International Symposium
Qualification of dynamic analyses of dams and their equipments
and of probabilistic assessment seismic hazard in Europe
31th August – 2nd September 2016 – Saint-Malo

Emmanuel Robbe, Julie Fouqué, Bruno Pallu

Session :

Seismic analyses of concrete dams : comparison between finite-element analyses and records

Saint-Malo © Yannick LE GAL

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.

JCOLD/CFBR COLLABORATION FOR CONCRETE DAMS COMPARISON BETWEEN FE ANALYSES AND RECORDS

- **Evaluate the existing and well-known methods for seismic assesment of gravity and arch concrete dams by comparison with records on dams**

- **Improvement of the FE analyses to better represent the earthquake records on concrete dams**

- **Assessment of the news FE methods**

- **2014's work :**
  - Comparison of the well-know FE method with massless foundation and Westergaard added masses with records
  - Show an important overestimation of the dam's response with the usual 5% damping for concrete

- **2015 work :**
  - New soil-structure and fluid-structure interaction method
  - Analyses on 1 earthquake for Tagokura gravity dam and Kurobe arch dam

- **2016's work :**
  - Consolidation of the method with additional analyses

SUMMARY

FINITE ELEMENT METHOD

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

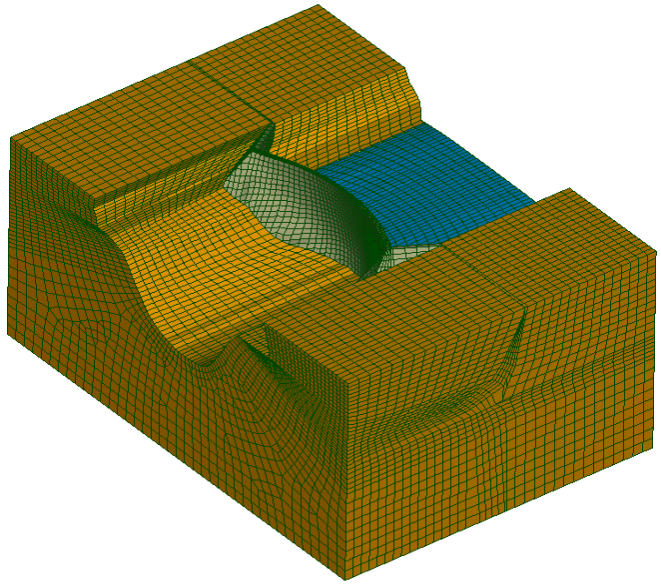
Massless foundation + Westergaard added masses	mass foundation + viscous-spring-boundaries + fluid finite element
- commonly used in engineering practice (ex. CIGB workshop in Lausanne 2015), easy to use (modal analyses..)	- less used and more complex : + take into account the propagation of the wave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

- **Goal :assess the consistency of the numerical results compare to records on concrete dams**

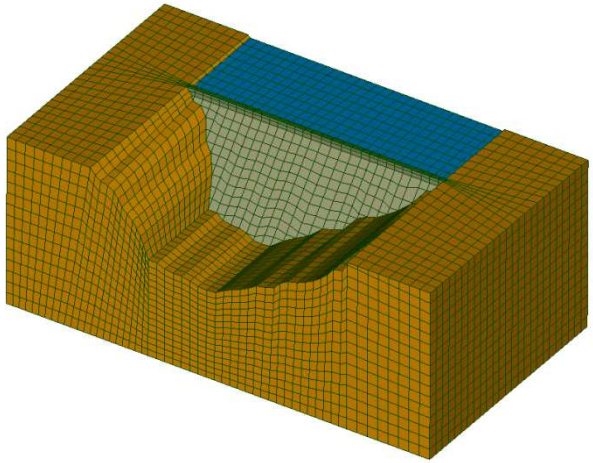
PRESENTATION OF IMPROVED FINITE ELEMENT ANALYSES

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)

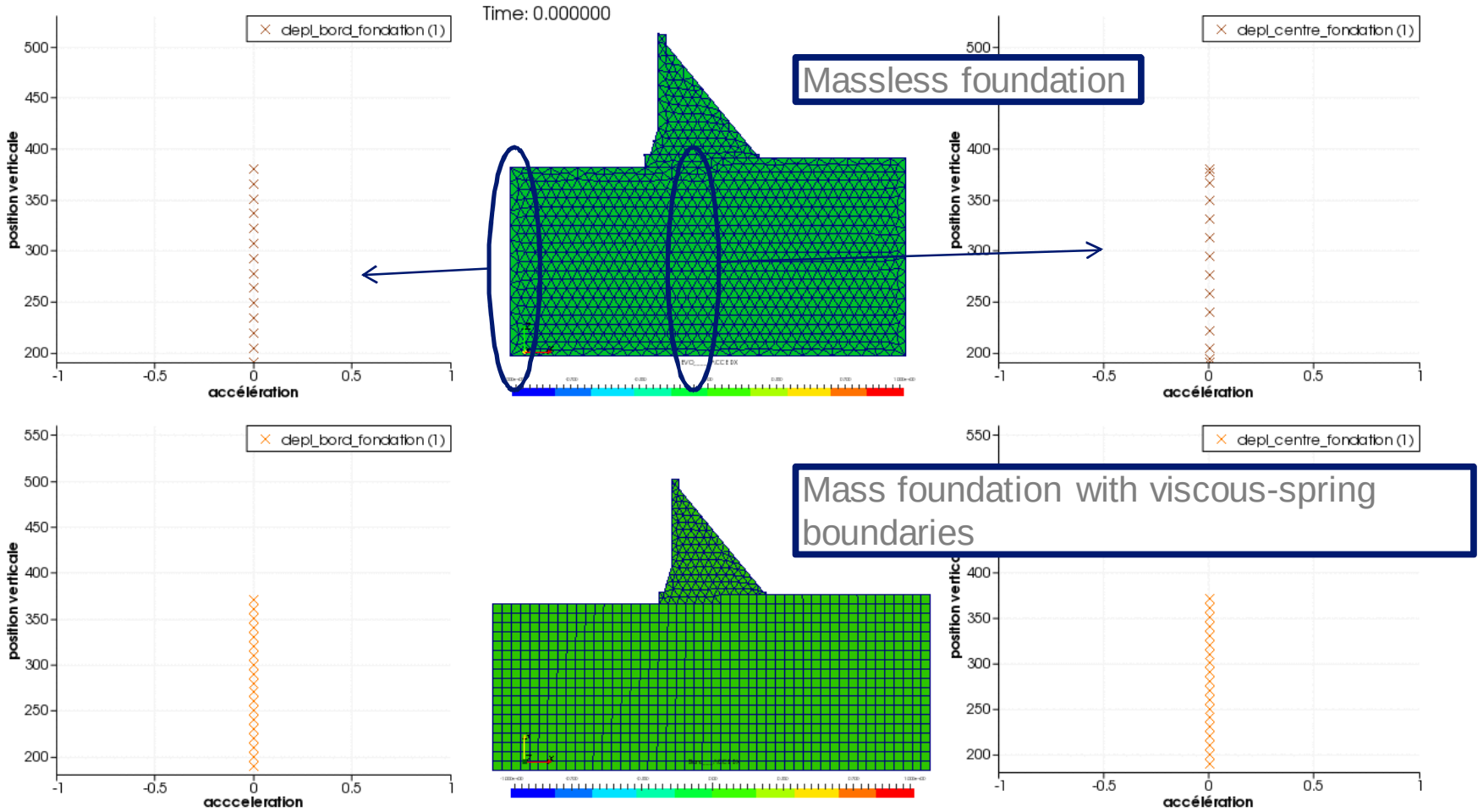


- **Test cases**
  - Comparison of simple to more complex test cases issue from the previous references



- **Software :**
  - Analyses are carried out with Code_Aster (made by EDF, open-source)
- **Incoming paper in the next 2017 WCEE conference**

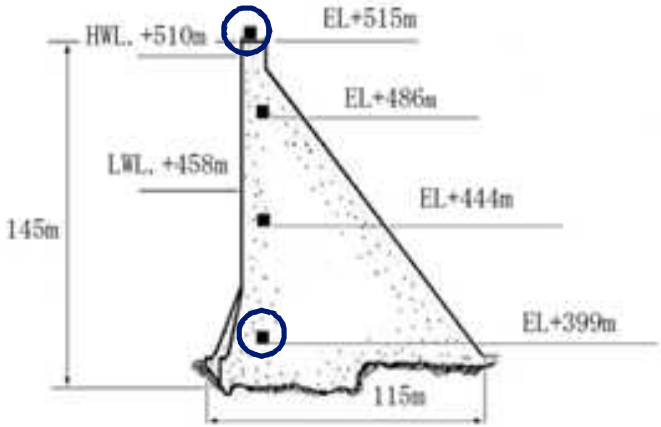
VISUALISATION OF THE EARTHQUAKE INPUT



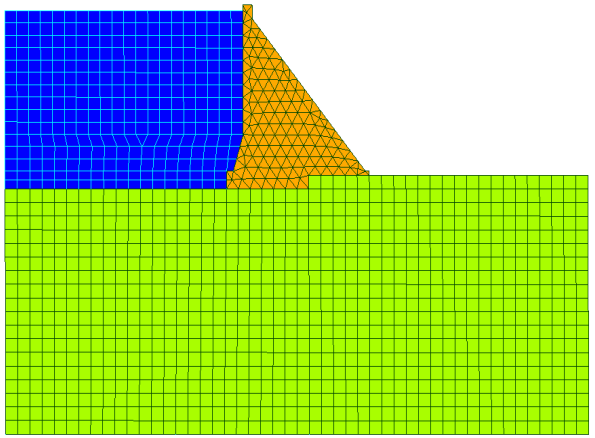
SUMMARY

BACK ANALYSIS OF DAMS
METHODS AND COMPARISON CRITERIA

- **Methodology**
  - Use of the bottom record as input signal for the FE analysis (us/ds and vertical direction for 2D analyses, 3 directions in cas of 3D model)
  - Comparison of the response in the crest (515) but also in the bottom (399) of the dam



- **Compared approaches**
  - Massless foundation and Westergaard added masses (5% concrete damping)
  - Viscous-spring boundary (VSB) and fluid element (1% concrete damping)



BACK ANALYSIS OF DAMS *DAMS AND EARTHQUAKE*

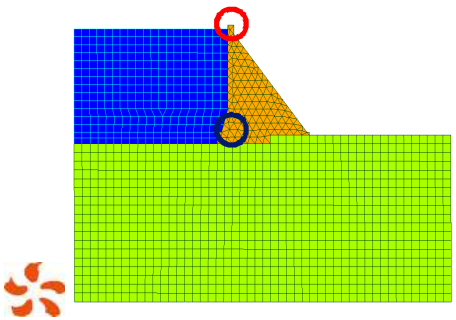
TAGOKURA dam

- Gravity dam
- Height : 145 m
- Crest length : 462m
- Dam Volume : 1950000 m3
- Japan

Earthquakes considered in october 2004 :

- 23th-17:56 : M6.8 - 0.09g
- 23th-18:03 : M6.3 – 0.03g
- 23th-18:34 : M6.5 – 0.07g
- 23th-23:34 : M5.3 – 0.06 g
- 27th-10:40 : M6.1 - 0.07g

2D finite-element analyses



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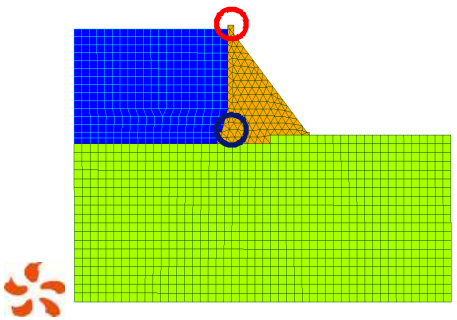


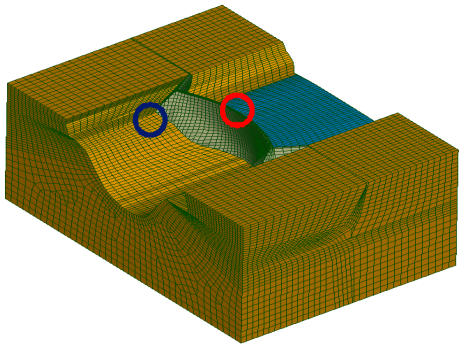
KUROBE dam

- Arch dam
- Height : 186 m
- Crest length : 492m
- Dam Volume : 1582000 m3
- Japan

Earthquakes considered :

-25/03/2007 : M6.9 - 0.023g
-11/03/2011 : M4.1 - 0.059g
-05/10/2011 : M5.2 - 0.106g

3D finite-element analyses



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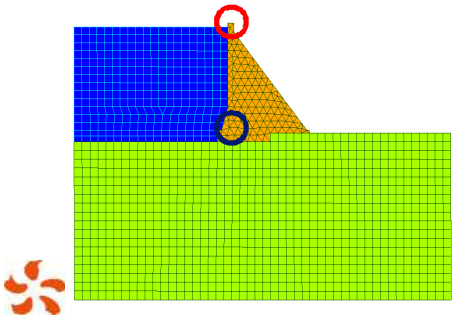

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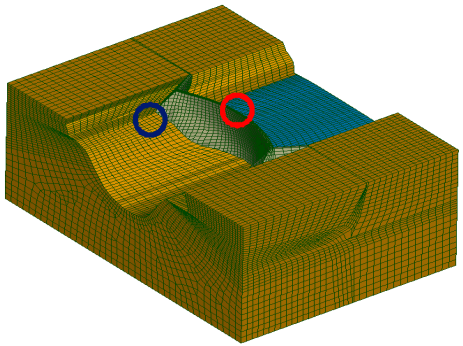


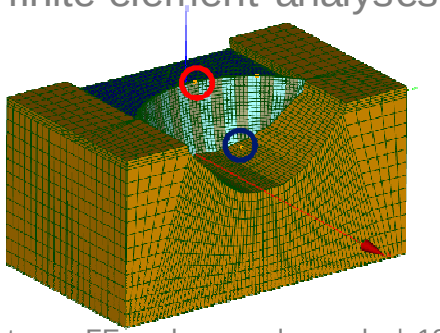
MONTICELLO dam

- Arch dam
- Height : 93 m
- Crest length : 312m
- Dam Volume : 249000 m3
- USA (CA)

Earthquake considered :

-22/05/2015 : M4.1 - 0.01g

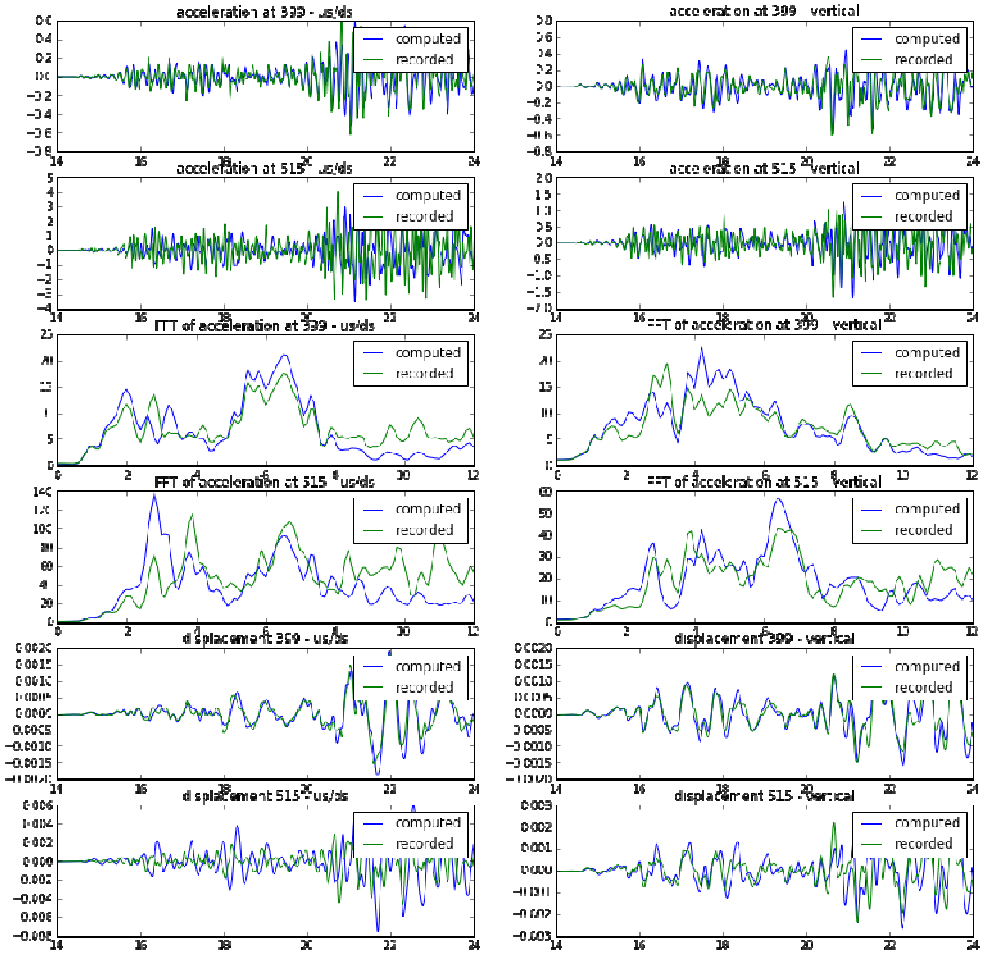
3D finite-element analyses



BACK ANALYSIS OF DAMS *HOW TO COMPARE ?*

- **In order to compare several results on several dams with several earthquakes, there is a need of a tool to compare results**

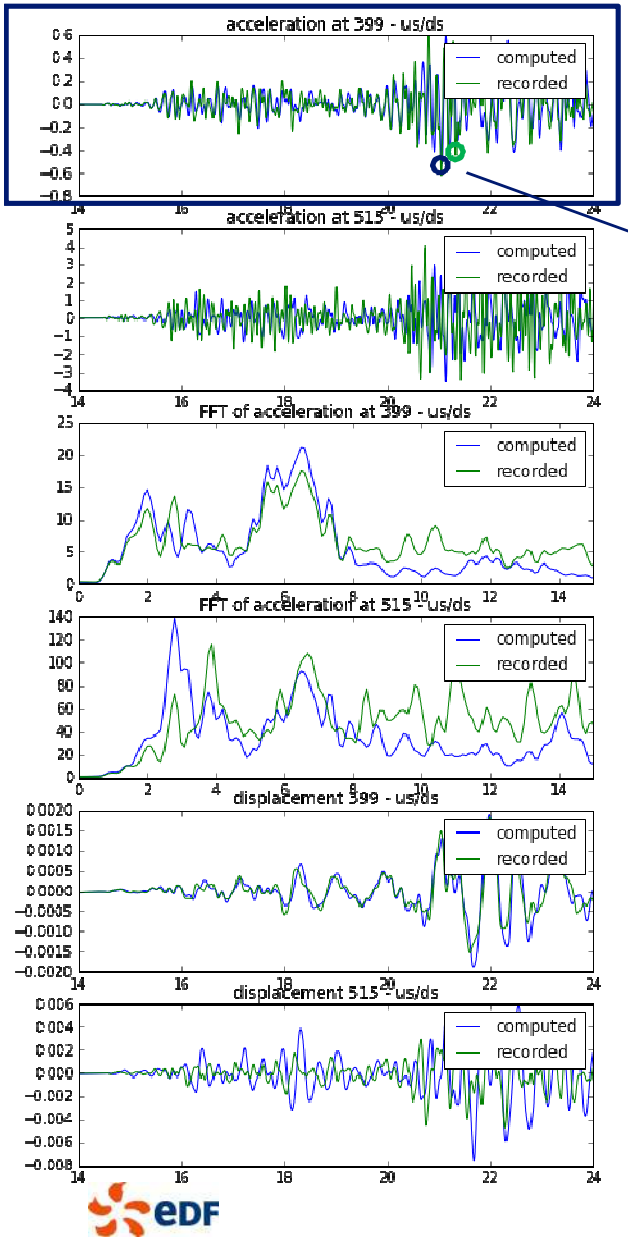
Results to compare for 1 dam and 1 earthquake



BACK ANALYSIS OF DAMS *HOW TO COMPARE ?*

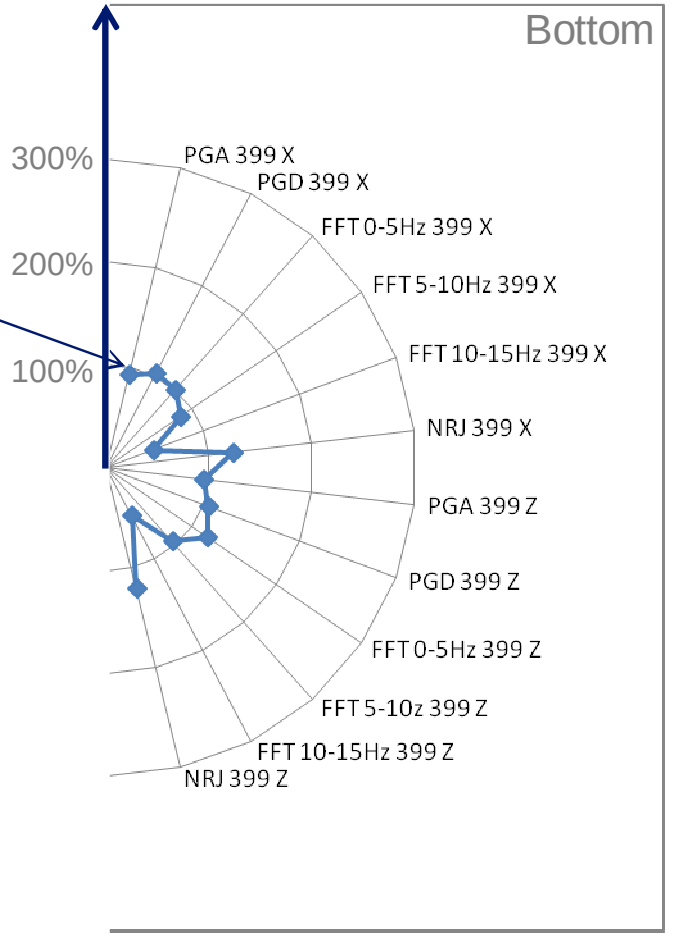
- **In order to compare several results on several dams with several earthquakes, there is a need of a tool to compare results**
- **Inspired by 'the goodness of fit' (Anderson 2004) method that gives some score to characterize how well a synthetic seismograms matches statistical characteristics of observed records.**
- **The following caracteristics are considered for concrete dams :**
  - Peak Ground Acceleration (PGA in each direction)
  - FFT of acceleration
  - Energy $I_{Ei}(t) = \int_0^t v_i^2(\tau) d\tau$
  - Peak Ground Displacement (PGD in each direction)

BACK ANALYSIS OF DAMS *HOW TO COMPARE ?*



PGA comp / PGA rec

Ratio Computed/Recorded (%)



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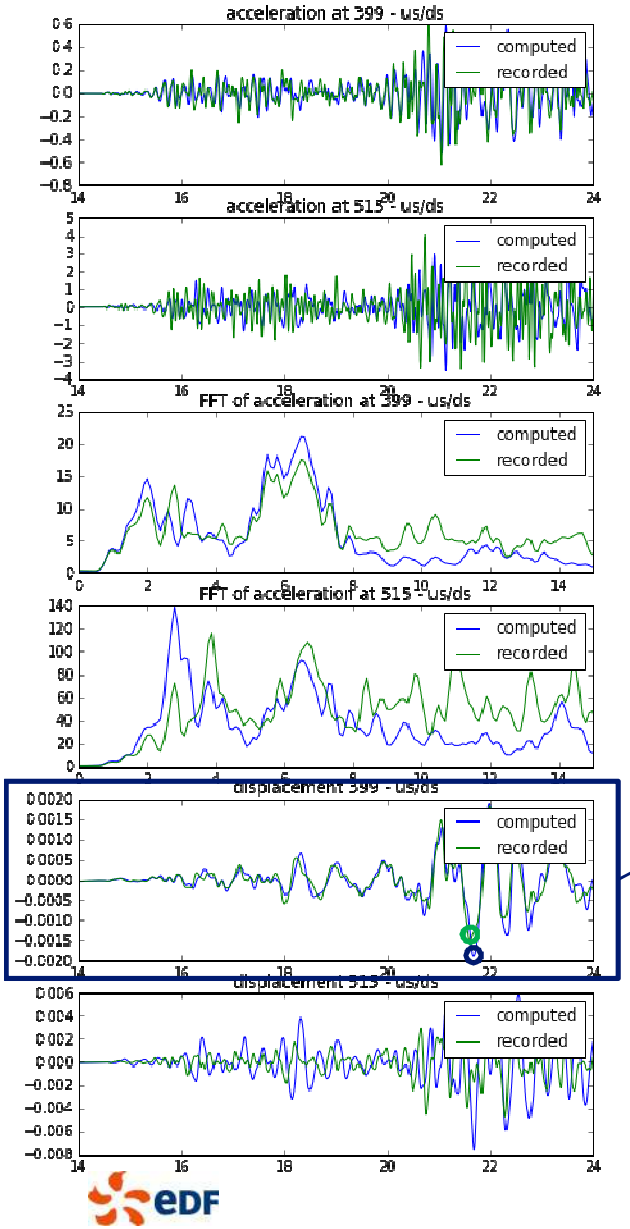
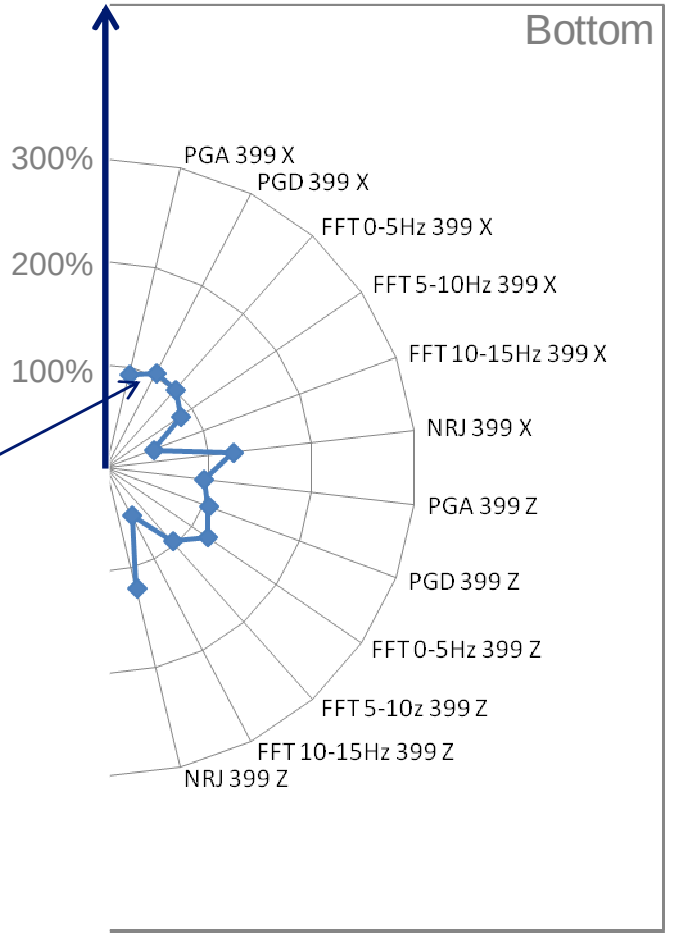


PGD comp / PGD rec

Ratio Computed/Recorded (%)



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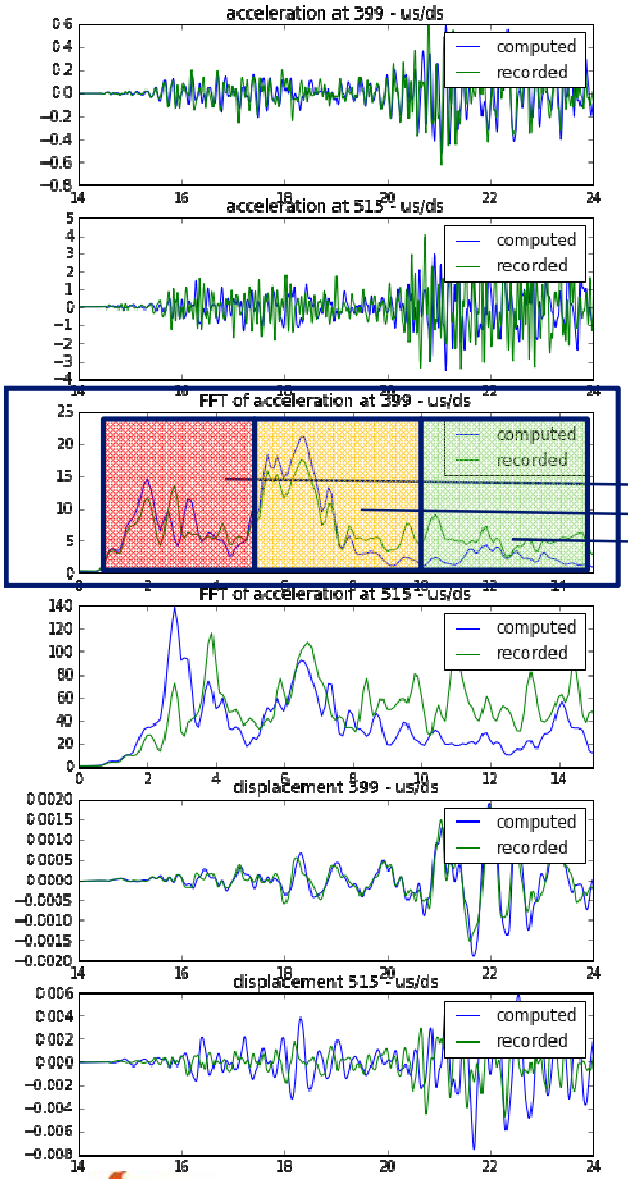
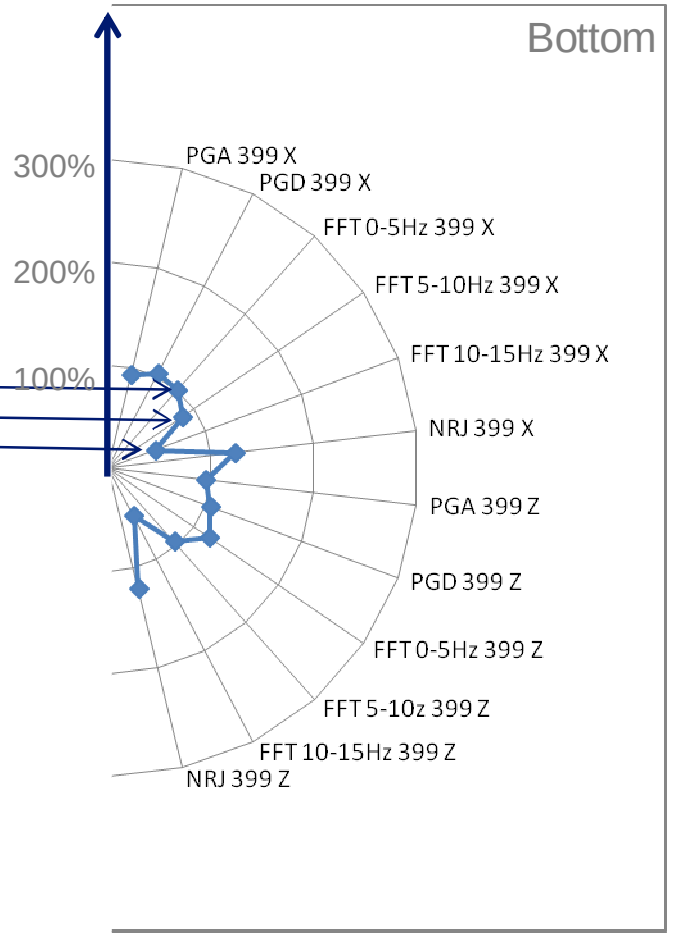


Mean (fft comp(f)/ fft rec(f))
For 1<f<5 Hz, 5<f<10 Hz,
10<f<15 Hz

Ratio Computed/Recorded (%)



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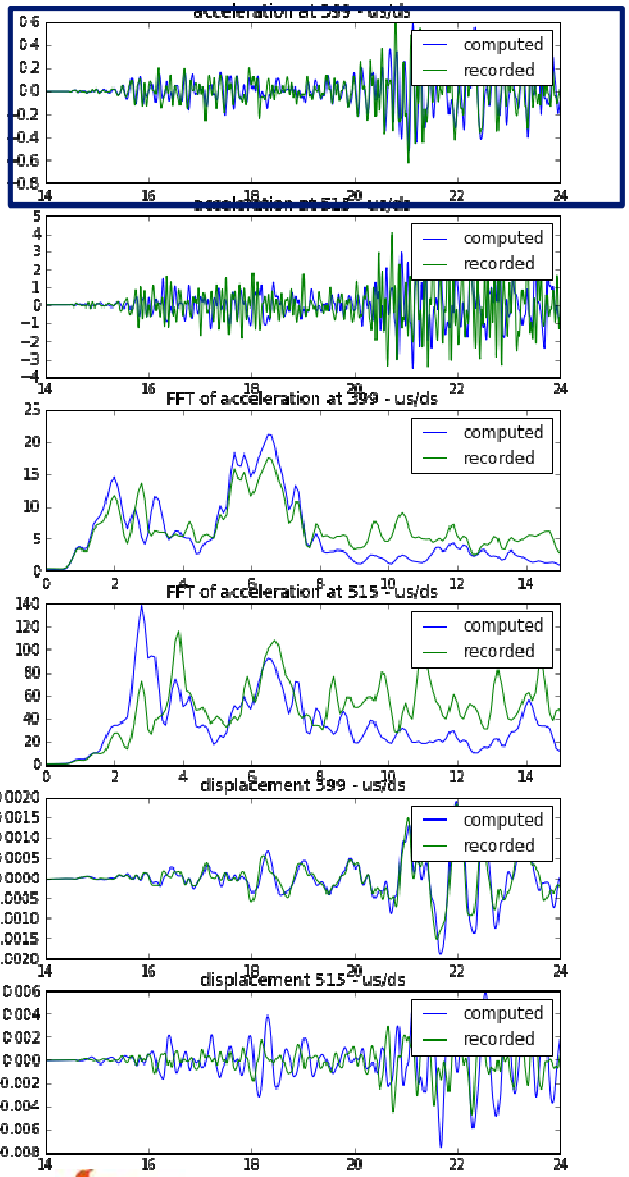
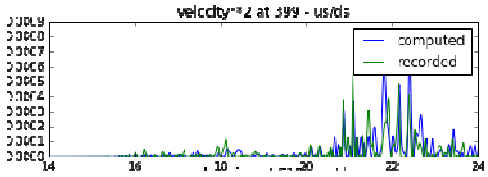
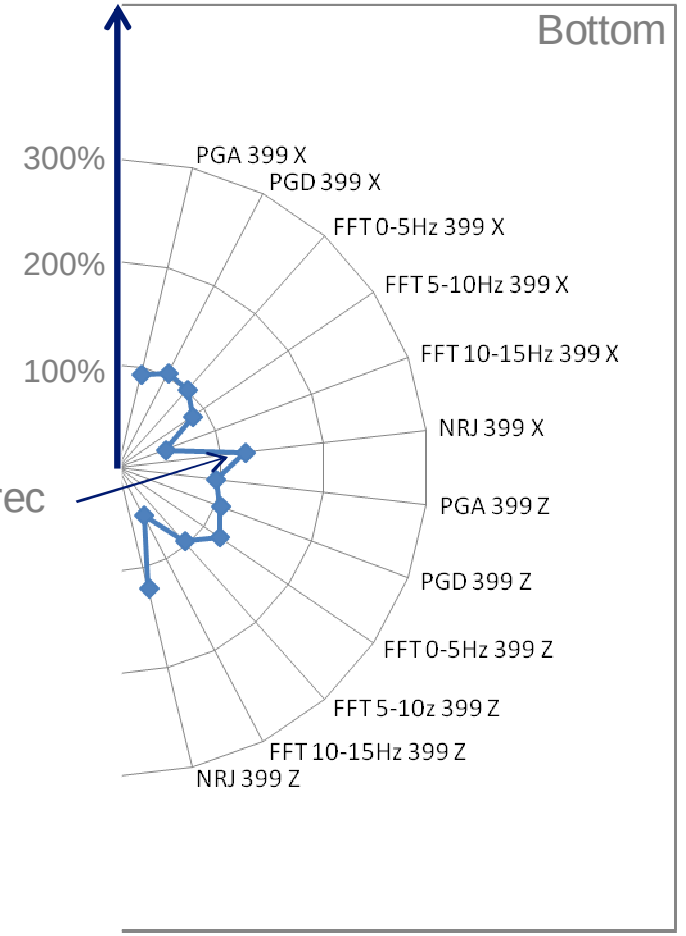




$$I_{Ei}(t) = \int_0^t v_i^2(\tau)d\tau$$

le comp/ le rec

Ratio Computed/Recorded (%)



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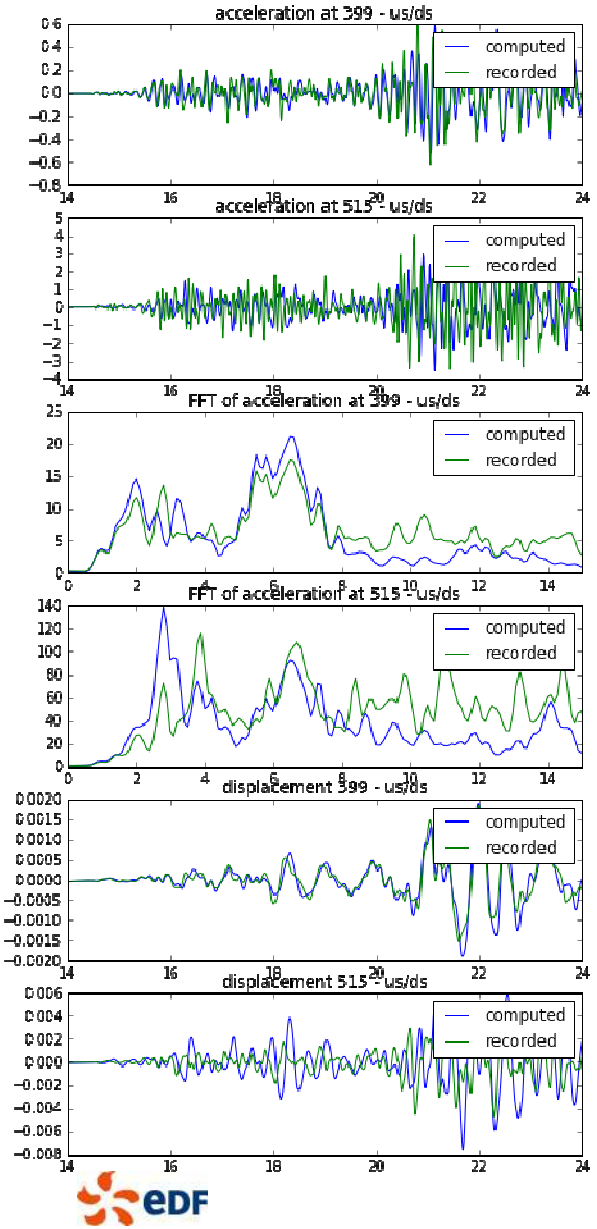
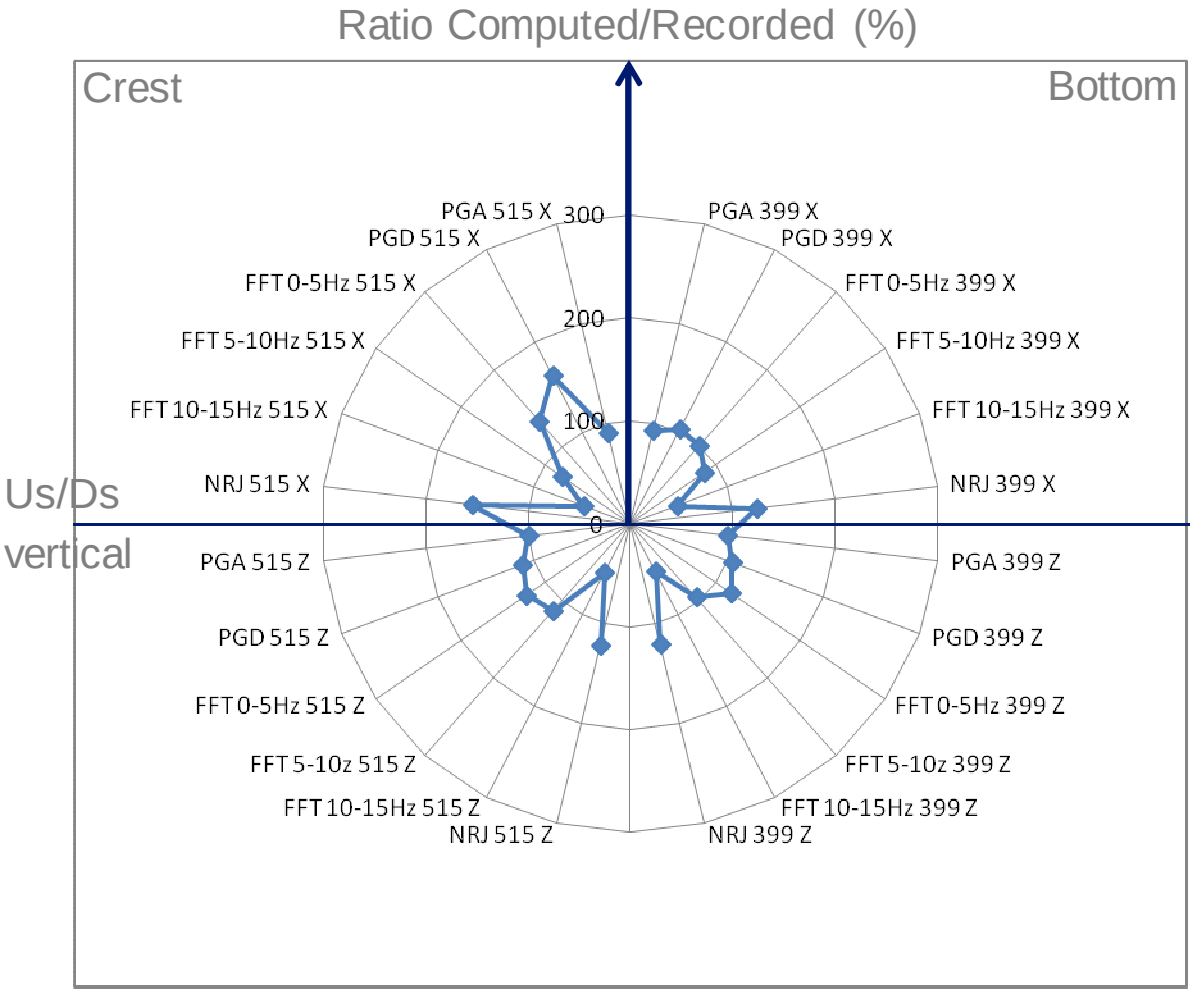
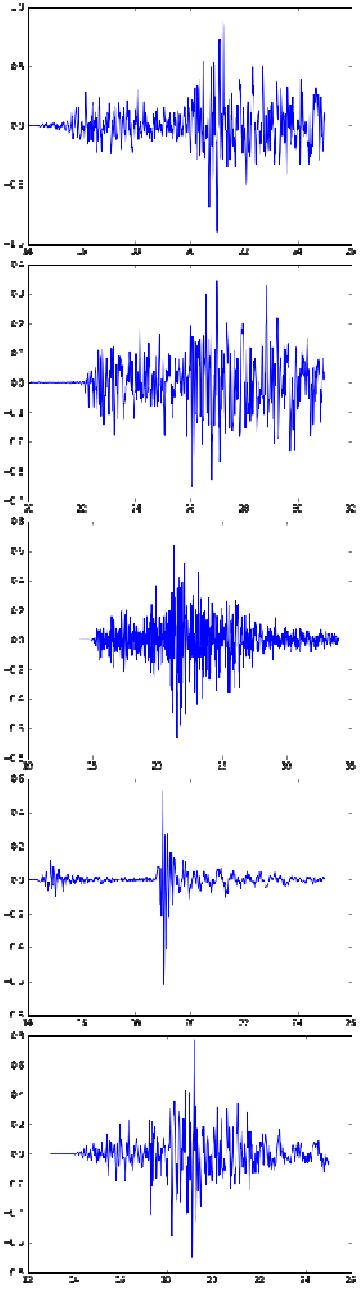
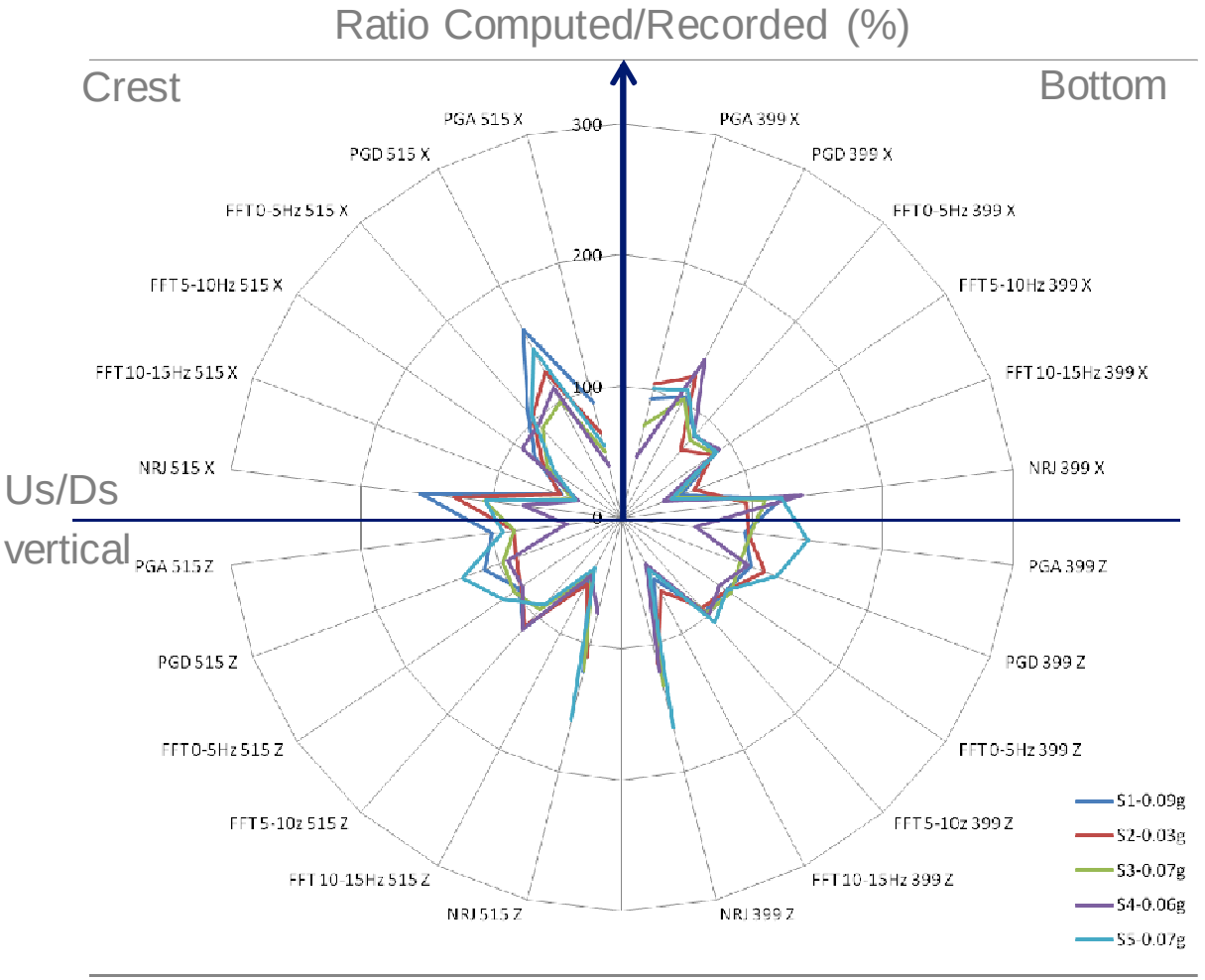




BACK ANALYSIS OF DAMS *TAGOKURA DAM*

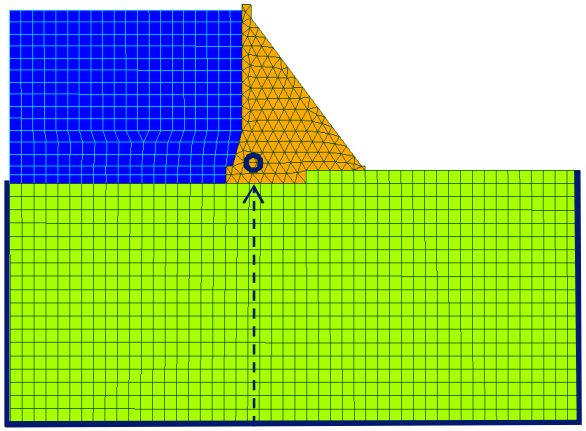
VISCOUS-SPRING BOUNDARIES WITHOUT DECONVOLUTION





BACK ANALYSIS OF DAMS *TAGOKURA DAM*
DECONVOLUTION PROCESS

Signal introcuded at the bottom of the foundation is slightly changed when reaching the bottom of the dam (where it was recorded)



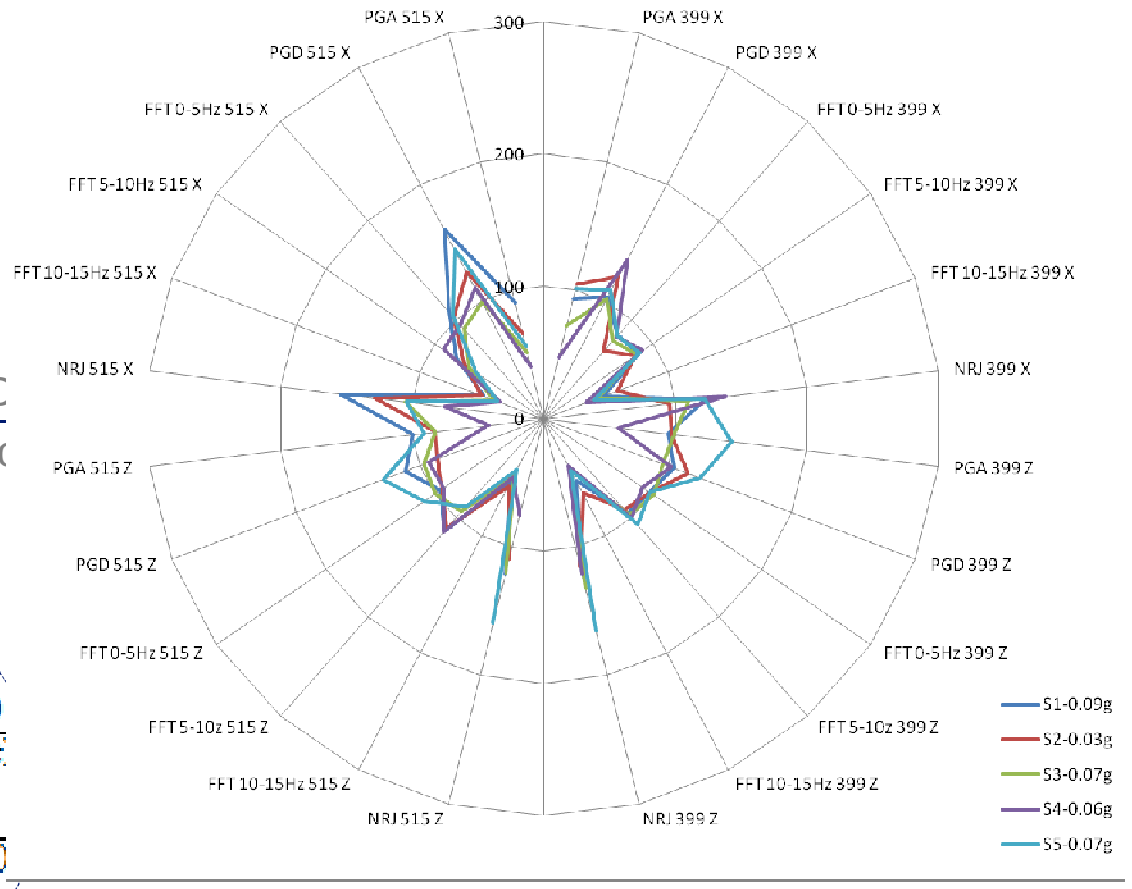
Us/D
vertic

$$acc_{x\,dec}(t) = fft^{-1}\left[fft[acc_{x_{rec}}(t)] \times \frac{fft[acc_{x_{rec}}(t)}{fft[acc_{x_{comp}}(t}\right.$$

$$acc_{z_{dec}}(t) = fft^{-1}\left[fft[acc_{z_{rec}}(t)] \times \frac{fft[acc_{z_{rec}}(t)}{fft[acc_{z_{comp}}(t}\right.$$

Smoothening of the ratio

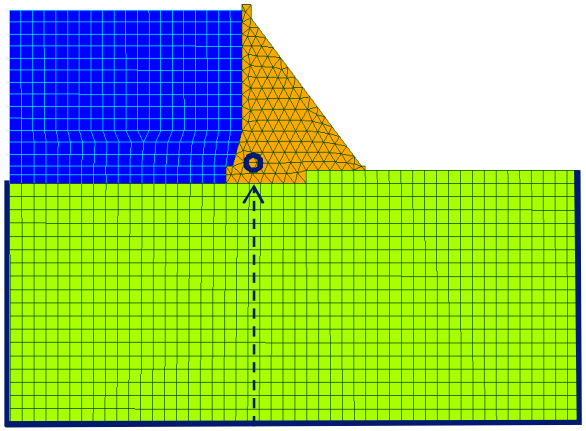
Ratio Computed/Recorded (%)



BACK ANALYSIS OF DAMS *TAGOKURA DAM*

VISCOUS-SPRING BOUNDARIES WITH DECONVOLUTION

Signal introcuded at the bottom of the foundation is slightly changed when reaching the bottom of the dam (where it was recorded)



$$acc_{x\,dec}(t) = fft^{-1}\left[fft[acc_{x_{rec}}(t)] \times \frac{fft[acc_{x_{rec}}(t)}{fft[acc_{x_{comp}}(t)}\right]$$

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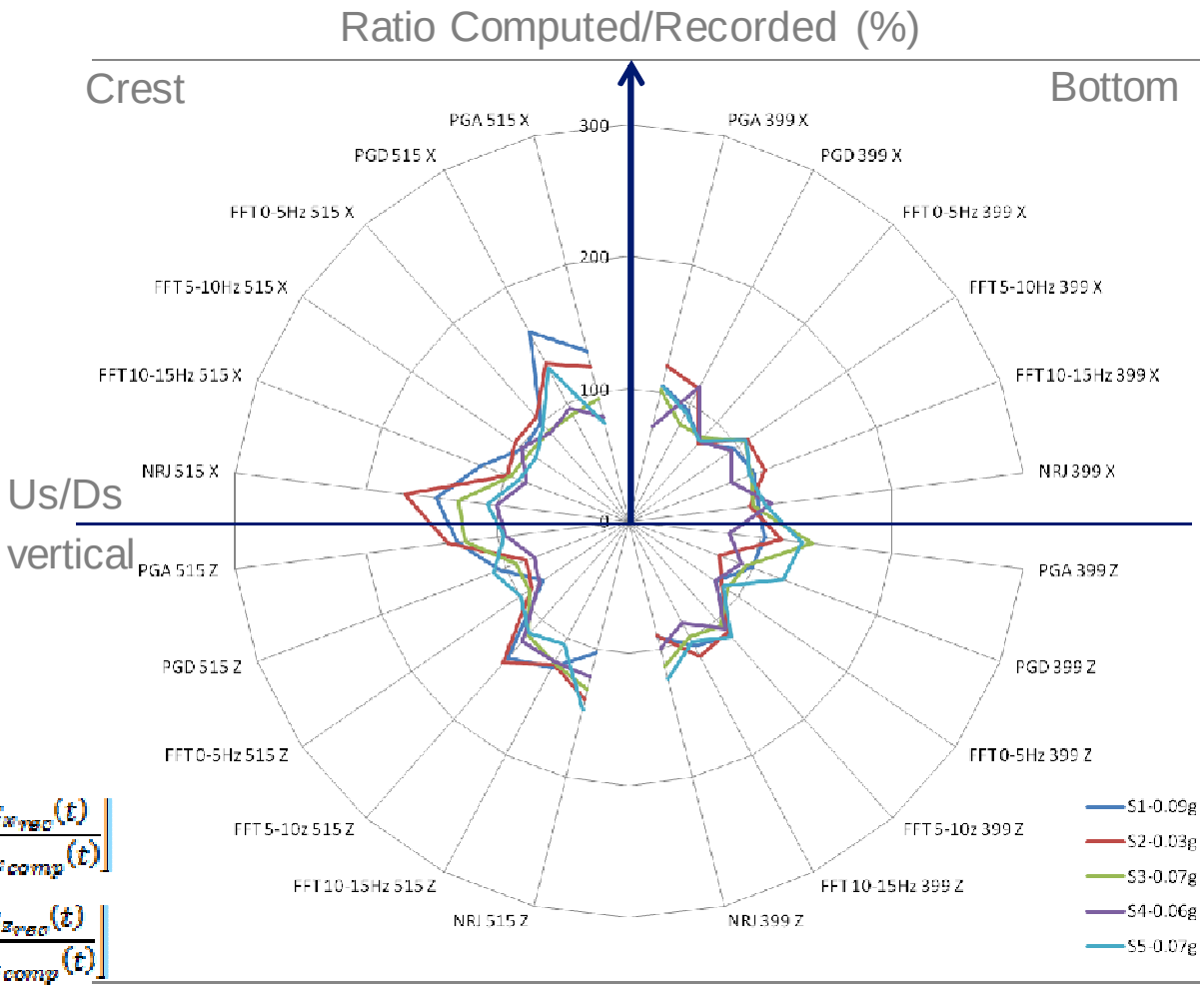
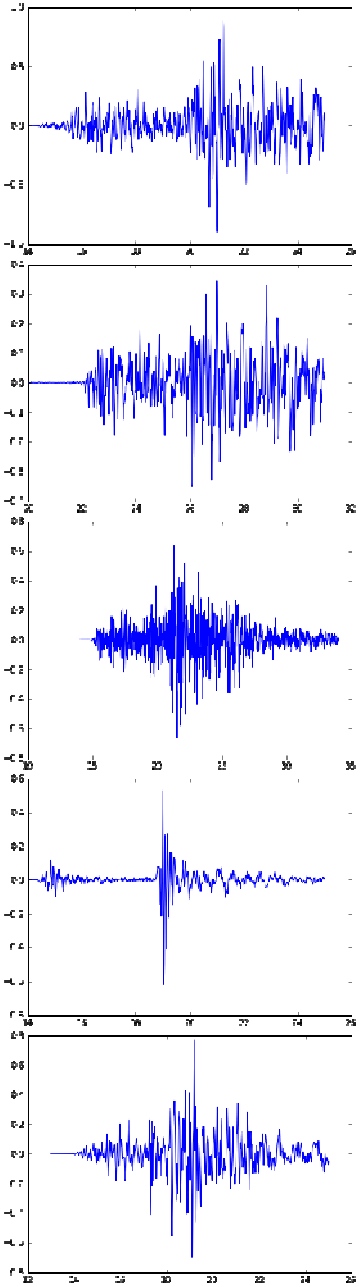
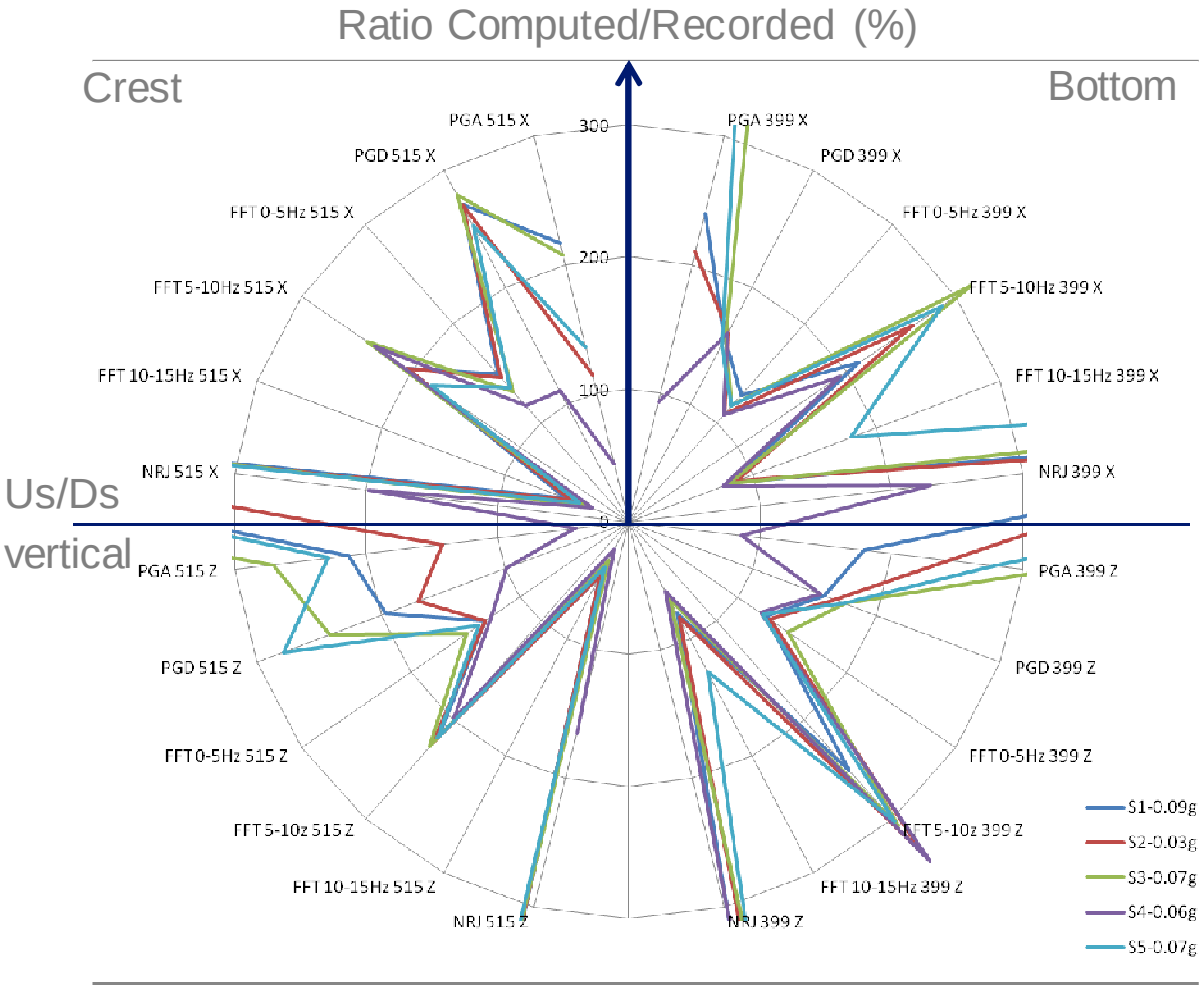


BACK ANALYSIS OF DAMS *TAGOKURA DAM*

MASSLESS / ADDED MASSES WITHOUT DECONVOLUTION





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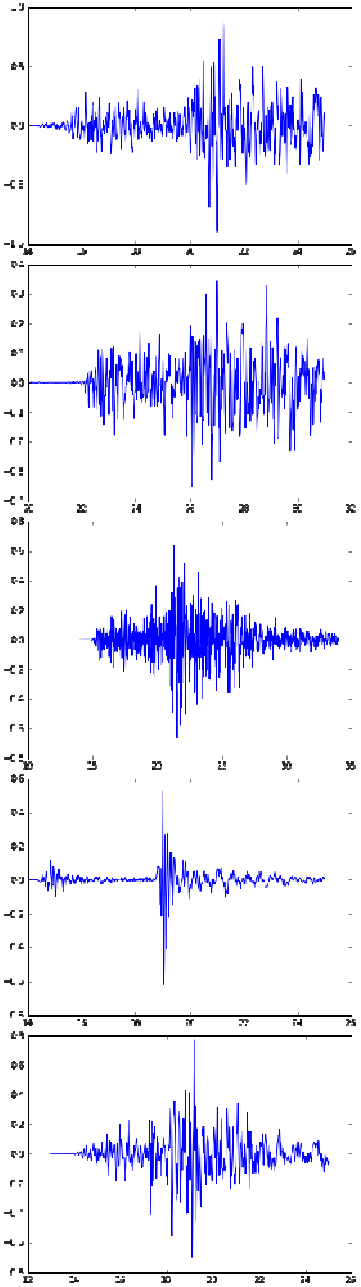
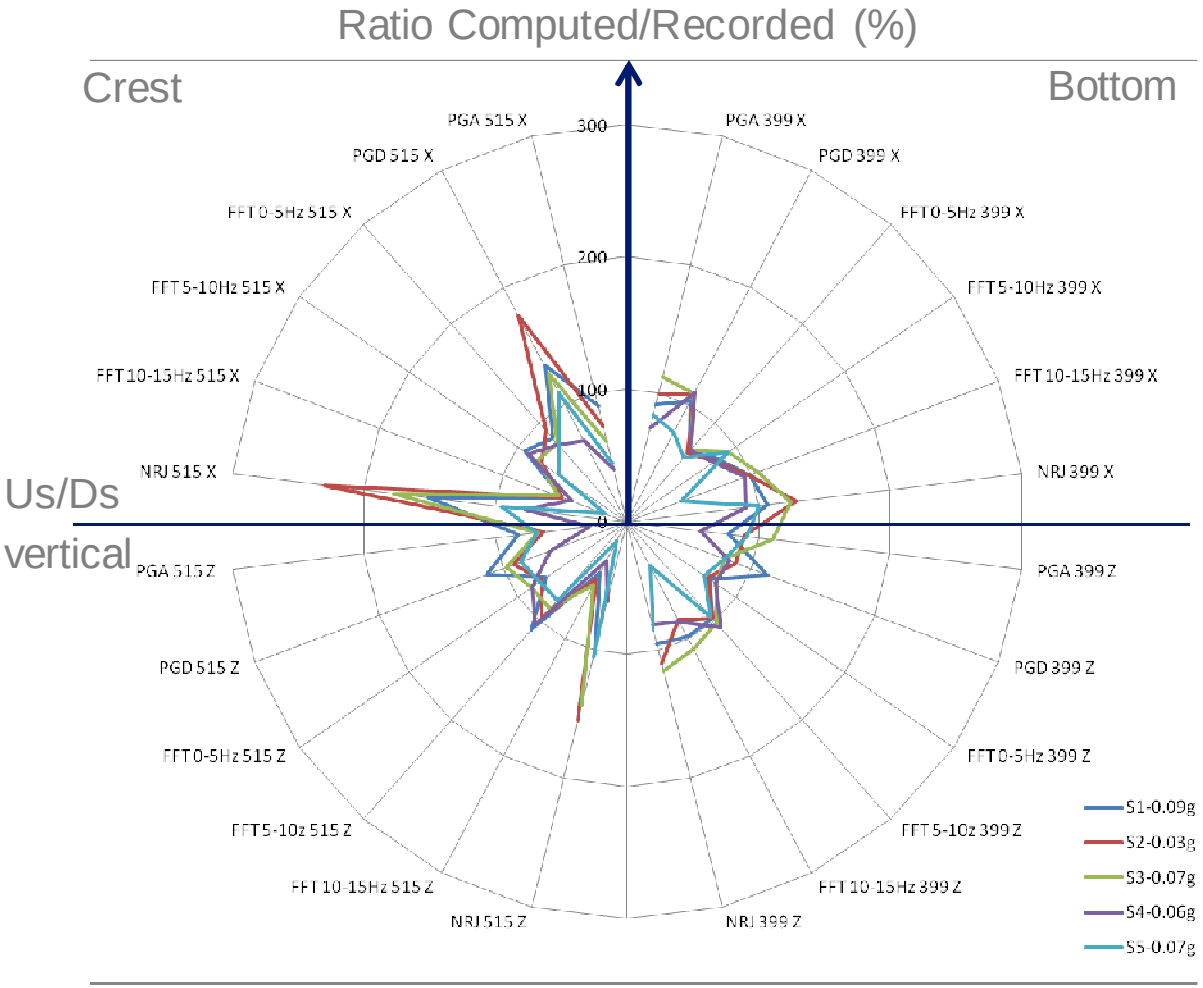
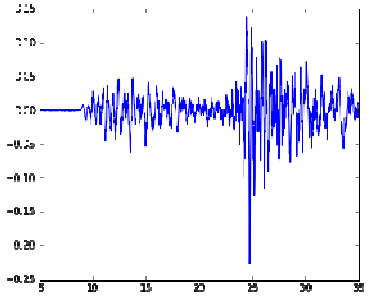
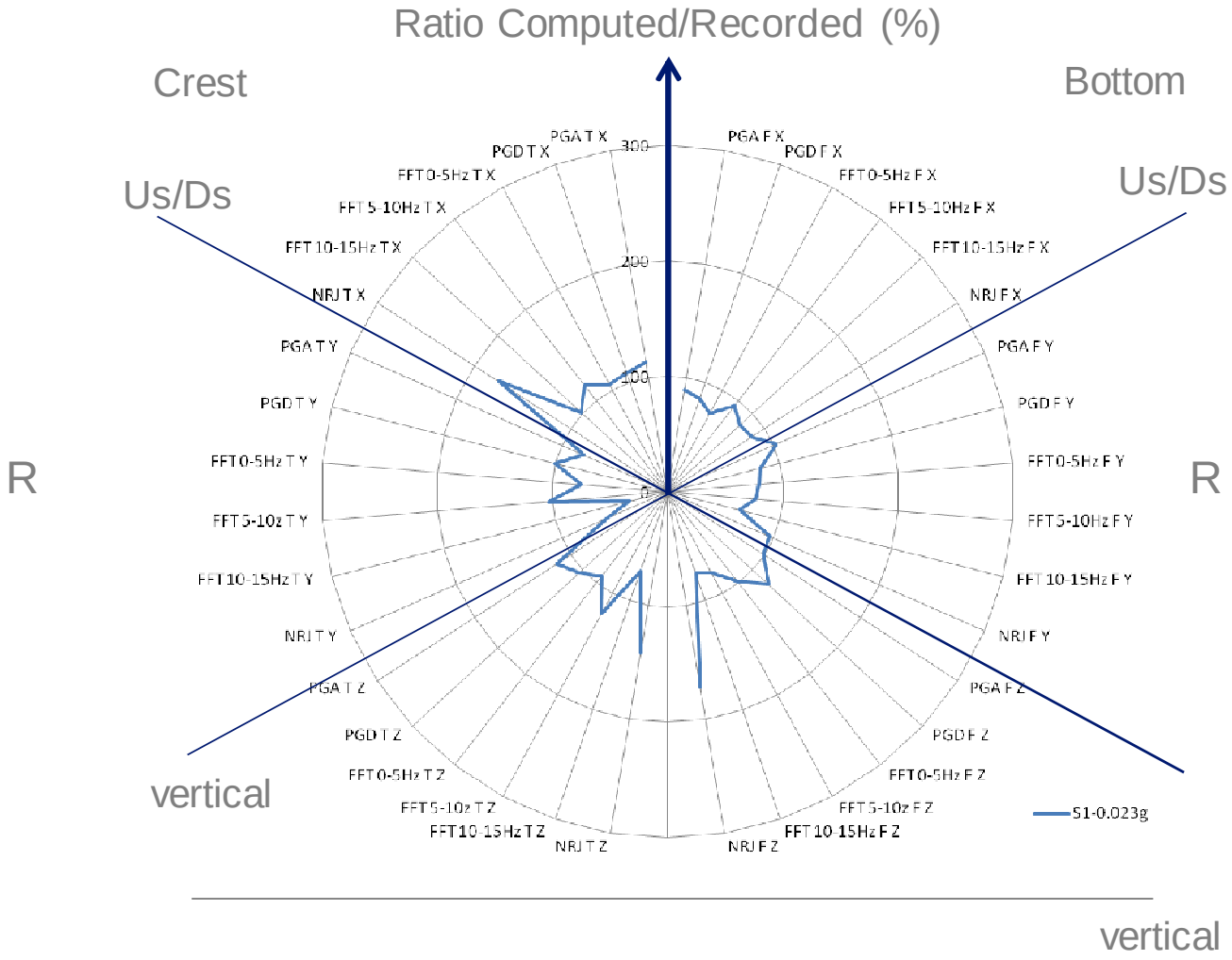




BACK ANALYSIS OF DAMS *KUROBE DAM*

VISCOUS-SPRING BOUNDARIES WITHOUT DECONVOLUTION





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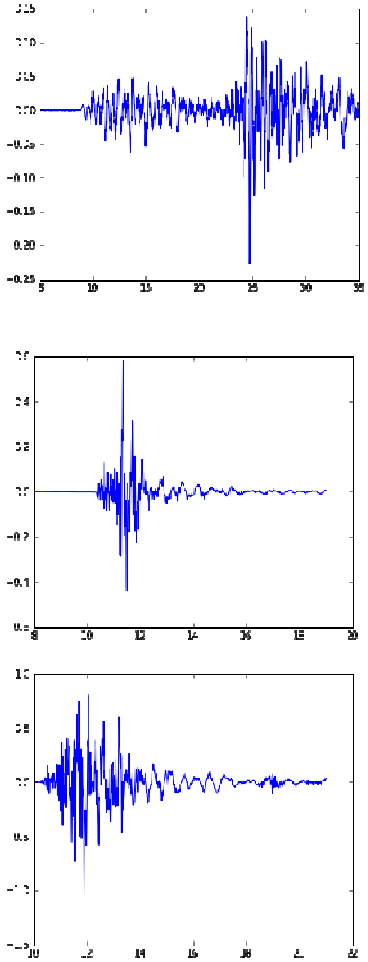
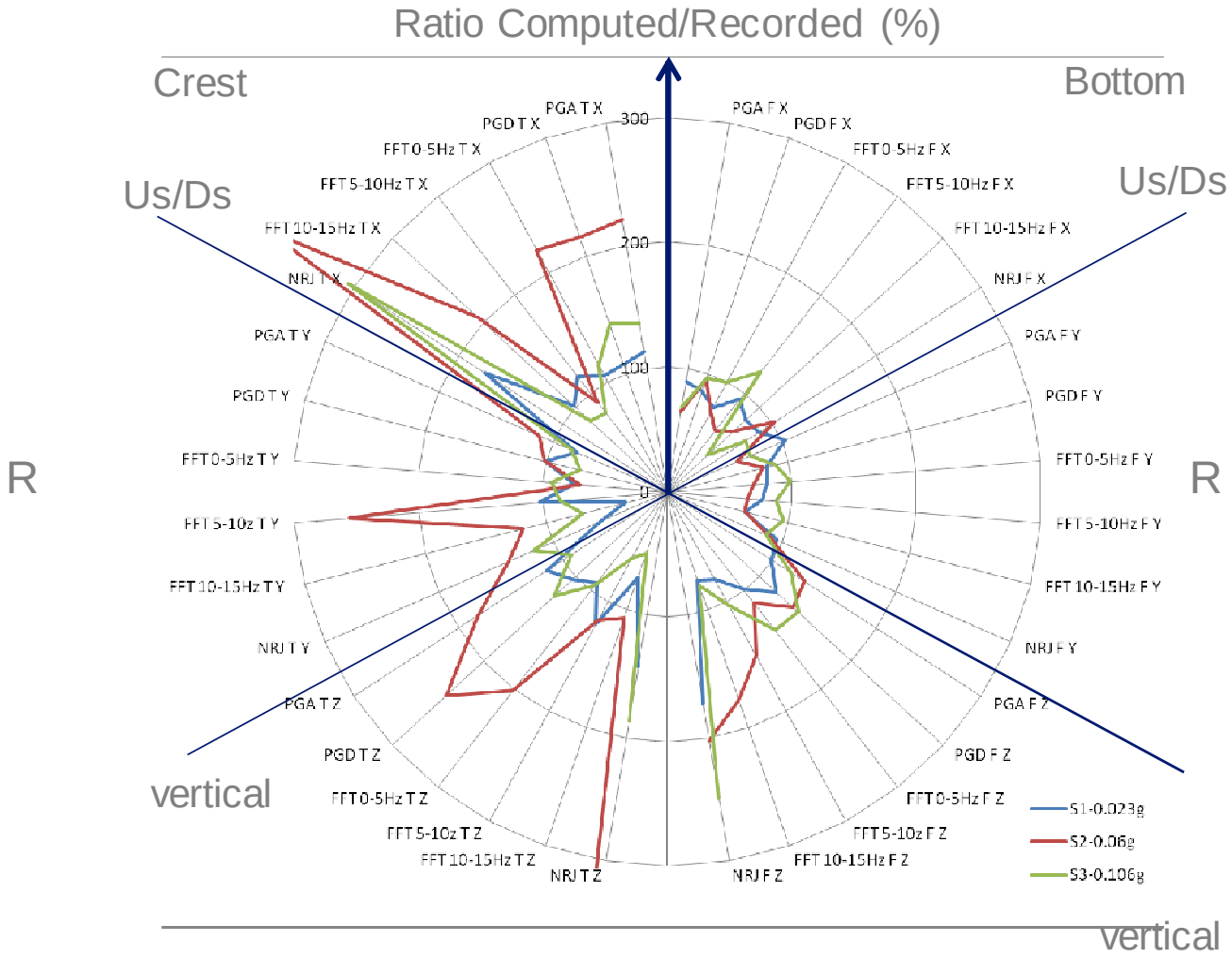
VISCOUS-SPRING BOUNDARIES WITHOUT DECONVOLUTION





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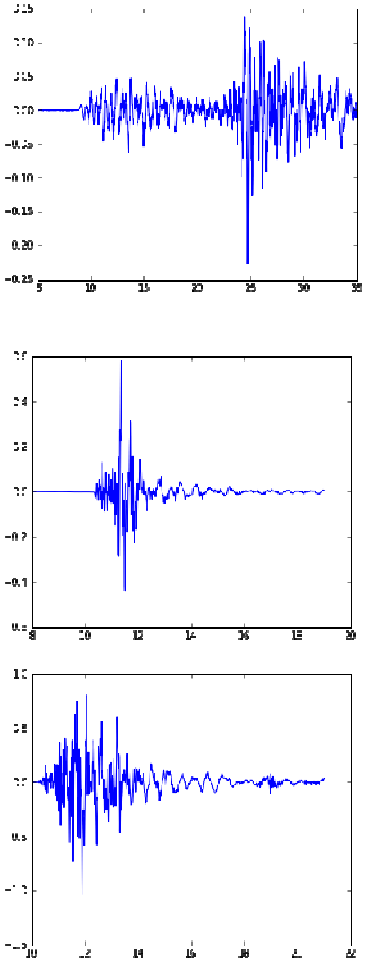
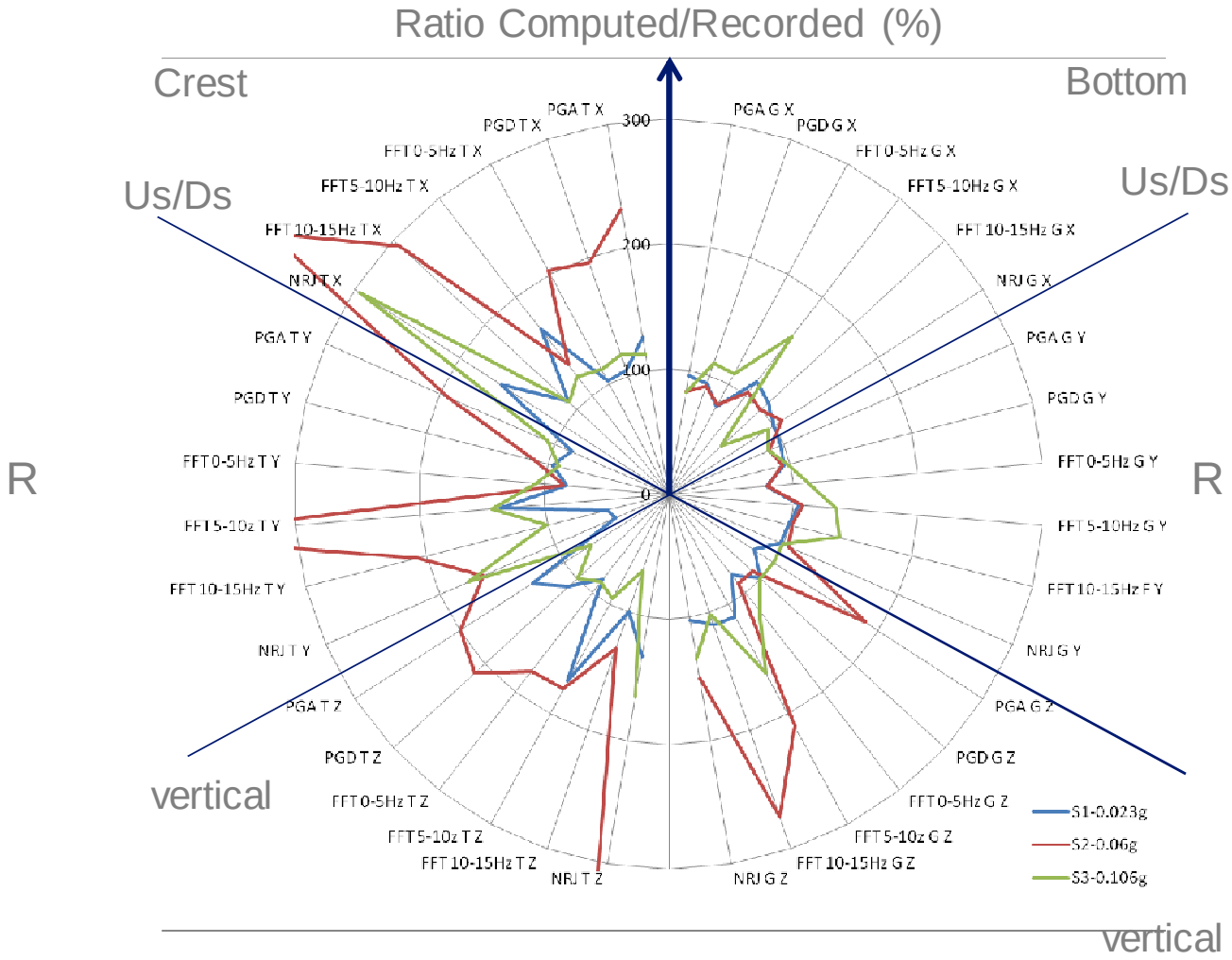
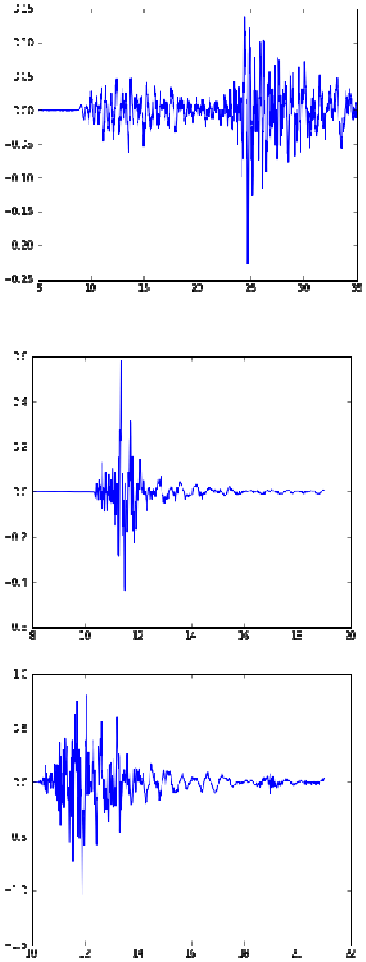
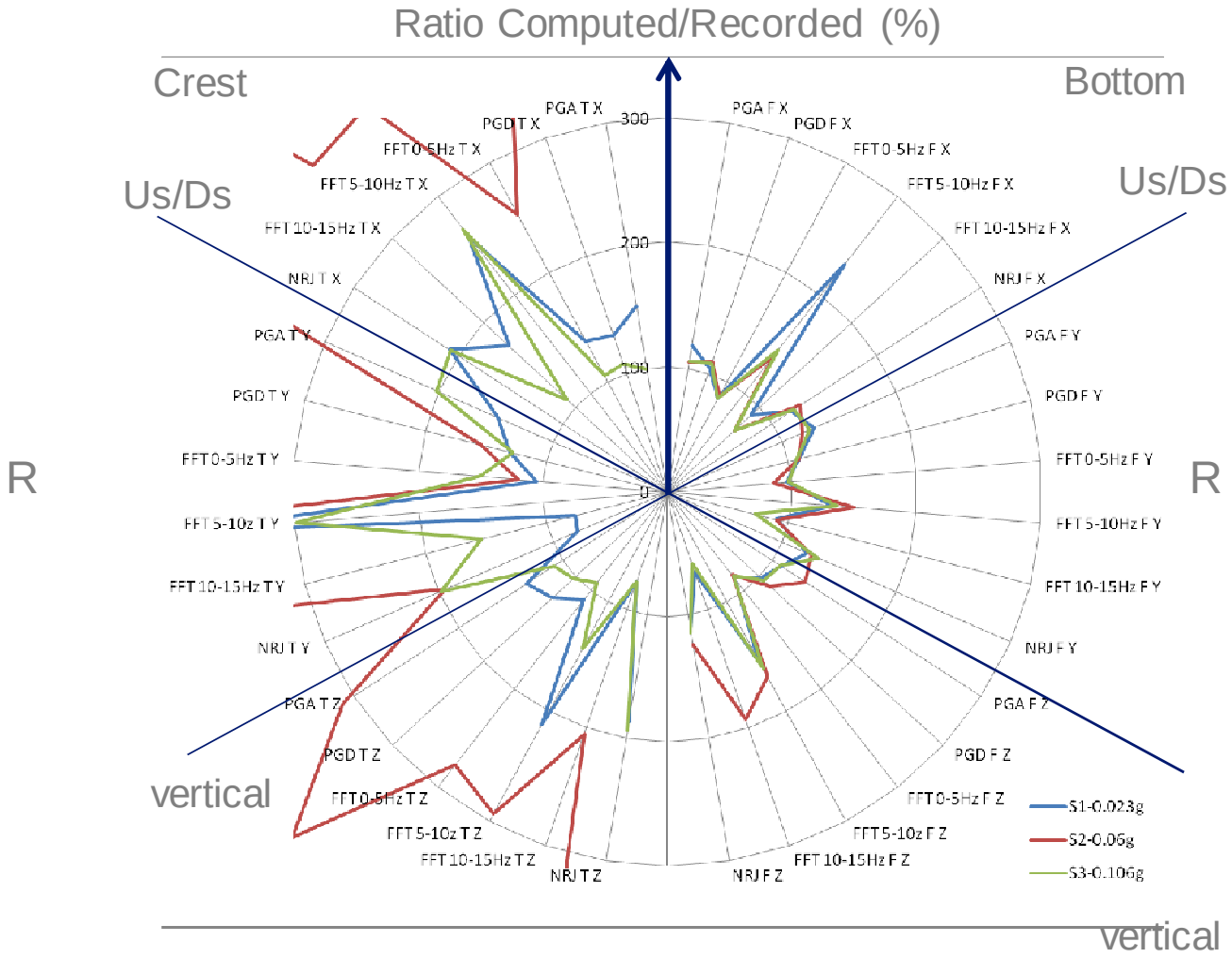




BACK ANALYSIS OF DAMS *KUROBE DAM*

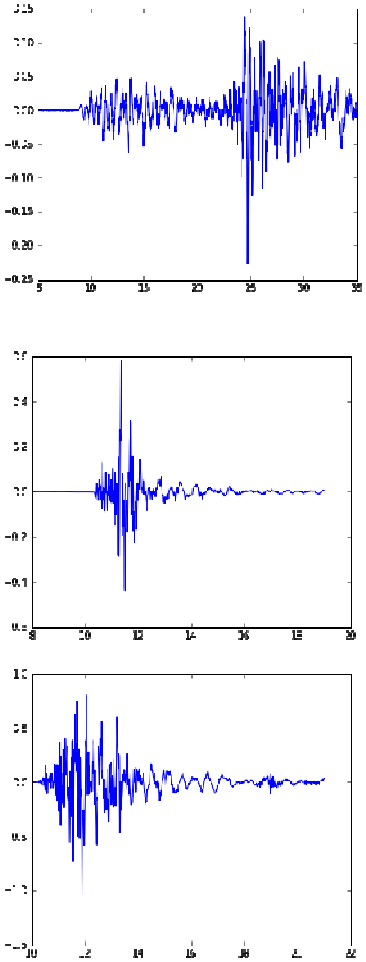
MASSLESS/ADDED MASSES WITHOUT DECONVOLUTION

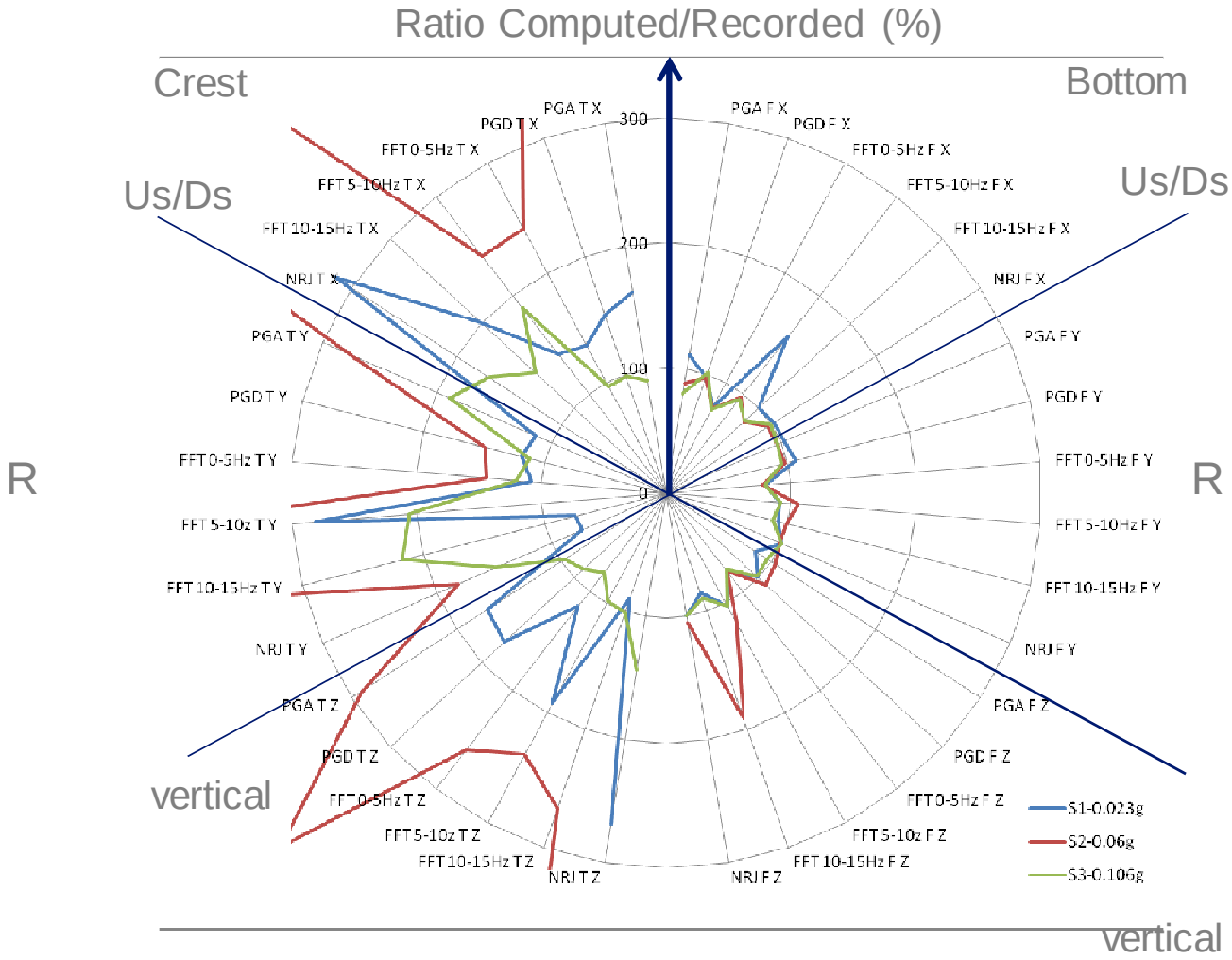




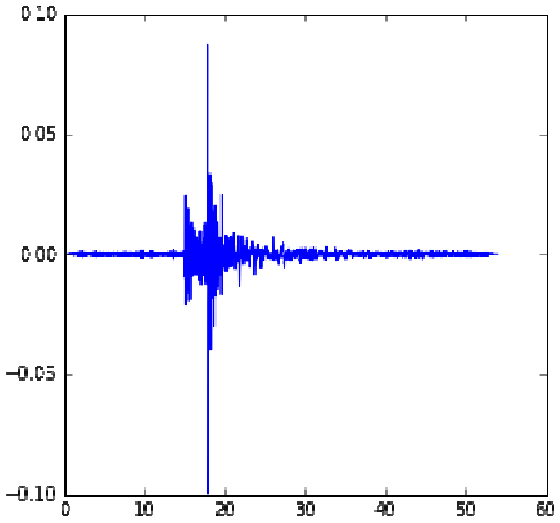
BACK ANALYSIS OF DAMS *KUROBE DAM*

MASSLESS/ADDED MASSES WITH DECONVOLUTION

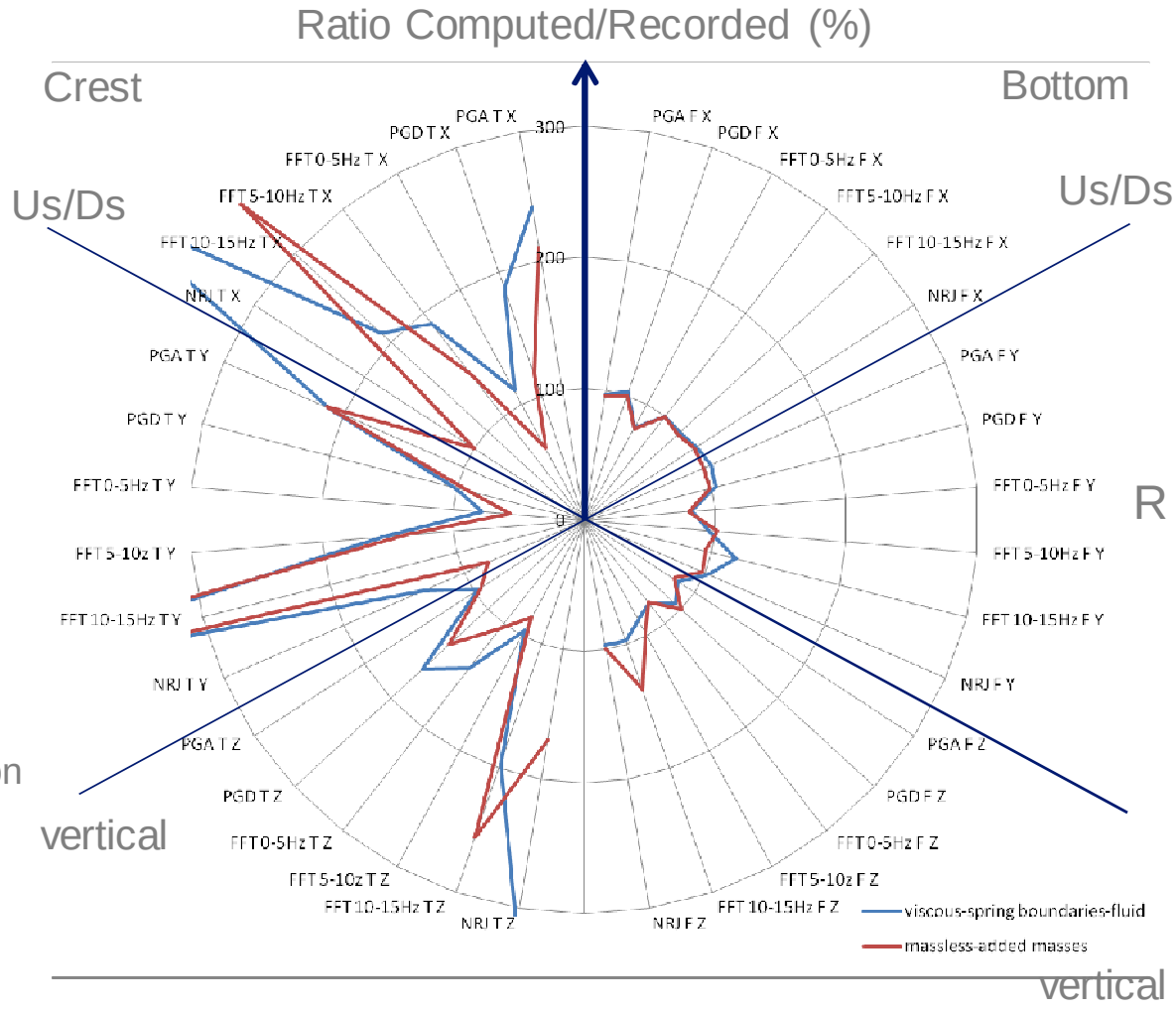




BACK ANALYSIS OF DAMS *MONTICELLO DAM*



R

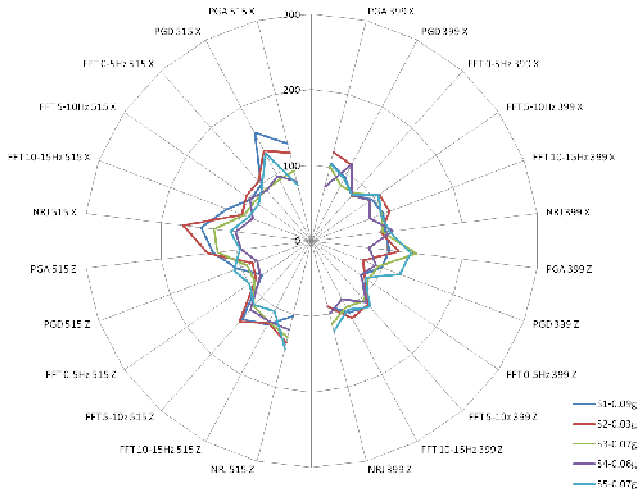


- 5% concrete damping for massless & added masses FE analysis
- 1% concrete damping for mass foundation + fluid FE analysis

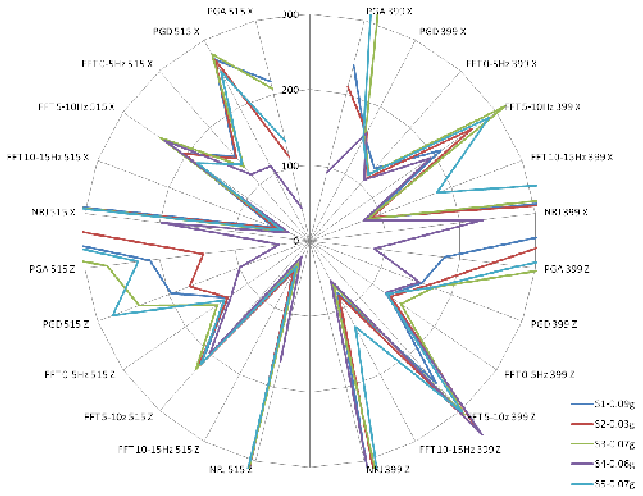
BACK ANALYSIS
SYNTHESIS

- **TAGOKURA dam**

Viscous-spring boundaries + fluid



Massless Found + added masses

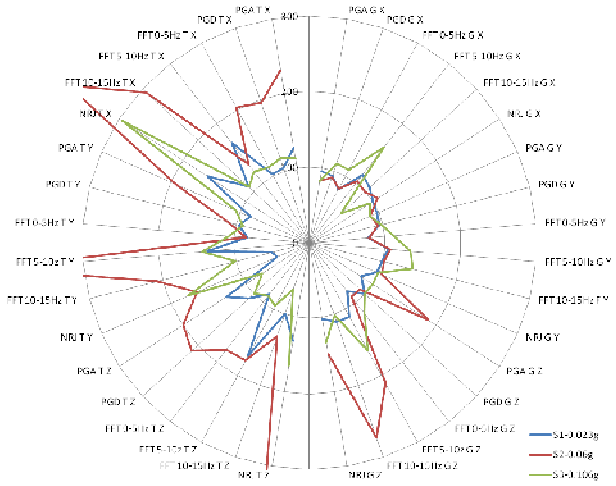


- Results are quite good for the 5 earthquakes
- better results with viscous-spring boundaries + fluid model

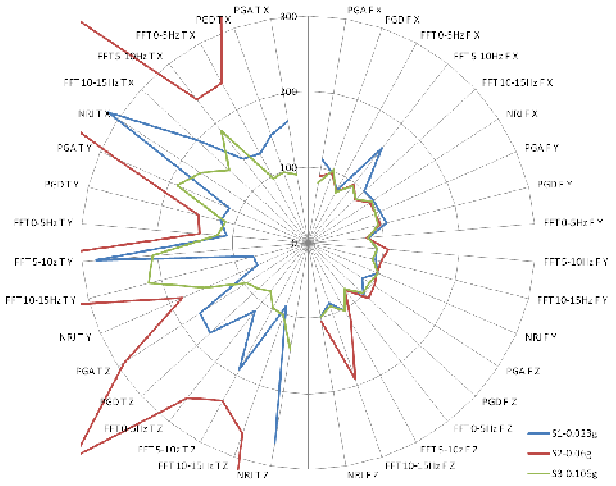
BACK ANALYSIS
SYNTHESIS

- **KUROBE dam**

Viscous-spring boundaries + fluid



Massless Found + added masses

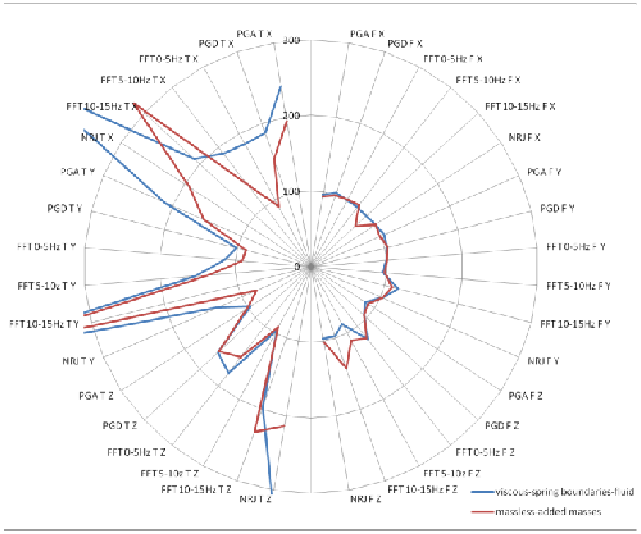


- With Viscous-spring boundaries + fluid model :
  - good for the 1st and 3rd earthquakes
  - Overestimates the 2nd earthquake (x2)
- Massless foundation + added masses
  - Slight overestimation of the 1st and 3rd earthquakes
  - Major overestimation of the 2nd earthquake

BACK ANALYSIS
SYNTHESIS

Viscous-spring boundaries + fluid Massless Found + added masses

- **Monticello dam**



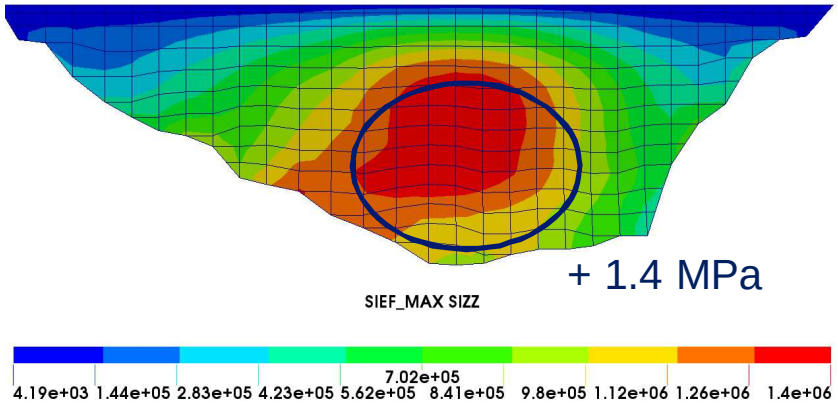
- Overestimation of the response of the dam in the crest
- Both methods give similar results
- Need more investigations to understand the differences

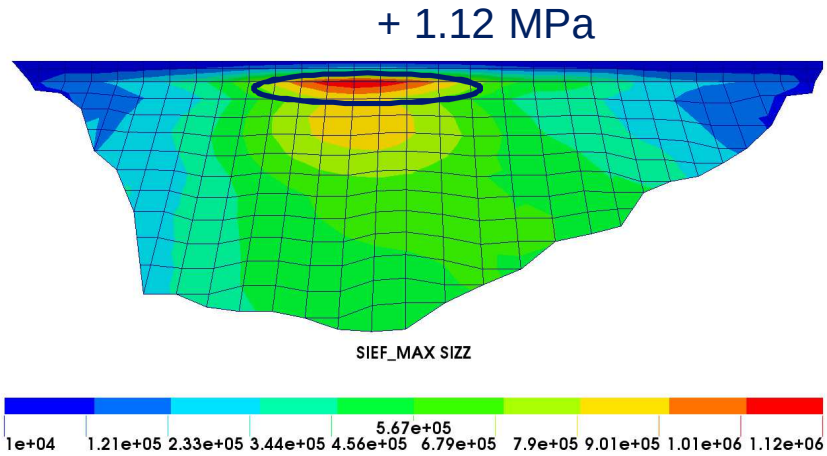
SUMMARY

3D BACK ANALYSIS OF TAGOKURA DAM

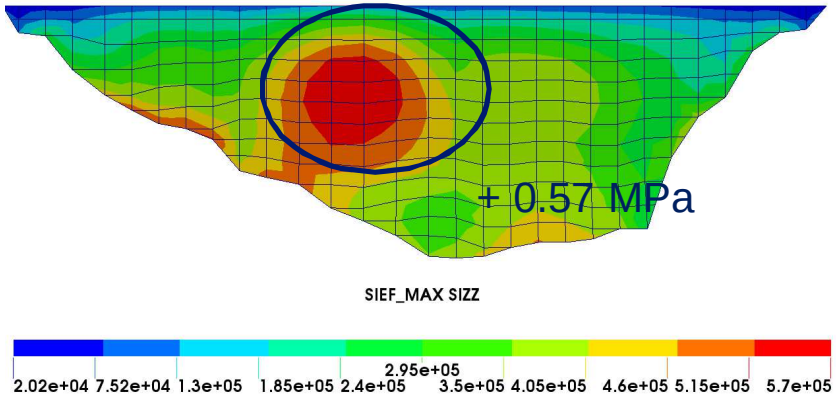
MAXIMUM DYNAMIC VERTICAL STRESSES ON THE FACE OF THE DAM

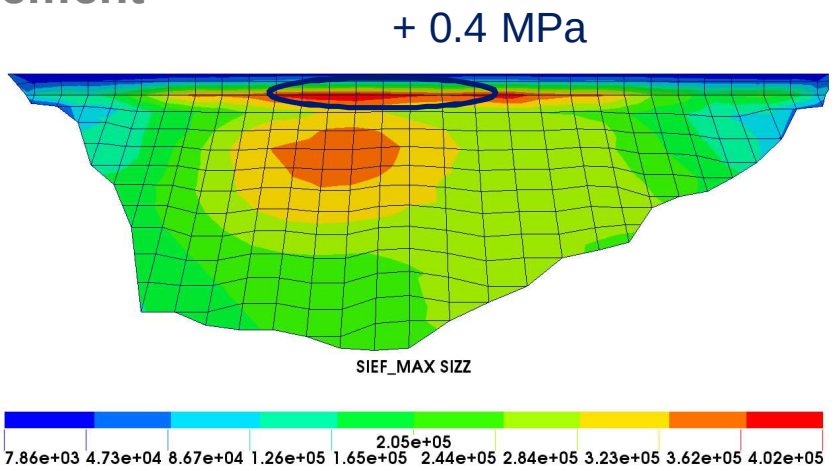
- **Massless foundation / Westergaard added masses**





- **Viscous-spring boundary model / fluid element**

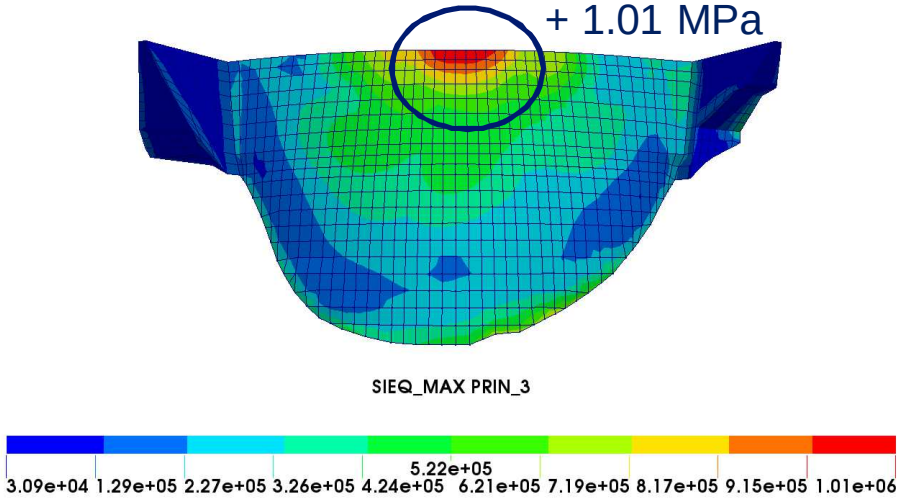




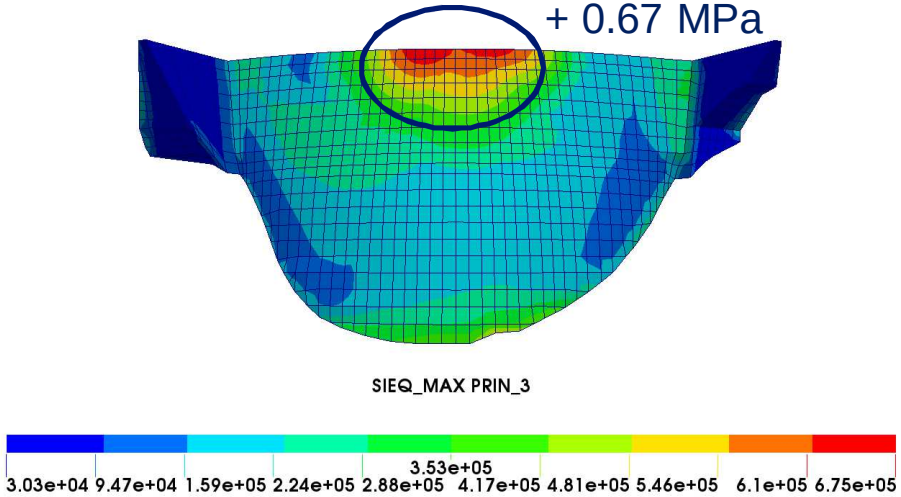
3D BACK ANALYSIS OF KUROBE DAM

MAXIMUM DYNAMIC PRINCIPAL STRESSES ON THE UPSTREAM FACE OF THE DAM

- **Massless foundation / Westergaard added masses**

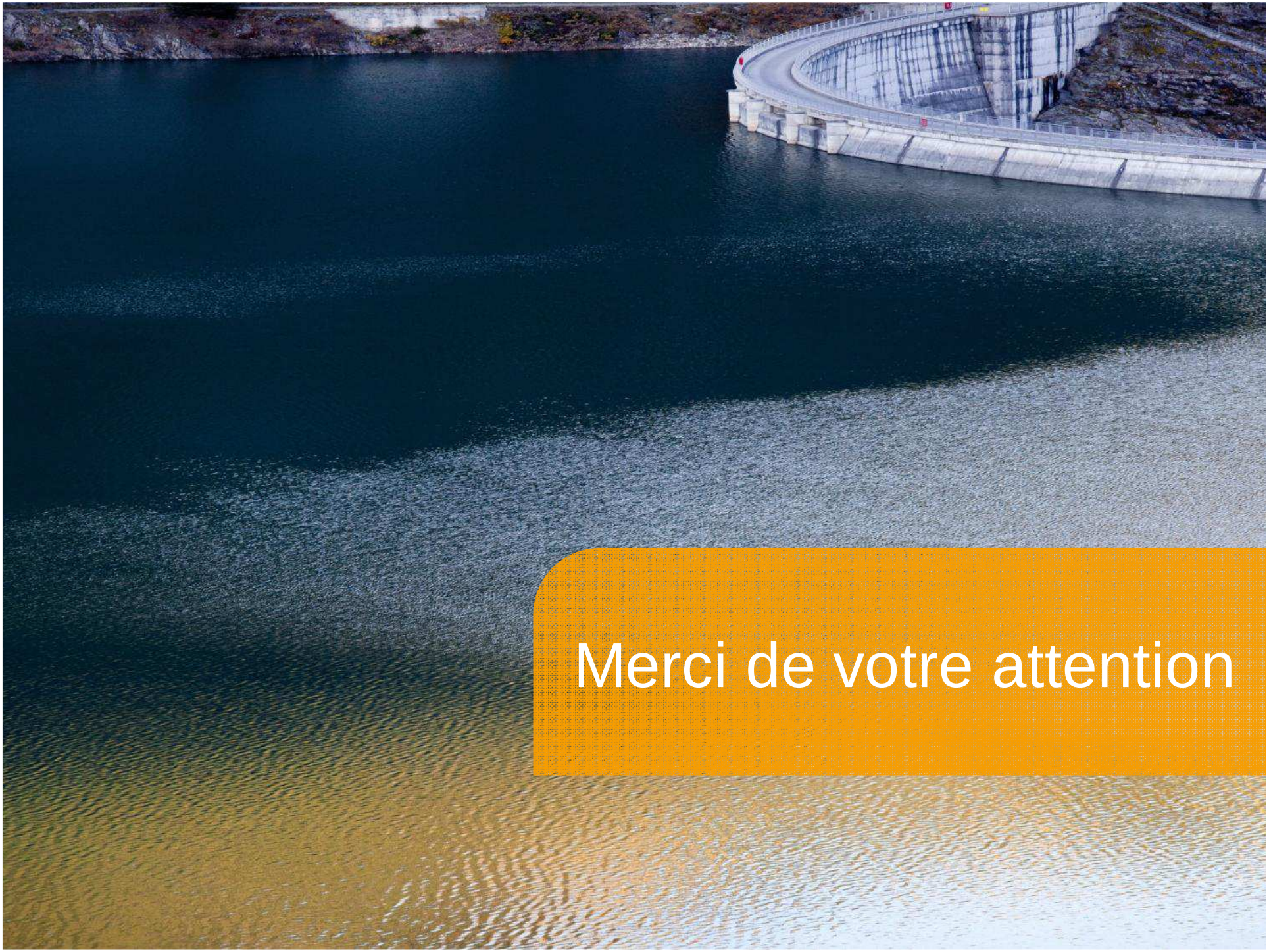


- **Viscous-spring boundary model / fluid element**



CONCLUSION

- **Development of better 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 Tagokura, Kurobe and Monticello dam :**
  - Development of a useful tool to compare multiple results for concrete dam
  - Good agreement of FE analyses with records for Tagokura dam
  - For arch dams, results are not constant and more investigations and analyses are required
- **More comparison between FE analyses and records on dams are needed but this require multiple skills :**
  - Complex FE analyses
  - Seismic data processing
  - Concrete dam's behavior knowledge


Merci de votre attention