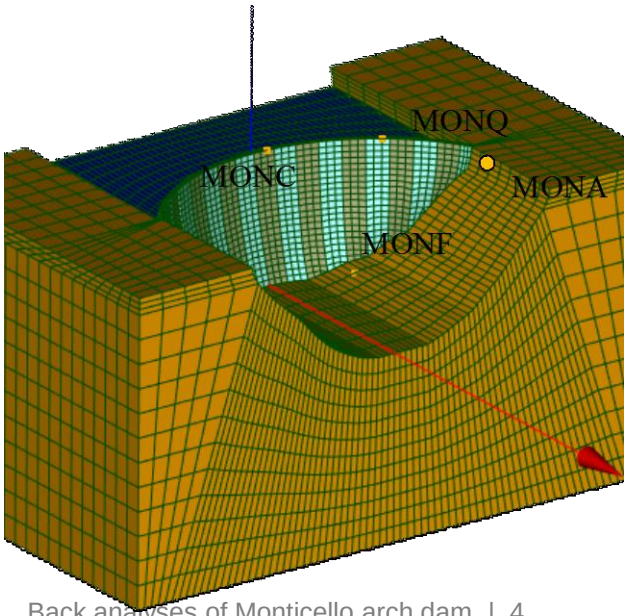
SUMMARY

INTRODUCTION AND CONTEXT

- **WHY ? Safety assessment of existing dams under seismic load**
- **HOW ? Improving our knowledge about dynamic behavior of concrete dams - improving and assessing the calculation methods : until recently, no 'real' data to evaluate our method !!!**
- **MEANS ?**
  - Participation at international benchmarks (ICOLD 2013&2015, USSD workshop on Monticello Dam 2016)
  - Ambient vibration tests on dams (2 gate-structures dams, 1 arch, 1 multiple arch) in 2015 and 2016
  - Research on the spatial variability of the seismic ground motion
  - Collaboration CFBR – JCOLD
    - Analysis on Acceleration Data of Dams Collected by JCOLD (135 gravity dams with 223 earthquake records, 22 arch dams with 59 records)
    - Comparison between records and FE analyses for Tagokura gravity dam and Kurobe arch dam.

MONTICELLO ARCH DAM WORKSHOP

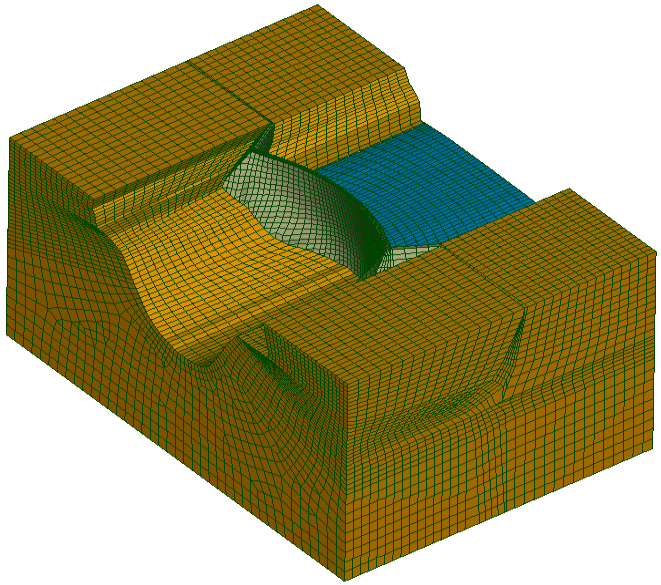
- **Blind prediction workshop organized in 2016 by USSD**
- **M4.1 earthquake recorded in 2015, 16km away from Monticello arch dam (93m high, California)**
- **Records provided at the toe of the dam (MONF) + shaking test + mechanical tests on concrete & rock core + drawings of dam**
- **Finite-Element analyses to compute accelerations at the crest (blind prediction)**
- **Comparison against measured data**



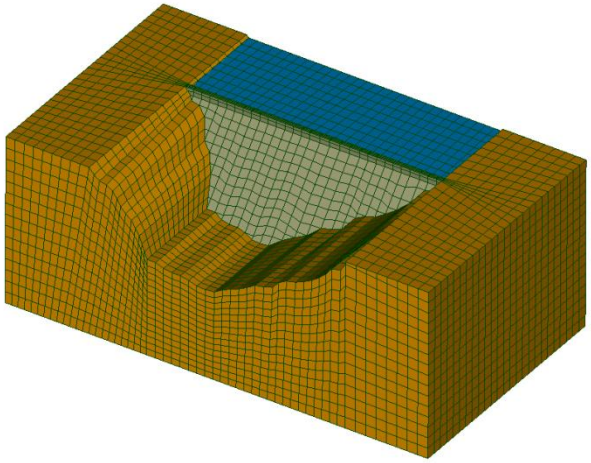
PRESENTATION OF IMPROVED FINITE ELEMENT ANALYSES

SOIL-STRUCTURE AND FLUID-STRUCTURE INTERACTION APPROACHES

- **References :**
  - Viscous-spring boundary model
    - Influence of seismic input mechanisms and radiation damping on arch dam response (Zhang Chuhan 2009)
    - Earthquake Response analysis of a gravity damp considering the radiation damping of infinite foundation (Y.S. Liu 2013)
  - Potential-based fluid method
    - Assessment of a potential-base fluid finite elements for seismic analysis of dam-reservoir systems (Najib Bouaanani 2008)



- **Test cases**
  - Comparison of simple to more complex test cases issue from the previous references



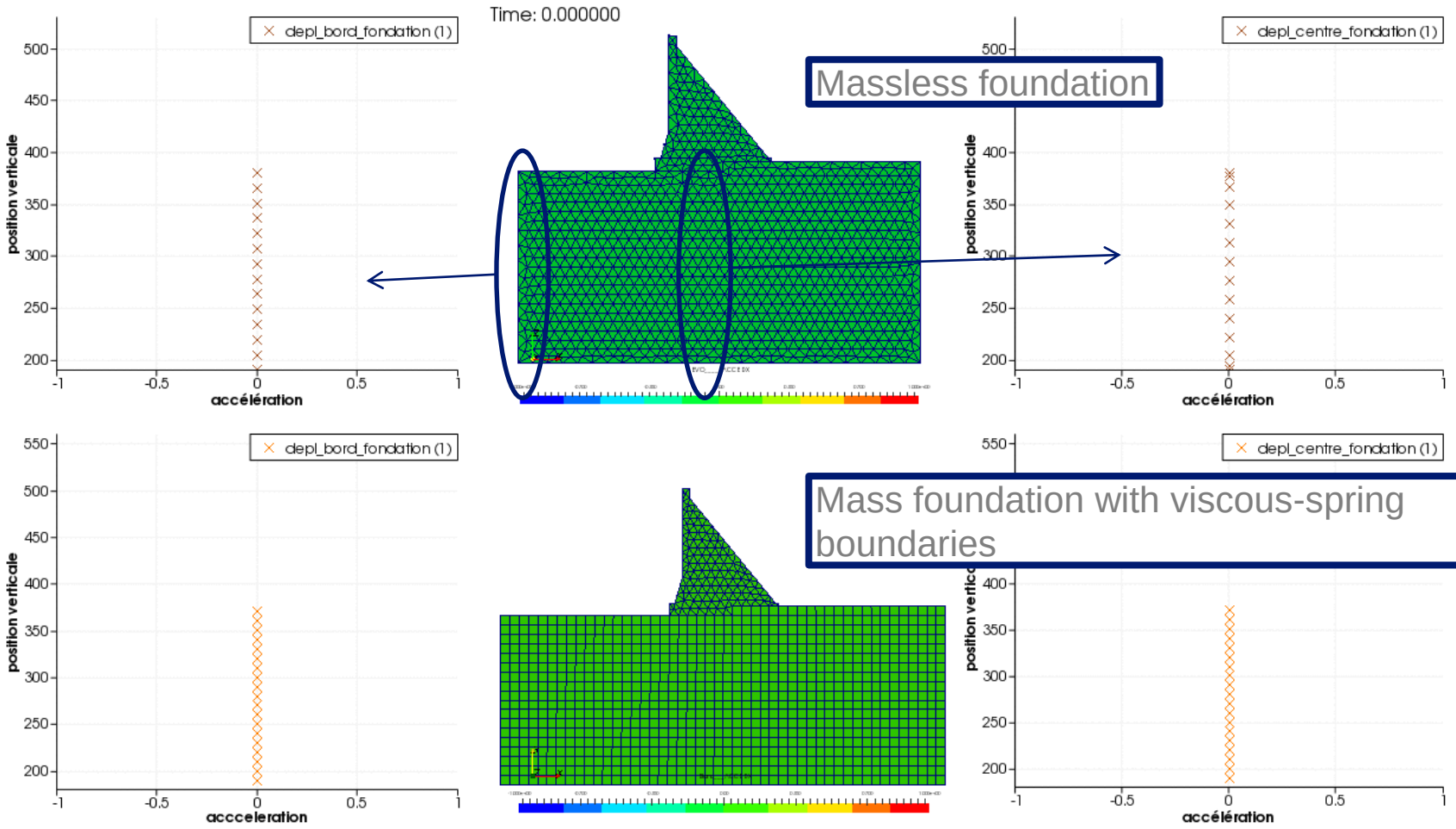
- **Software :**
  - Analyses are carried out with Code_Aster (made by EDF, open-source)

FINITE ELEMENT METHODS

- **Comparison of Time-history analyses with 2 methods**

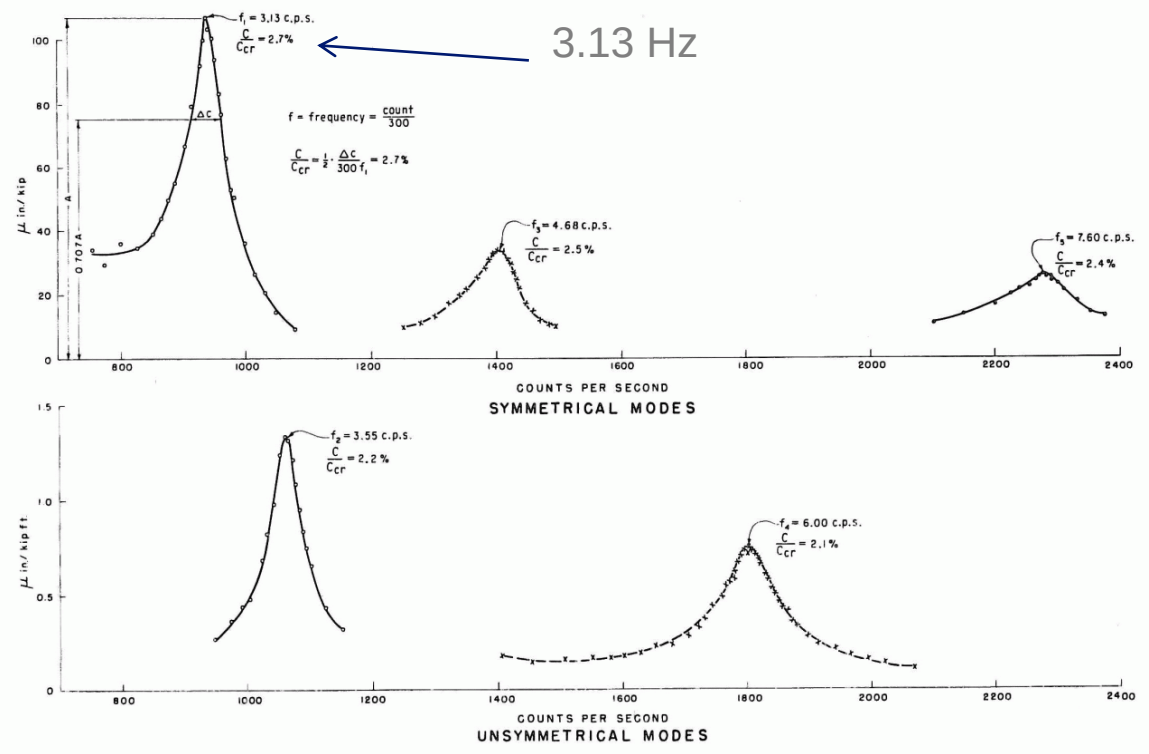
Massless foundation + Westergaard added masses	mass foundation + viscous-spring-boundaries + fluid finite element
- commonly used in engineering practice (ex. CIGB workshop in Lausanne 2015), easy to use (modal analyses..)	- less used and more complex : + take into account the propagation of the wave in the foundation and radiative damping + compressibility of the water
- 1 damping source only : concrete material damping (usualy 5%)	- concrete material damping (1-5%), radiation damping in the foundation and in the reservoir
- the whole foundation is roughly subjected to the same acceleration	- waves spreads verticaly from the bottom of the foundation to the top.

VISUALISATION OF THE EARTHQUAKE INPUT



BACK ANALYSIS OF MONTICELLO ARCH DAM
MATERIAL PROPERTIES AND CALIBRATION OF THE MODEL

- **From concrete and rock mechanical test :**
  - 2450 kg/m3 density
  - $E_{concrete}$ = 35000 MPa, E_{rock} = 30000 MPa
- **Adjusted by shaking test :**



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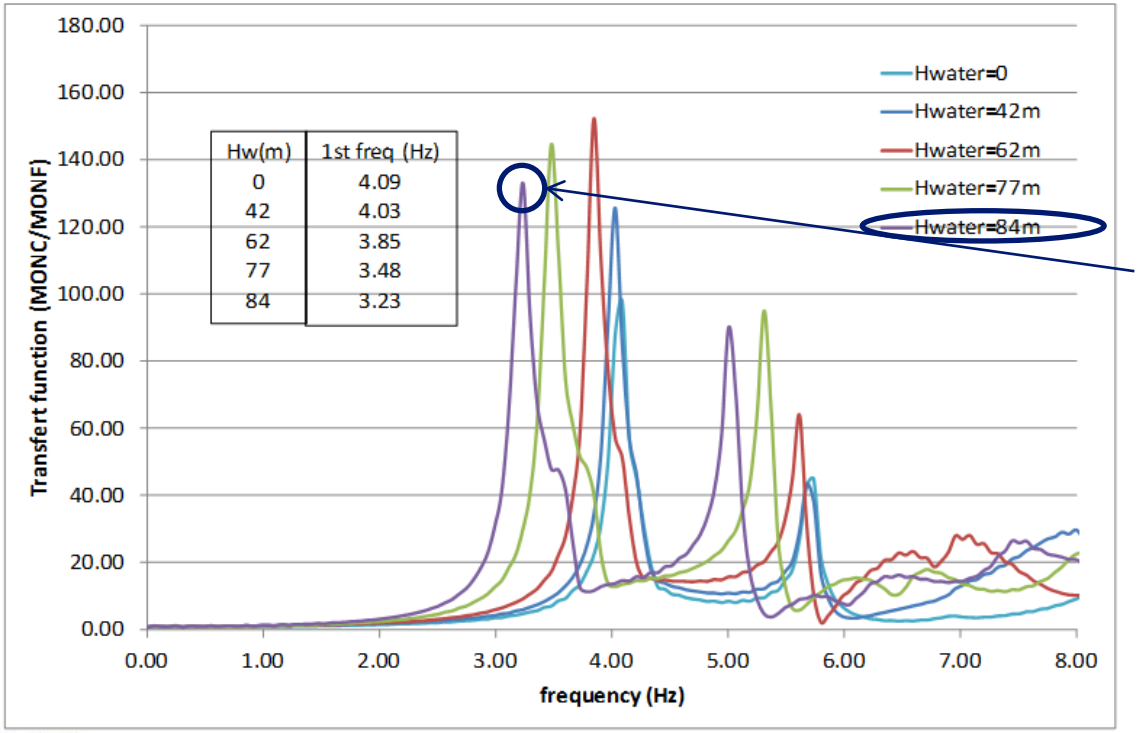

Transfert function between crest / toe of the dam for different water level :

For the water level of the shaking test :

F= 3.23 Hz with Ec=35000 MPa
F= 3.13 Hz with Ec=30000 MPa

BACK ANALYSIS OF MONTICELLO ARCH DAM
MATERIAL PROPERTIES AND CALIBRATION OF THE MODEL

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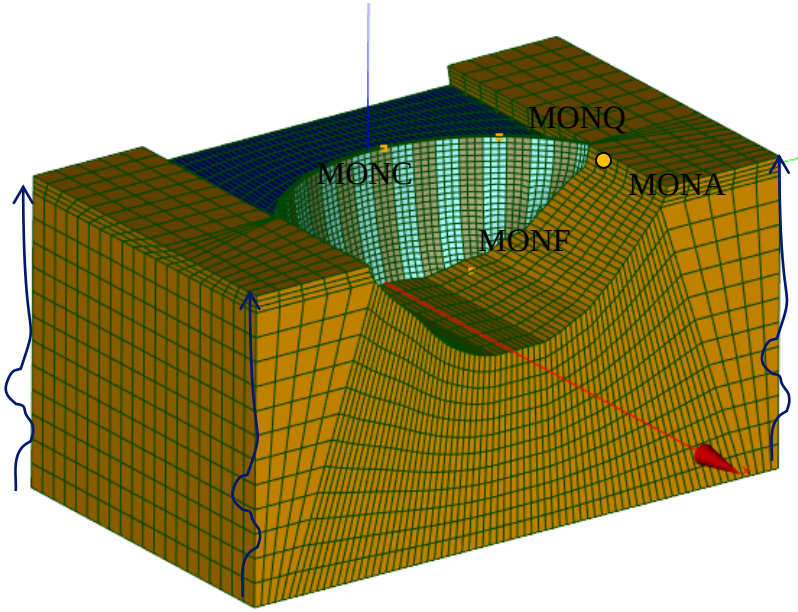
  - 2450 kg/m3 density
  - $E_{concrete}$ = 35000 MPa, E_{rock} = 30000 MPa
- **Adjusted by shaking test :**
- **Concrete damping**
  - Between 1 – 5% (from similar comparison between records and FE analyses) : 1% chosen here due to the very low intensity of the earthquake.
- **Additional damping due to the viscous-spring boundaries around the foundation**

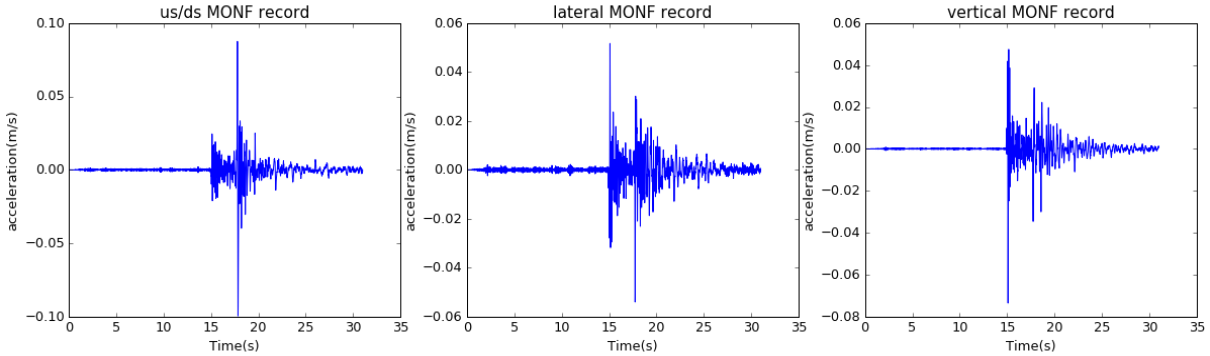
→ **Overall : total damping is generally higher than 5% to fit the records**

BACK ANALYSIS OF MONTICELLO ARCH DAM
SEISMIC INPUT

- **Acceleration time histories are introduced as compression and shear waves travelling verticaly from the bottom to the top of the foundation**

- **Deconvolution process to define input such as accelerations computed at the toe of the dam fit the accelerations recorded**

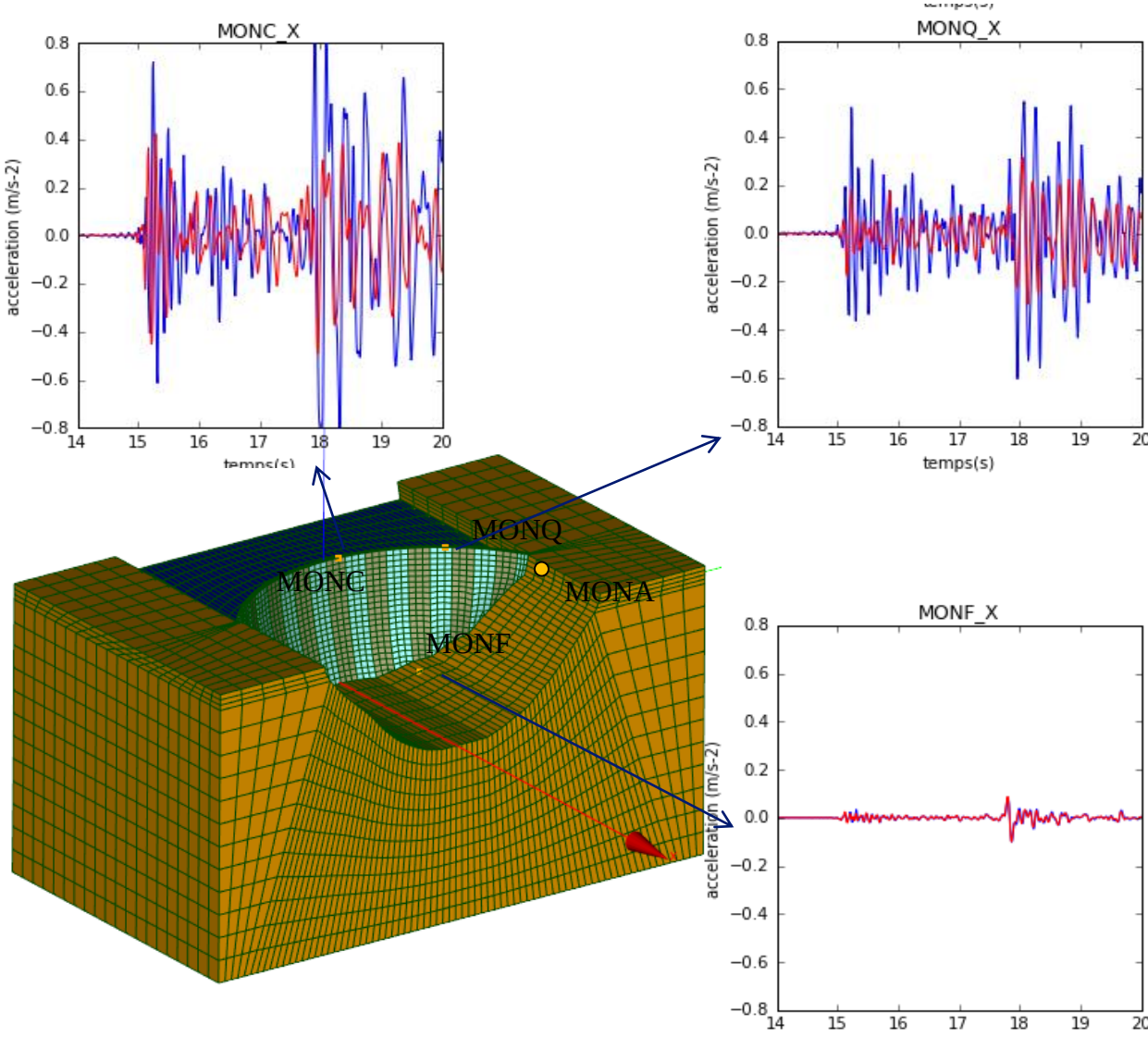




BACK ANALYSIS OF MONTICELLO ARCH DAM

TIME-HISTORY ACCELERATION COMPARAISON

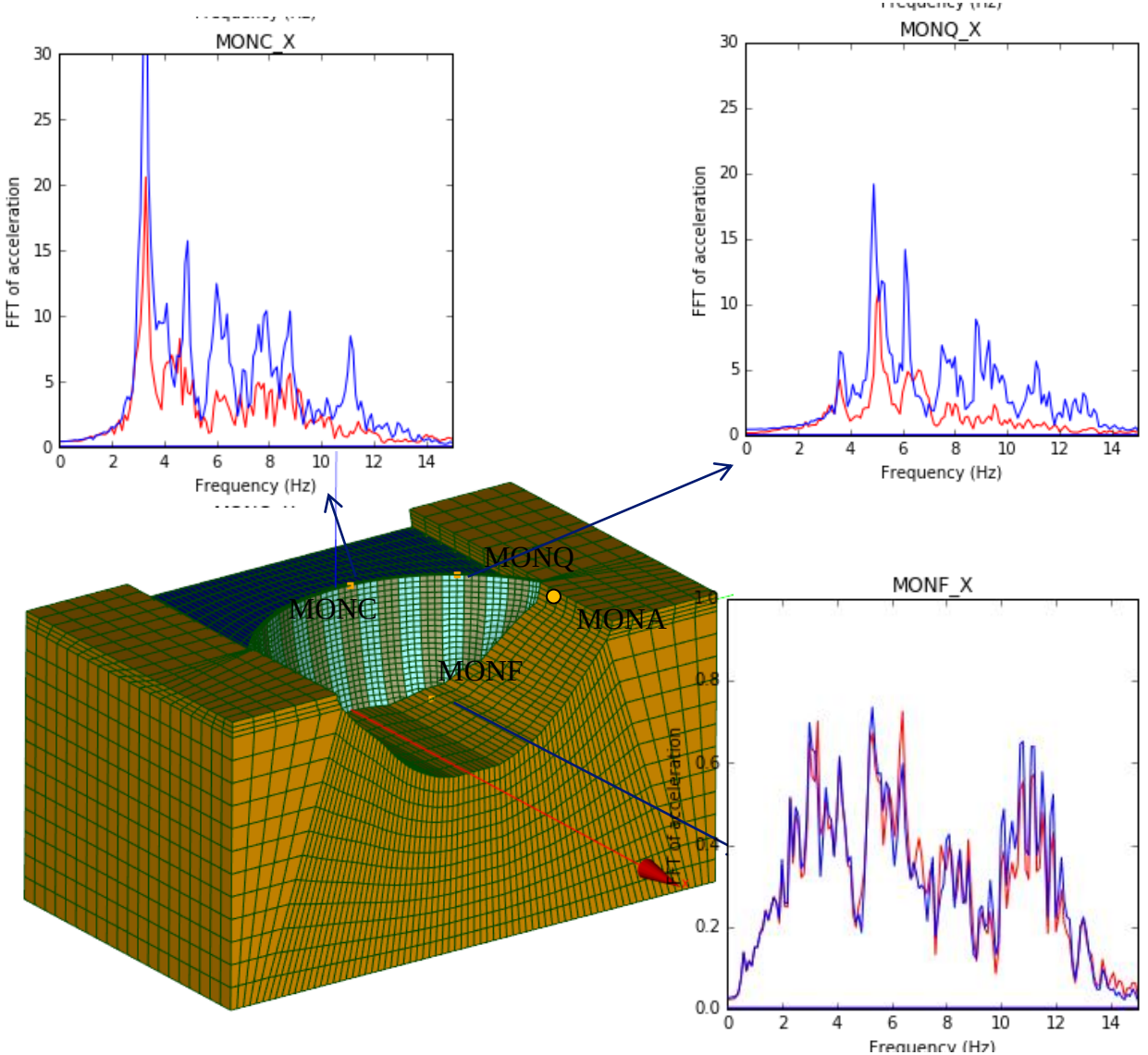
- **Blue computed**
- **Red recorded**
- **Input correctly introduced**
- **At the crest : FE model overestimates the response of the dam (x2)**



BACK ANALYSIS OF MONTICELLO ARCH DAM

FREQUENCIES COMPARAISON

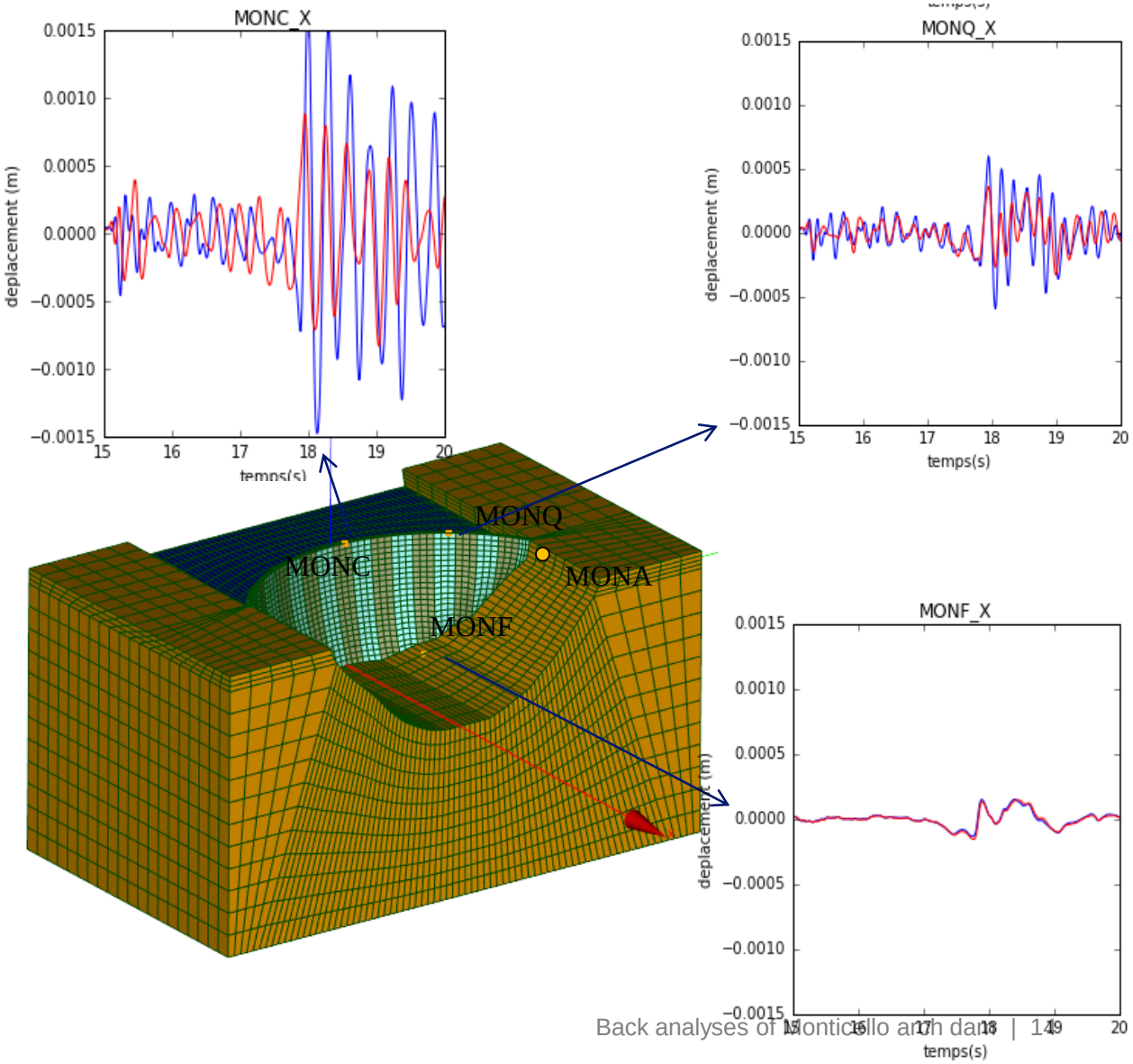
- **Blue computed**
- **Red recorded**
- **Frequencies of modes are correctly predicted**
- **Overestimation of the amplitude**
-



BACK ANALYSIS OF MONTICELLO ARCH DAM

DISPLACEMENT COMPARAISON

- **Blue computed**
- **Red recorded**
- **Overestimation of the displacements at the crest**



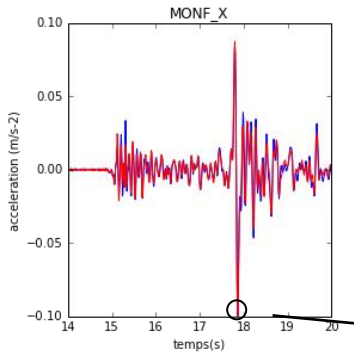
BACK ANALYSIS OF MONTICELLO ARCH DAM

CONCLUSION OF THE PREDICTION AND ADDITIONAL ANALYSES PROPOSED

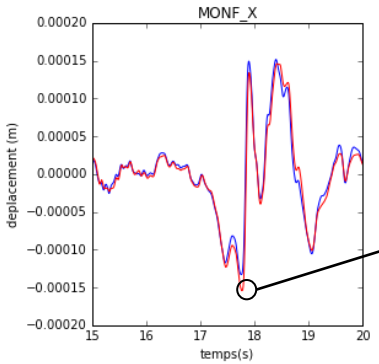
- **Prediction cannot be considered completely satisfying:**
  - Input correctly introduced in the FE model
  - Accelerations computed at the crest higher than the recorded ones.
  - Eigenfrequencies are correctly computed, but amplitudes are not.
  - Displacements at the crest, particularly in the upstream/downstream direction, are overestimated.
- **Additional analyses proposed**
  - Correction of the Rock Young Modulus
  - Influence of the concrete damping
  - Partial absorption of pressure wave at the reservoir bottom
  - Change of the earthquake input

ADDITIONNAL ANALYSES FOR MONTICELLO ARCH DAM

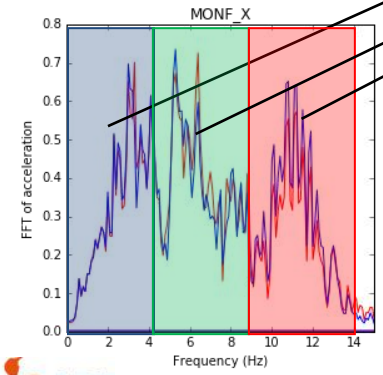
HOW TO COMPARE ?



PGA_{comp}/PGA_{rec}



PGD_{comp}/PGD_{rec}

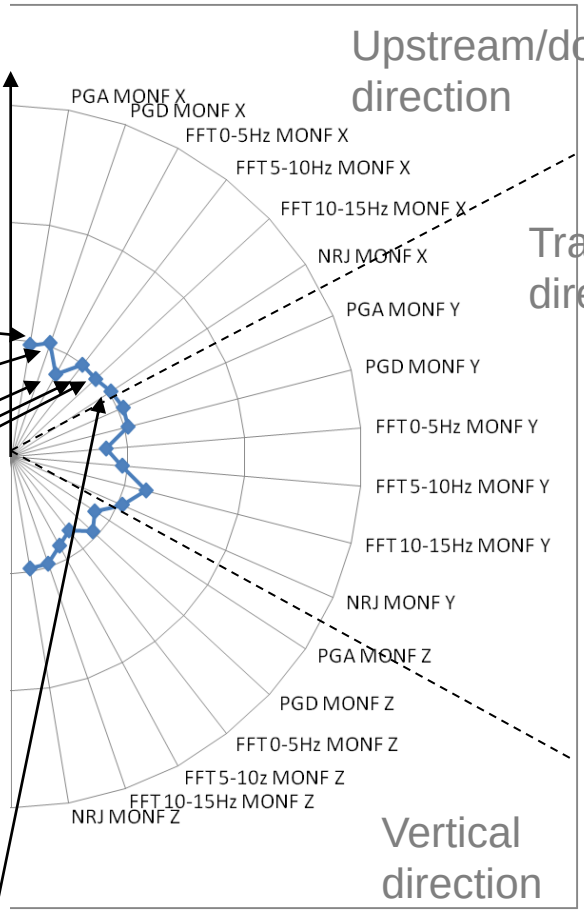


Mean (fft comp(f)/ fft rec(f))

For 1<f<5 Hz

5<f<10 Hz,

10<f<15 Hz,

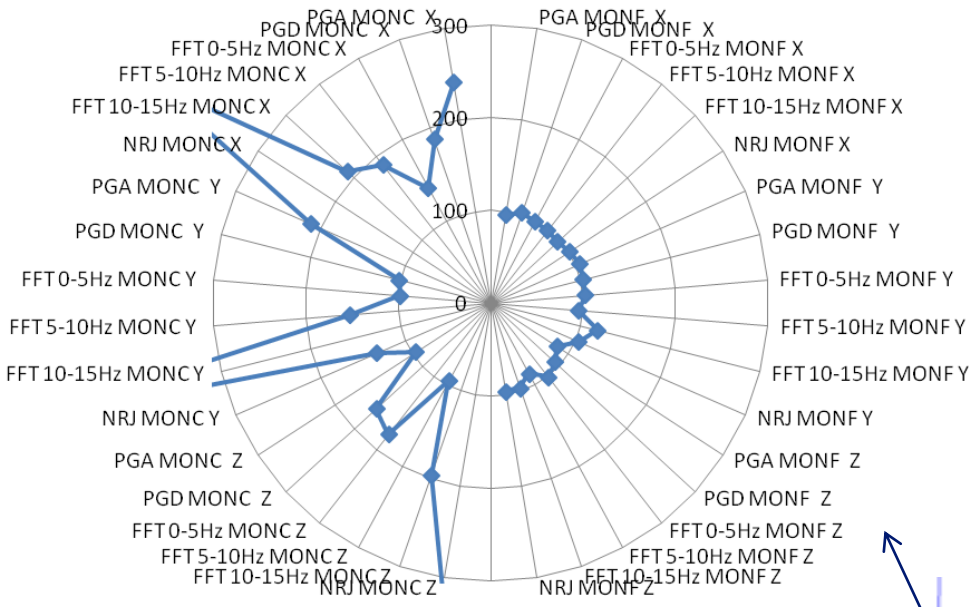


$$\int_0^t v_{comp}^2 \, \tau \, d\tau \Big/ \int_0^t v_{rec}^2 \, \tau \, d\tau$$

BACK ANALYSIS OF MONTICELLO ARCH DAM

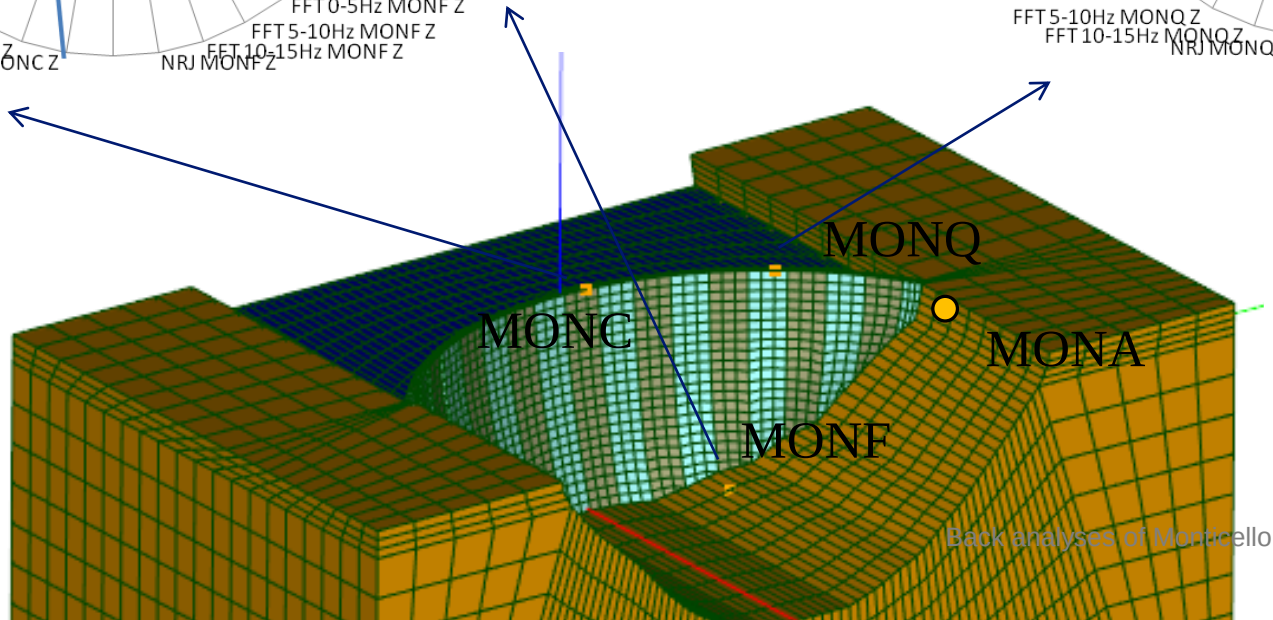
COMPARISON OF THE INITIAL PREDICTION AGAINST MEASURED DATA

MONC



MONF

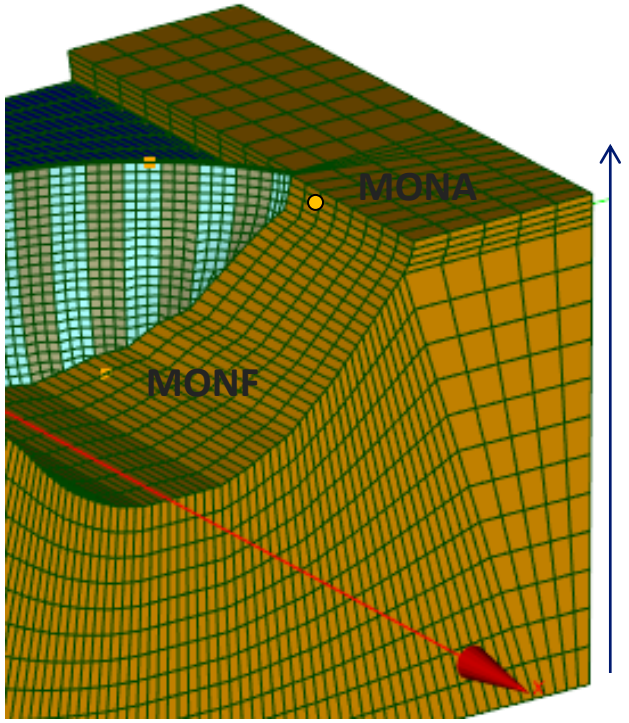
MONQ

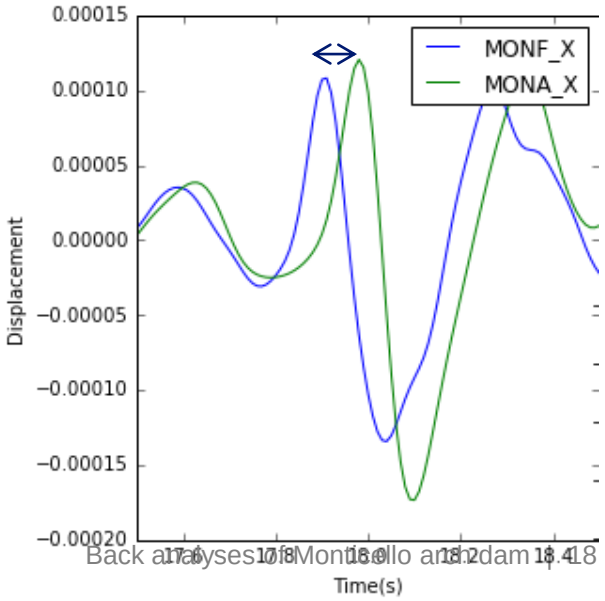


BACK ANALYSIS OF MONTICELLO ARCH DAM
CORRECTION OF THE ROCK YOUNG MODULUS

- **With recording devices at different levels of the foundation, it's possible to get some information of the wave velocity in the rock :**
  - From displacement : delay for the shear and compression waves to travel verticaly from MONF to MONA
    - 0.06s for shear waves
    - 0.04s for compression waves
  - Vertical distance between devices : 84m

→ Dynamic Rock Modulus : 10 000 MPa

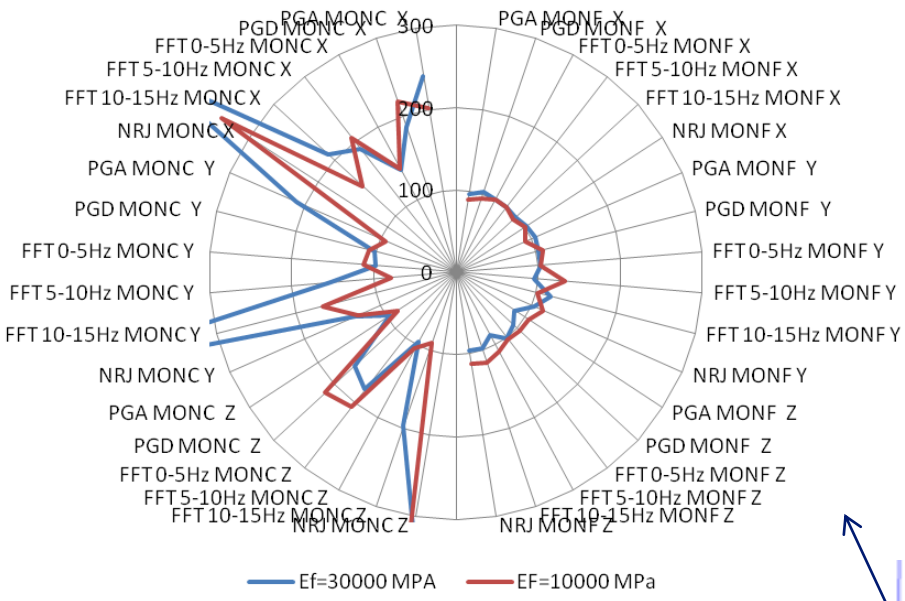




BACK ANALYSIS OF MONTICELLO ARCH DAM

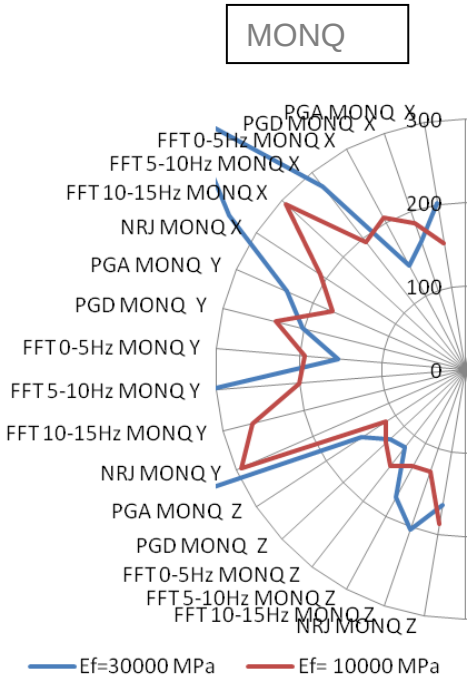
CORRECTION OF THE ROCK YOUNG MODULUS

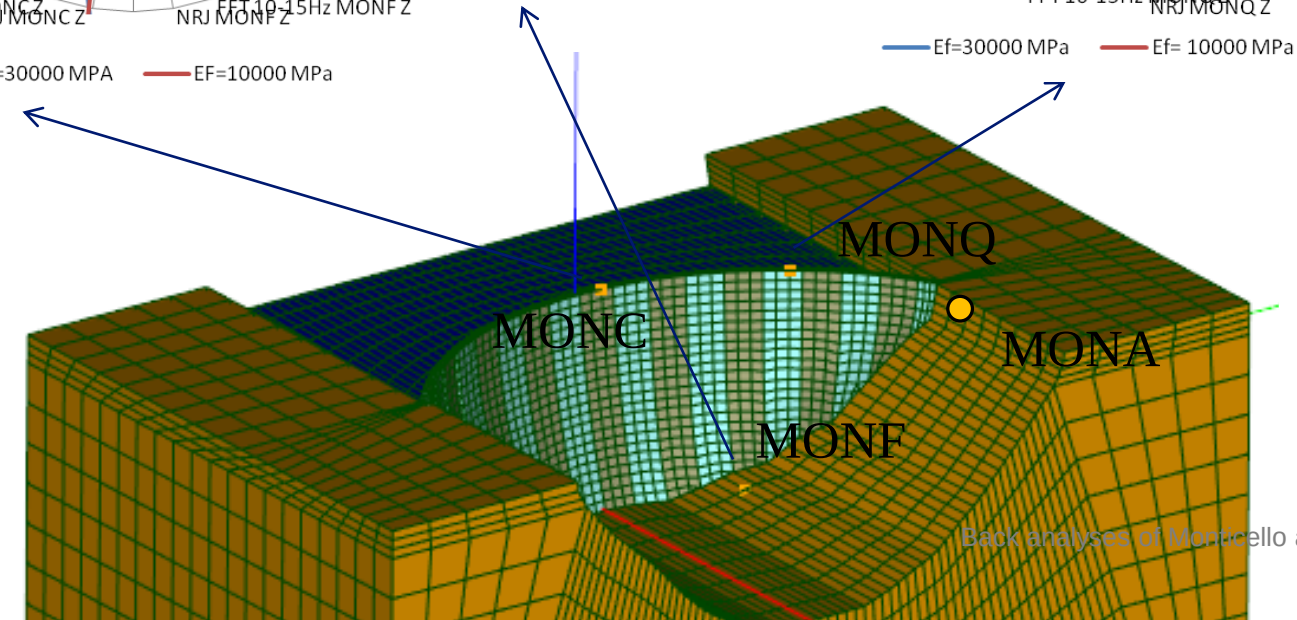
MONC



MONF

MONQ

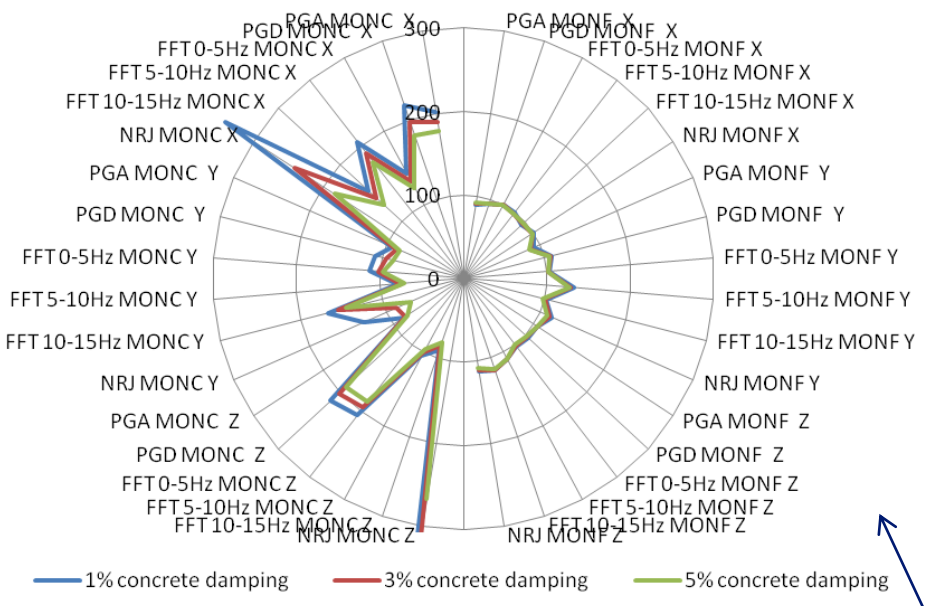




BACK ANALYSIS OF MONTICELLO ARCH DAM

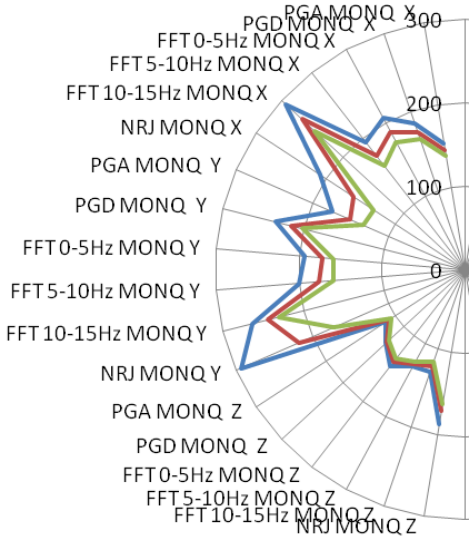
CONCRETE DAMPING : 1%, 3% AND 5%

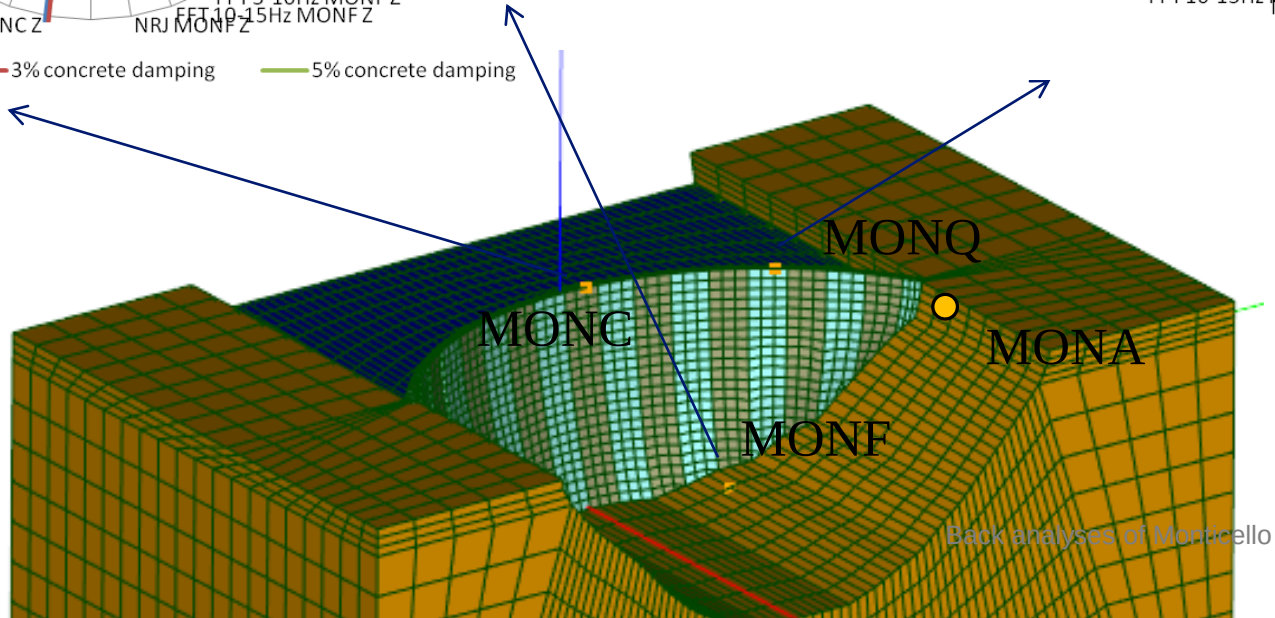
MONC



MONF

MONQ



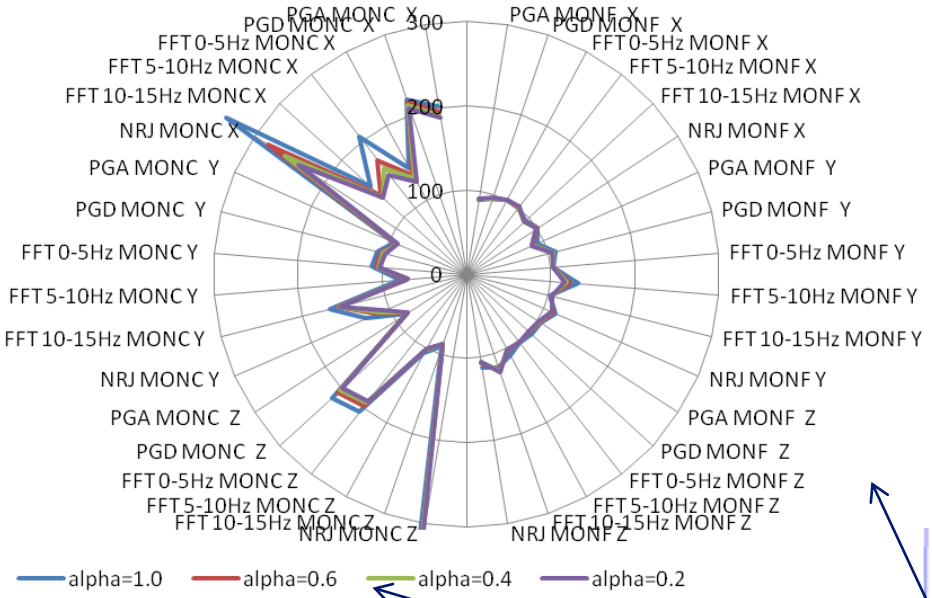


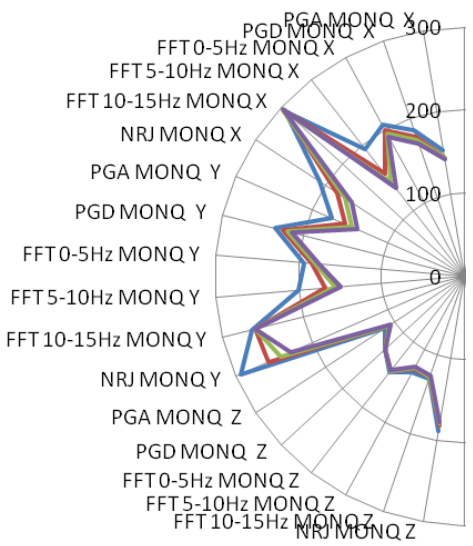
BACK ANALYSIS OF MONTICELLO ARCH DAM
PARTIAL ABSORPTION OF PRESSURE WAVES AT THE RESERVOIR BOTTOM

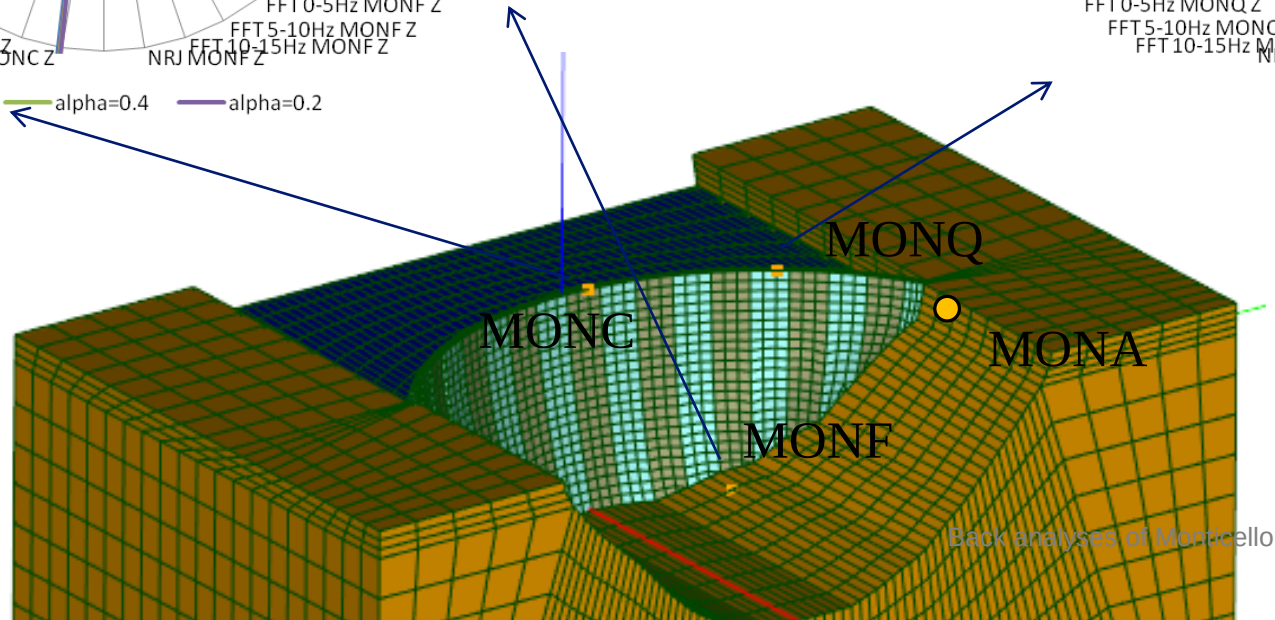
MONC

MONF

MONQ

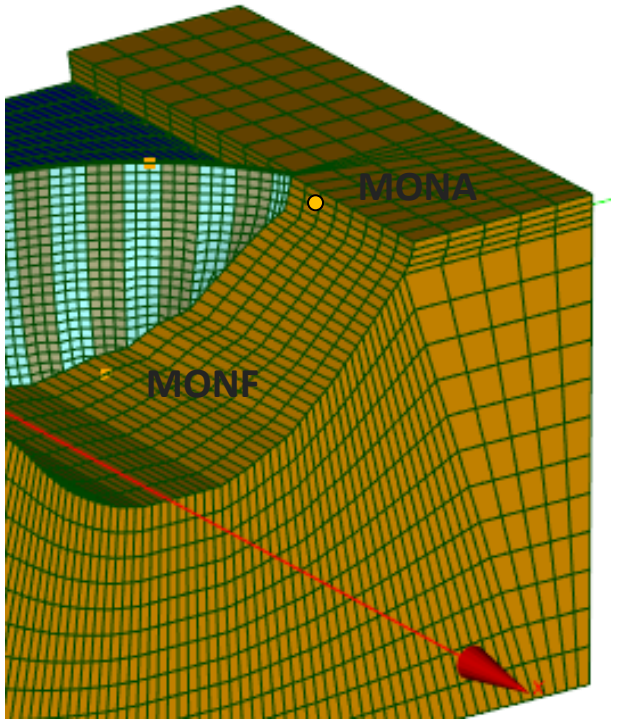






BACK ANALYSIS OF MONTICELLO ARCH DAM
EARTHQUAKE INPUT

- **At first records at the toe of the dam (MONF) used as input.**
- **Use of the records on the abutment of the dam (MONA) as input**



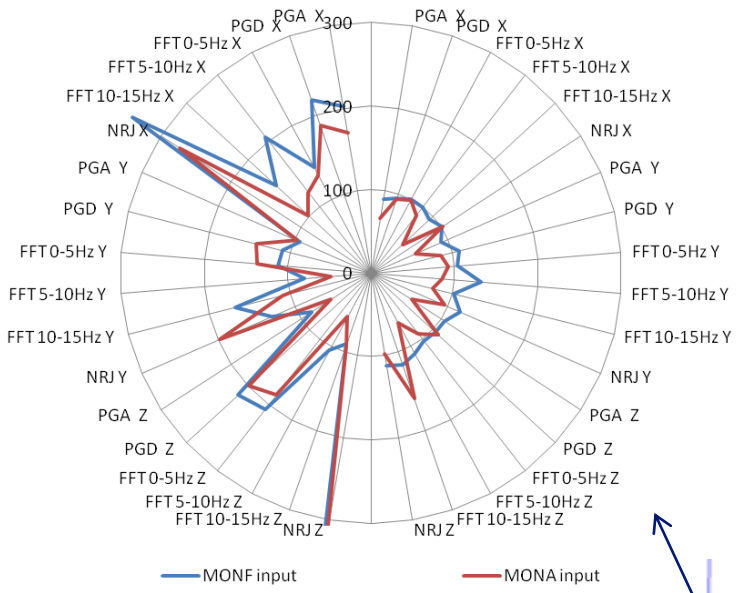
BACK ANALYSIS OF MONTICELLO ARCH DAM
CHANGE OF INPUT

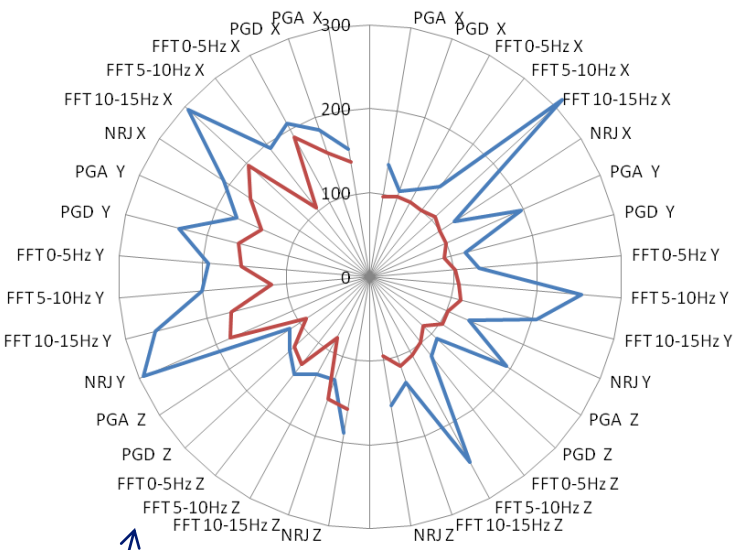
MONC

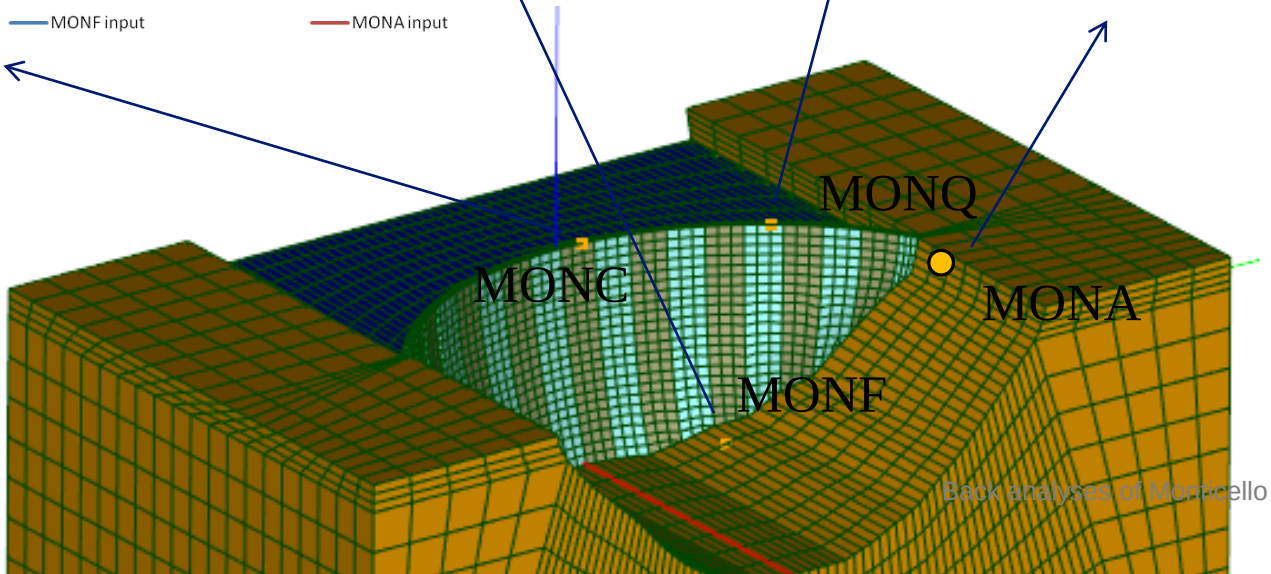
MONF

MONQ

MONA







BACK ANALYSIS OF MONTICELLO ARCH DAM

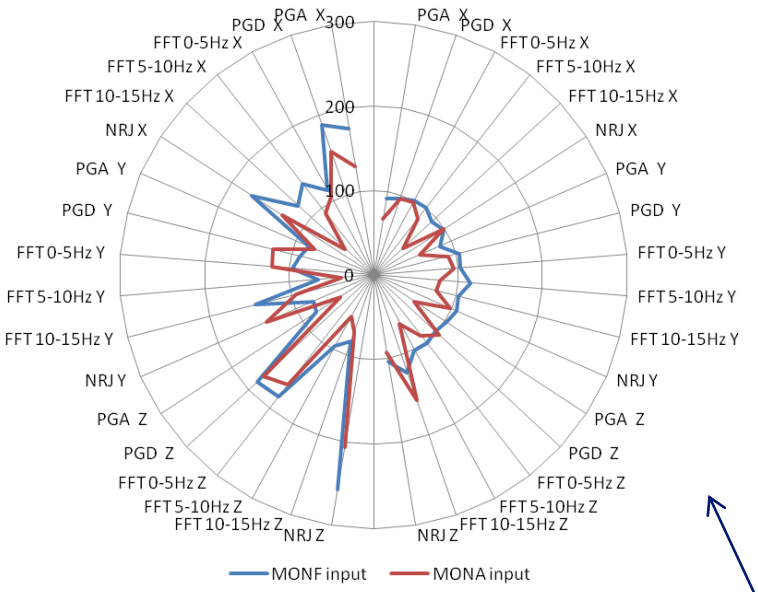
FINAL ASSUMPTIONS : 3% CONCRETE DAMPING / 10000 MPA ROCK / SEDIMENT ABSORPTION

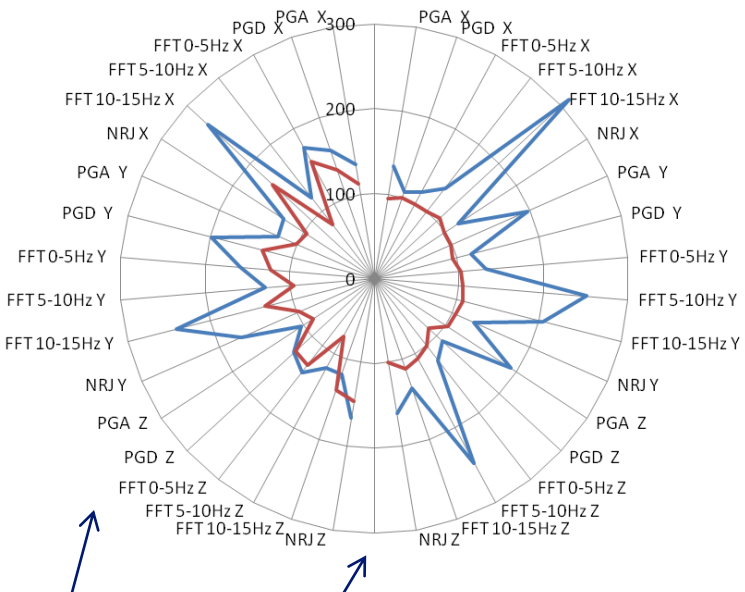
MONC

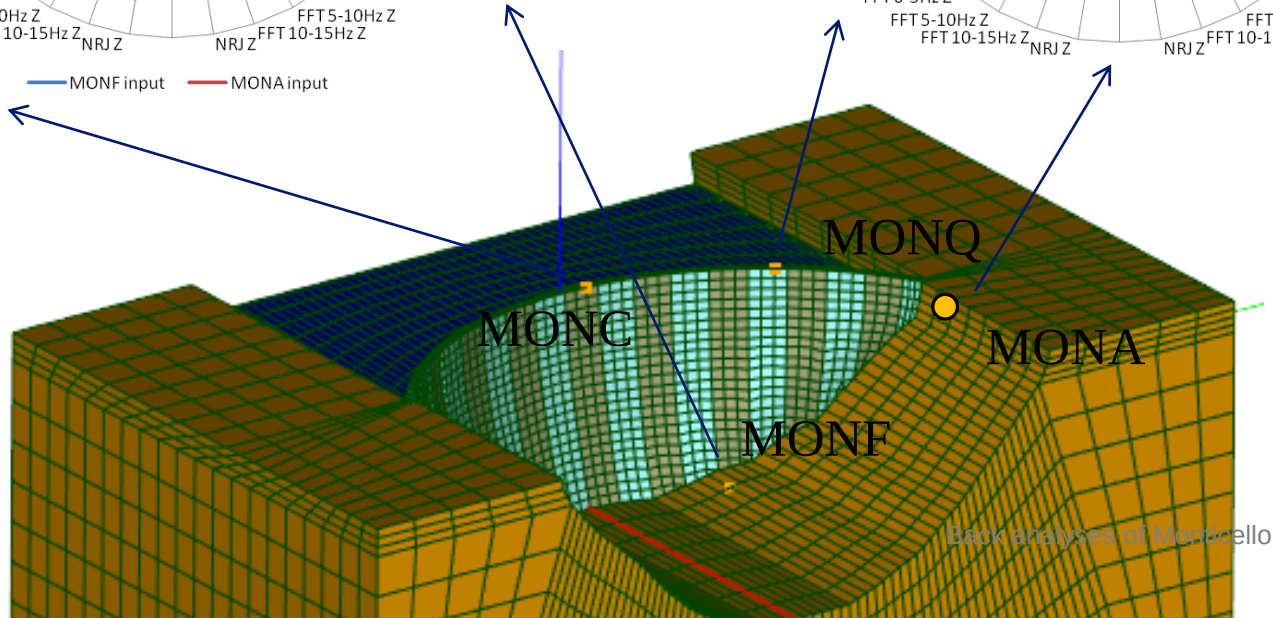
MONF

MONQ

MONA

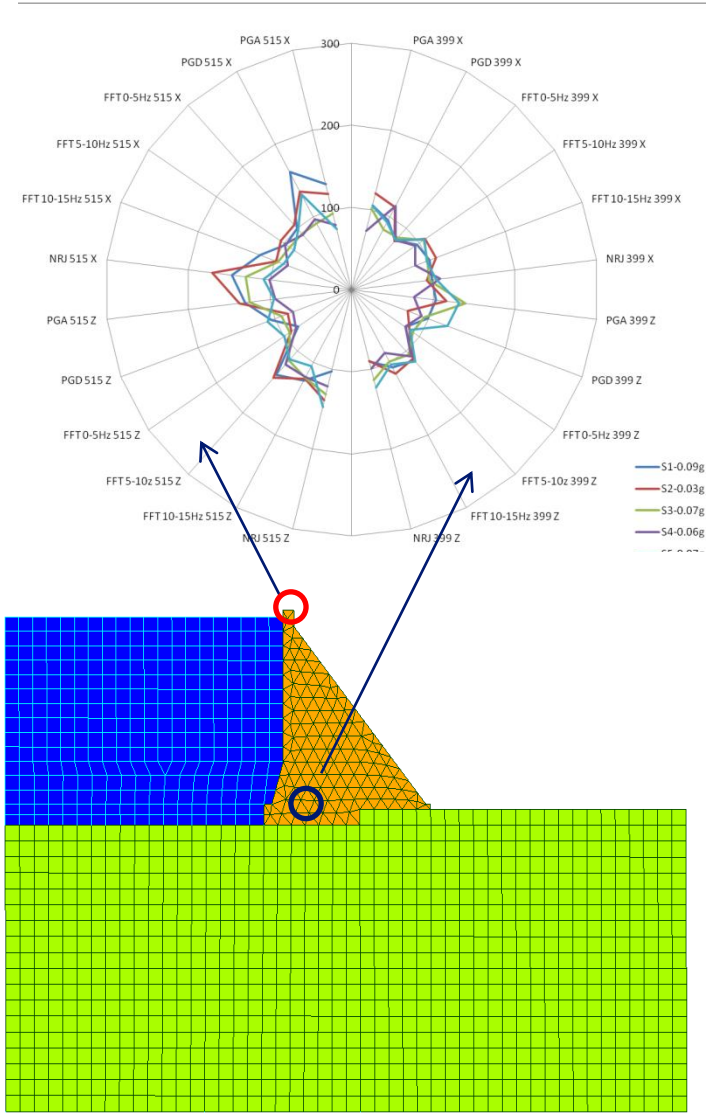




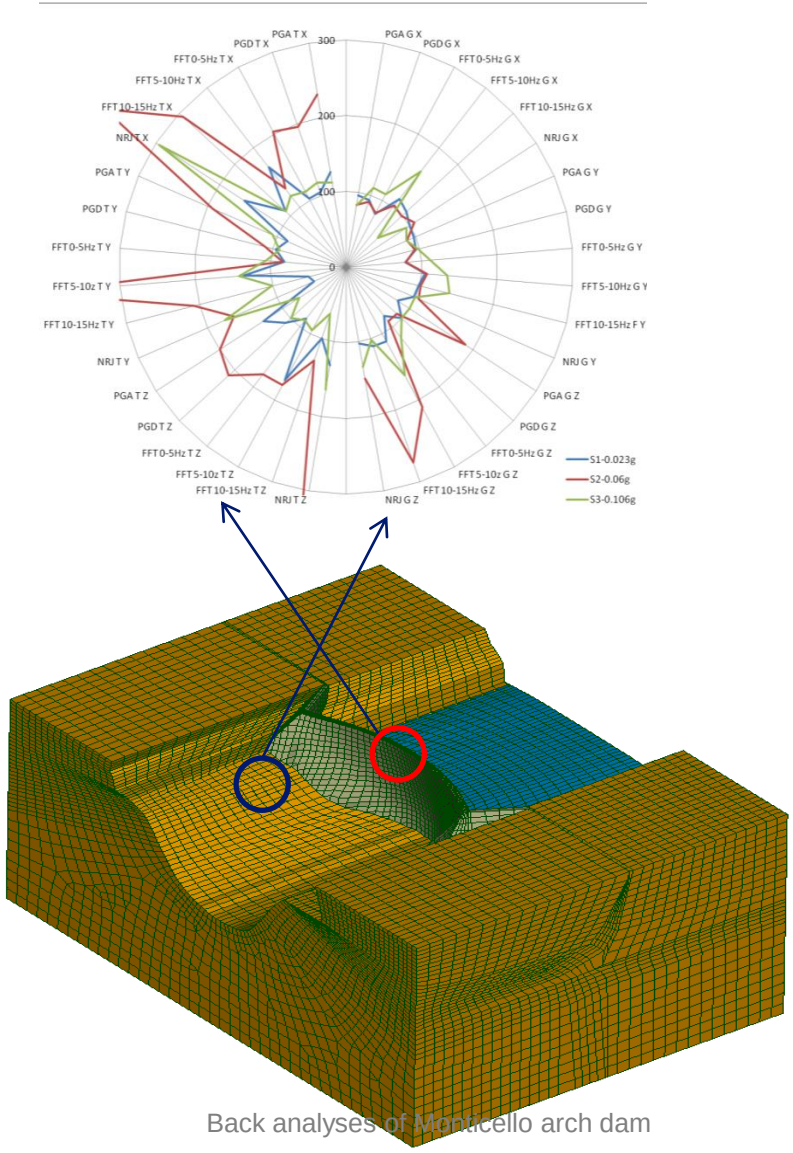


BACK ANALYSIS OF OTHER DAMS

TAGOKURA GRAVITY DAM AND KUROBE ARCH DAM FOR SEVERAL EARTHQUAKES



Overall damping between 10-20 % !)



Back analyses of Monticello arch dam

CONCLUSION

- **Development of FE approach to take into account soil-structure and fluid-structure interaction**
  - Based on verified bibliography
  - Validated on test case
  - Available in the EDF finite-element software Code_Aster (for engineers)
- **Comparison with records on Monticello dam :**
  - Blind prediction roughly overestimates 2x the response of the dam
  - Additional improvements but still overestimates by factor 1.5
  - Small earthquake : but let's try to be good with small before big
- **More details about similar studies**
  - 16th World Conference of Earthquake engineering in Chile
  - Next 2017 USSD conference

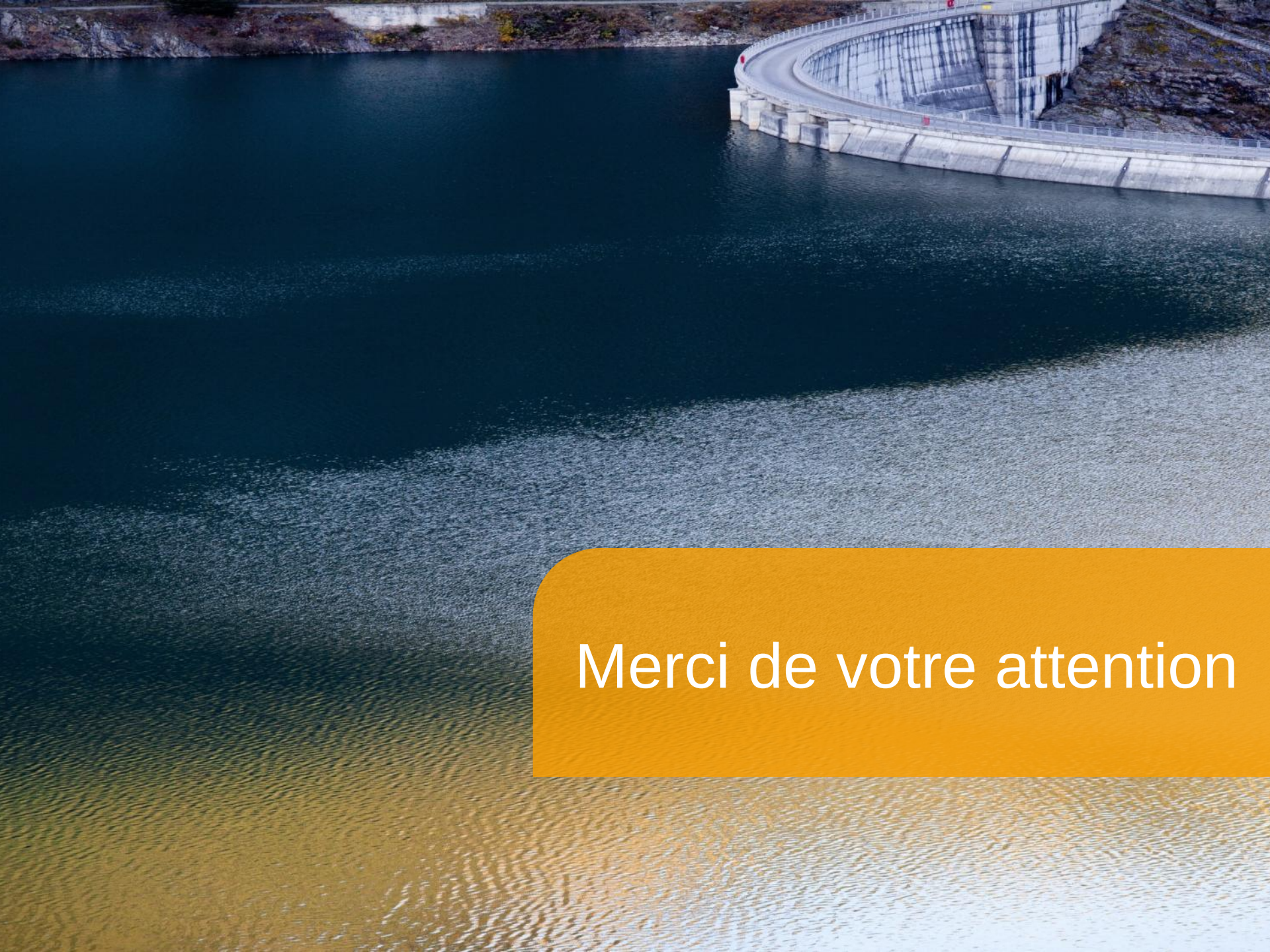
CONCLUSION

- **More comparisons between FE analyses and records on dams are needed but this requires :**
  - Complex FE analyses
  - Seismic data processing
  - Concrete dam's behavior knowledge
  - And….

EARTHQUAKES RECORDS ON DAMS !!!

  - Records can really help engineers to built better model to assess the safety of dams under earthquake (and avoid overestimation of the dam's response)
  - Can be temporary

  - **Concrete dams behave well under earthquake : let's prove it !**


Merci de votre attention