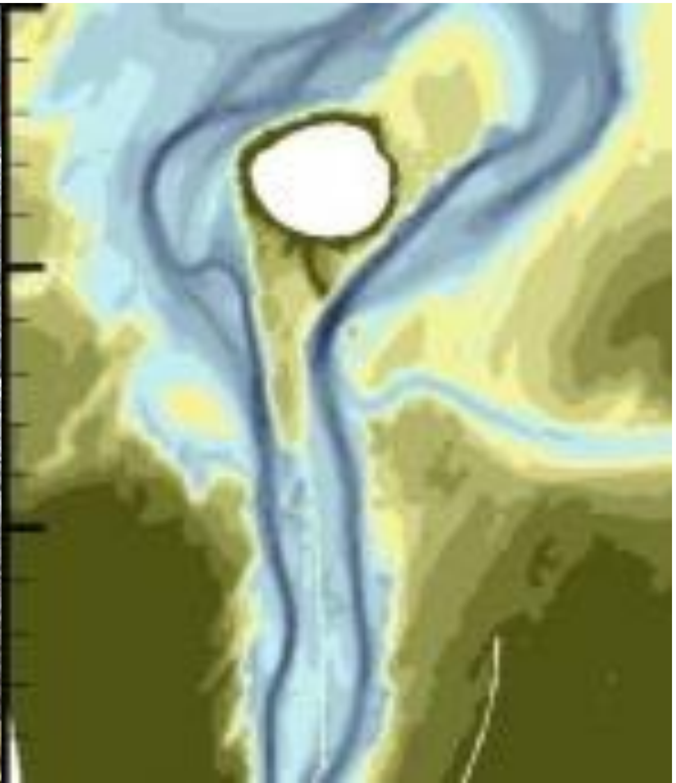
International Symposium
Qualification of dynamic analyses of dams and their equipments
and of probabilistic assessment seismic hazard in Europe
31th August – 2nd September 2016 – Saint-Malo

Frédéric ANDRIAN.

Session : Discussion on qualification of seismic analysis of dams

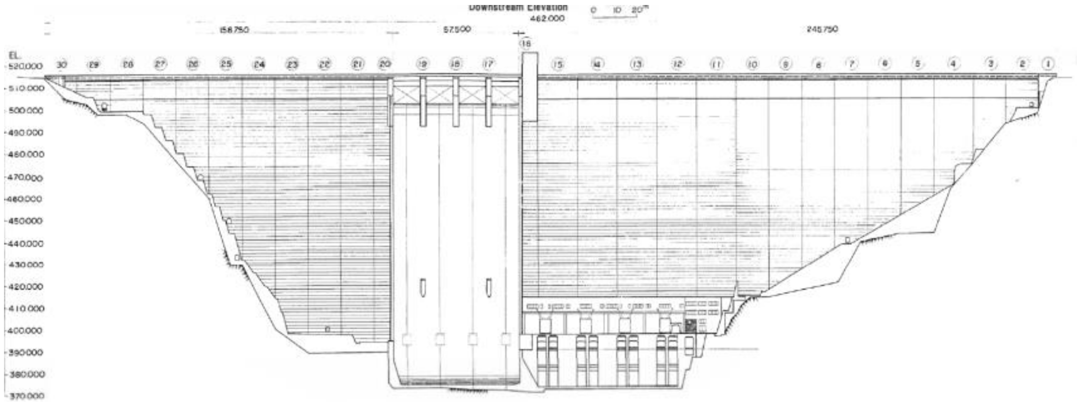
Effects of radiative boundary conditions on seismic analysis of gravity dams



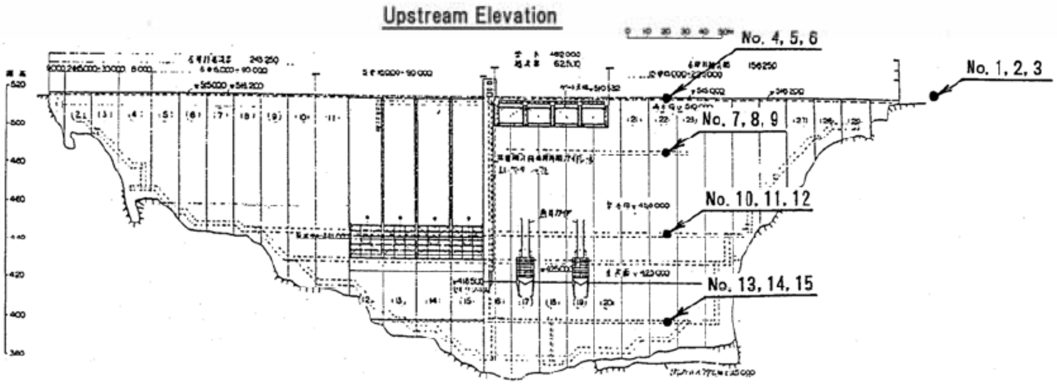
SUMMARY

Reference dam and records

- **Tagokura dam**
  - Concrete gravity
  - Height: 145m
  - Crest Length: 462m
  - L/H ratio = 3.2:1

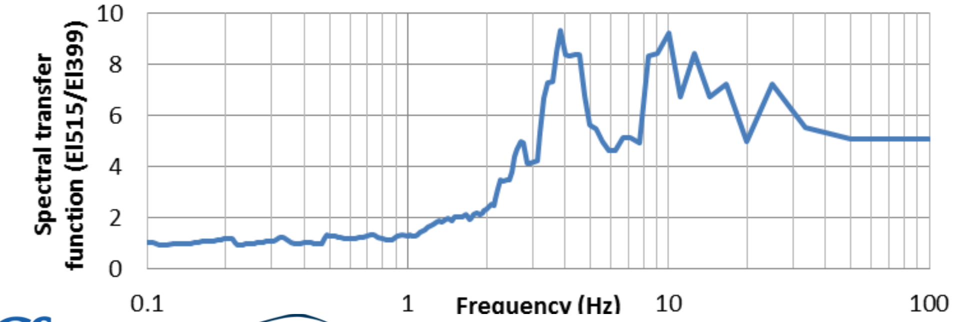


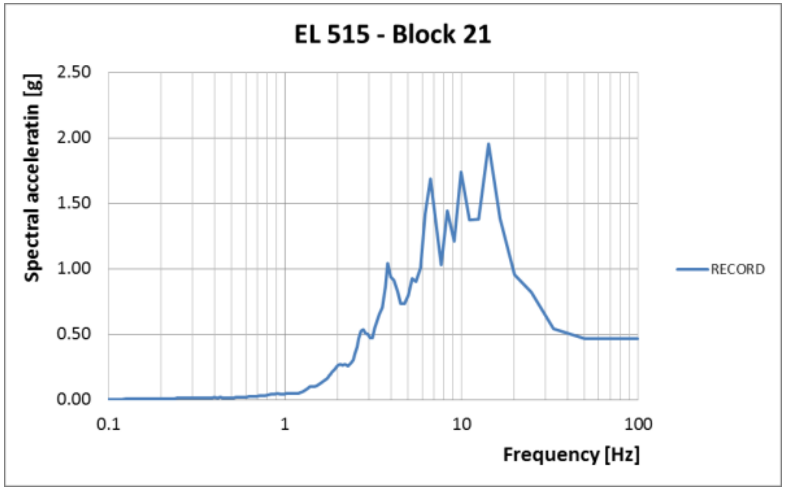
- **5 sets of 3D seismographs**
  - El. 399 ~ Low level gallery
  - El. 514.8 ~ Crest

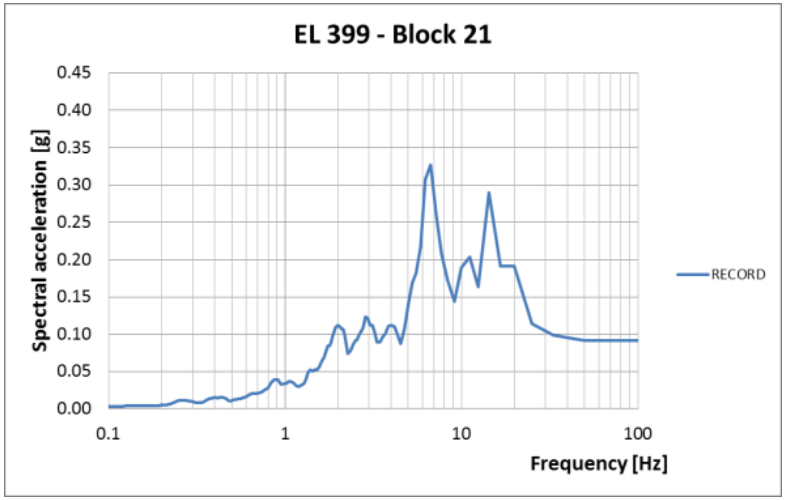


Reference dam and records

- **2004 Niiagata- Chuetsu Earthquake**
  - PGA
    - ❖ ~ El. 399 max acceleration
    - ❖ 0.9 m/s²
  - Maximum crest acceleration
    - ❖ 4.5m/s²
  - Spectral transfer function
    - ❖ Spectrum El. 515 divided by spectrum at El. 399

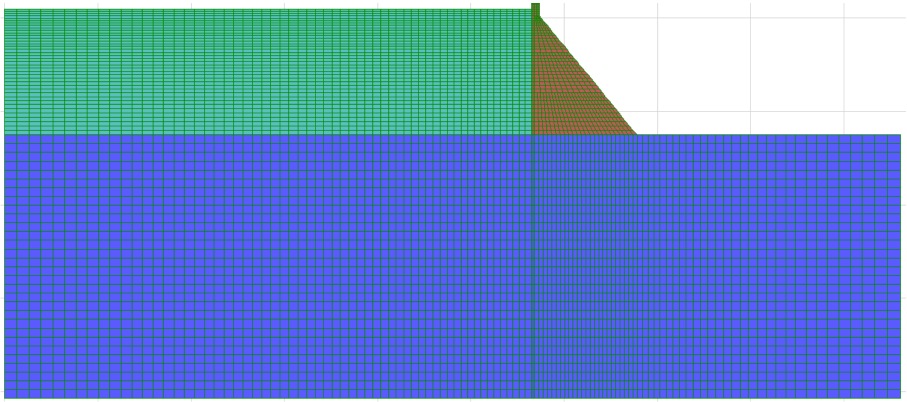


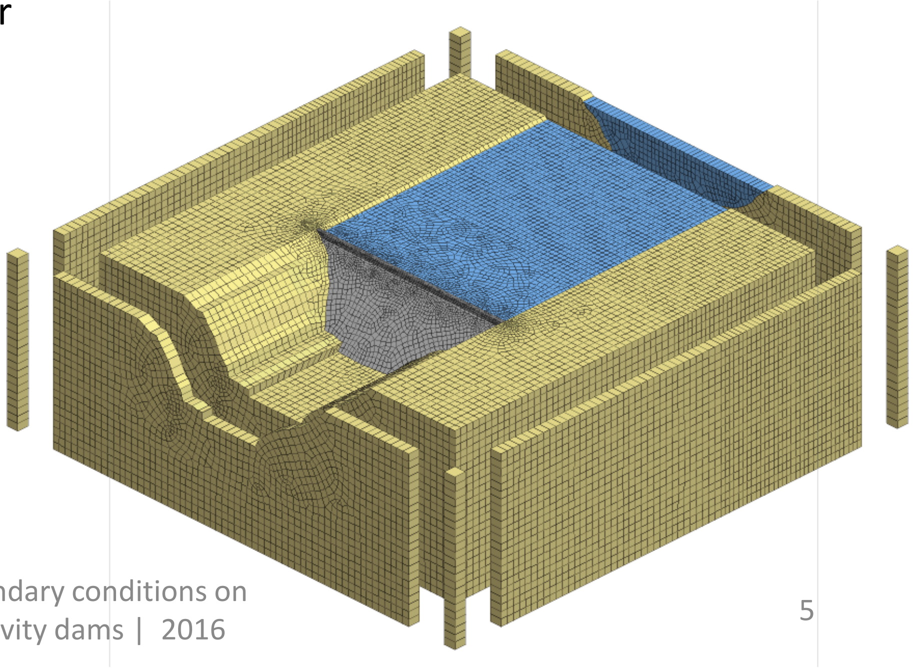




Used calculation methodology

- **FLAC / FLAC3D, Itasca**
  - Explicit finite difference codes
  - Foundation with mass and stiffness
  - **Radiative boundary conditions**
    - ❖ About 10 dams calculated at design or diagnostic stage
    - ❖ Already used for Nuclear Power Plant facilities and geotechnical analyses
  - Non-linear calculations (if necessary)
    - ❖ Interface logic (DEM) at the dam / foundation contact



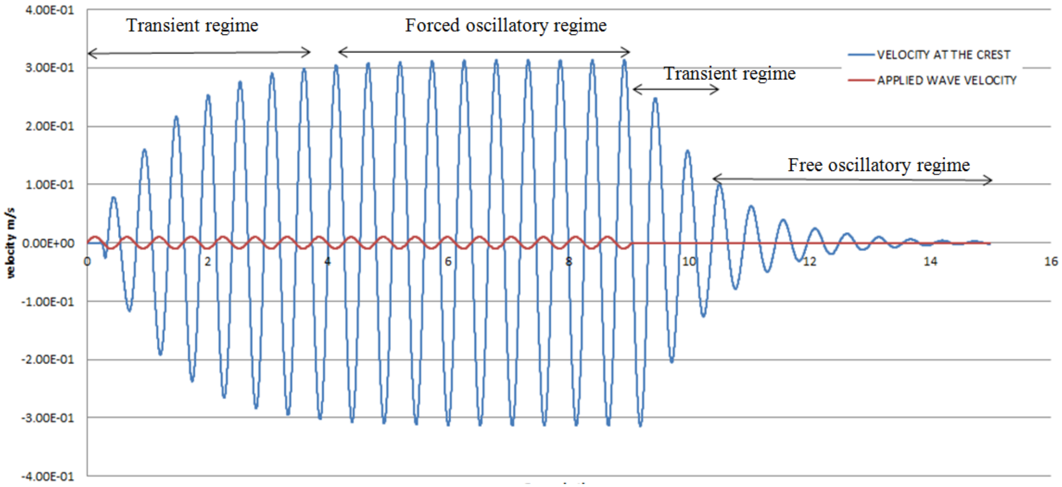


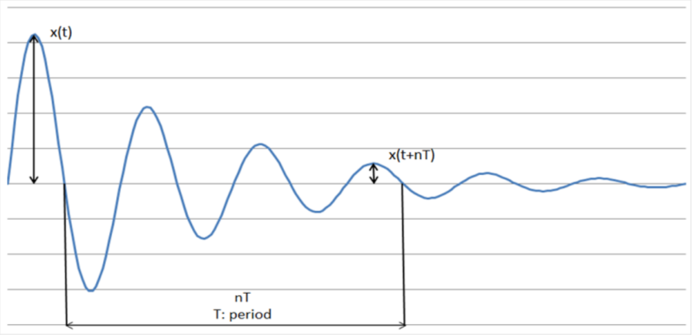
Maximum crest acceleration calibration (2014)

- **Calculation methodologies**
  - Standard method
    - ❖ Fixed foundation boundary conditions (reflective)
  - Complete method
    - ❖ Radiative boundary conditions
- **Max. crest acceleration crest results**
  - Standard method
    - ❖ Required damping ratio: from 8.5% to 15%
    - ❖ From 15% to 5% damping ratio: maximum crest acceleration divided by a factor 3.
  - Complete method
    - ❖ Required damping ratio < 5%

Modeling methodology of interactions (2015)

- **Targets**
  - Model more accurately interactions
    - Dam / Foundation
    - Dam / Reservoir
    - (but also Reservoir / Foundation)
  - Assess radiation damping if any
    - Use of logarithmic decrement
    - Suitable for damping ratio < 25-50%

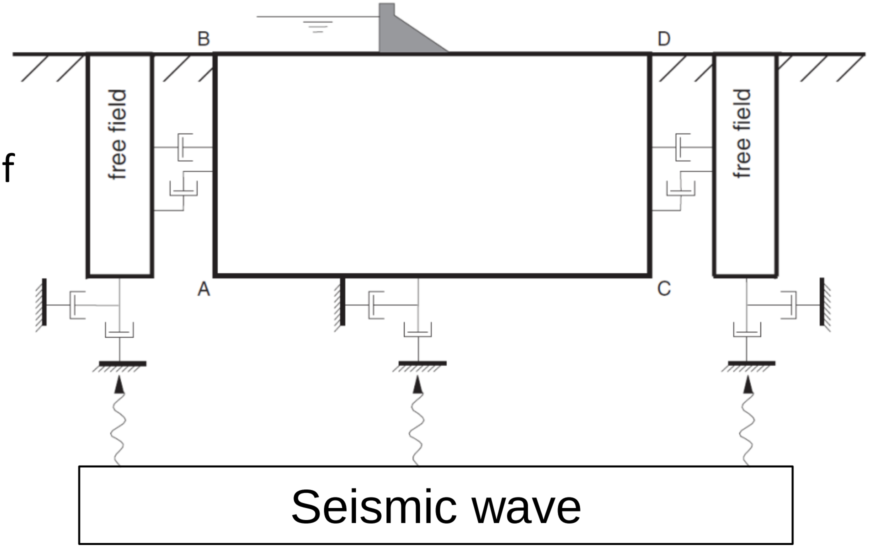




$$\delta = \frac{1}{n} \ln \frac{x(t)}{x(t+nT)}, \qquad \zeta = \frac{1}{\sqrt{1+\left(\frac{2\pi}{\delta}\right)^2}}.$$

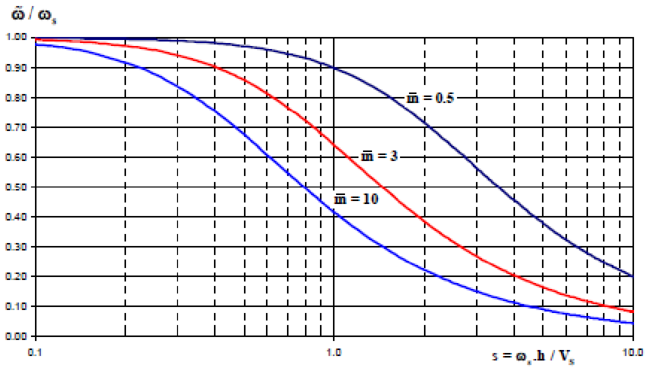
Modeling methodology of interactions (2015)

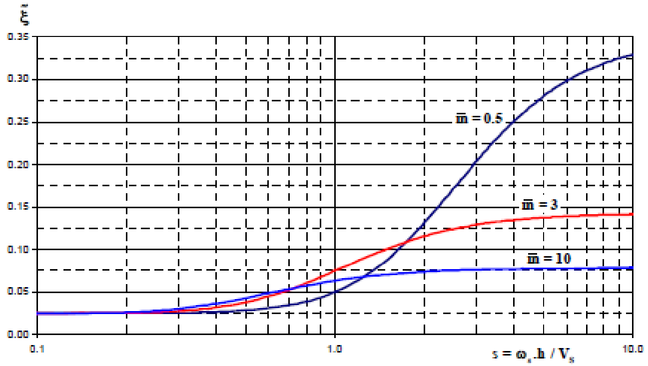
- **Dam / foundation interaction**
  - Foundation with mass and stiffness
  - Radiative boundary conditions
    - ❖ Free-field conditions at the lateral boundaries (incl. Reservoir)
    - ❖ Semi-infinite conditions at the bottom of the model
    - ❖ No wave trapping
  - Input at the model bottom
    - ❖ Propagation toward the upper parts

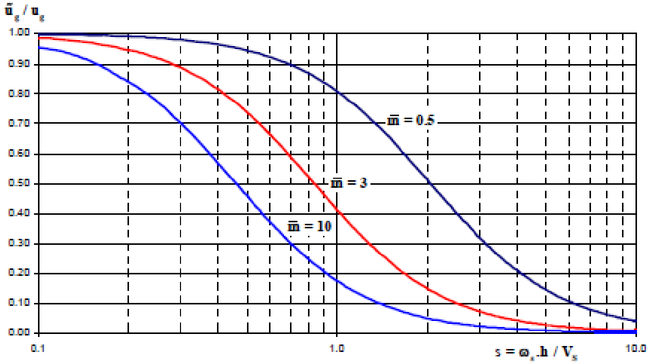


Modeling methodology of interactions (2015)

- **Dam / foundation interaction - Results**
  - 10 - 12% equivalent damping ratio at low frequencies
  - Higher damping ratio at higher frequencies
    - ❖ Out of the range of logarithmic decrement method (>20-25%)
    - ❖ To be assessed by means of spectral method for example
  - Flexible foundation => higher damping ratio
    - ❖ Consistent with Pecker et al.







Modeling methodology of interactions (2015)

- **Dam / Reservoir interaction – Analytic formulation (Ref. VIERA RIBERIO et al.)**
  - Hydrodynamic pressure field

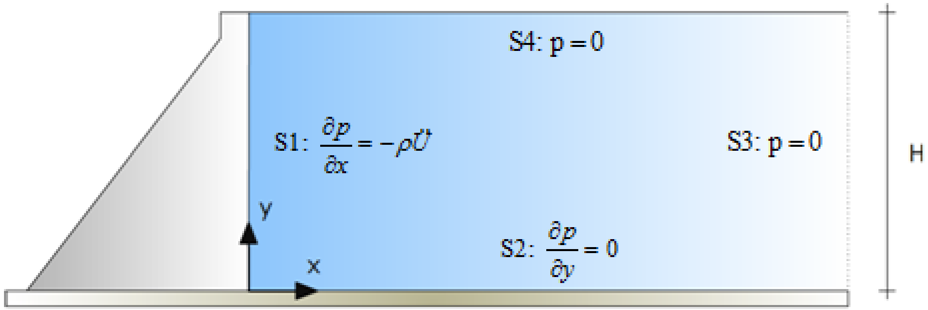
$$\nabla^2 p = \frac{1}{c^2} \cdot \frac{\partial^2 p}{\partial t^2}$$

  - Hypothesis: harmonic solution

$$p(x, y, t) = P(x, y) e^{-i\omega t}$$

$$\nabla^2 P + \left(\frac{\omega}{c} \right)^2 P = 0$$

  - Boundary conditions



Modeling methodology of interactions (2015)

- **Dam / Reservoir interaction – Analytic formulation (Ref. VIERA RIBERIO et al.)**
  - Reservoir Eigen frequency: $f_R = \frac{c}{4H}$
    - ❖ If $f_{dam} < f_R$: Real solution ~ added mass regime
      - ➢ *If incompressible water ($c \rightarrow \infty$), Westergaard solution (very specific case!)*
    - ❖ If $f_{dam} = f_R$: Resonance
    - ❖ If $f_{dam} > f_R$: Complex solution ~ wave propagation

Modeling methodology of interactions (2015)

Dam / Reservoir interaction – Validation of the numerical model

- Water modeled as elements
  - ❖ Lagrangian formulation in FLAC/FLAC3D (mesh deformation with the material deformation)
  - ❖ vs. Eulerian formulation (fixed mesh but material motion) ~ used in CFD

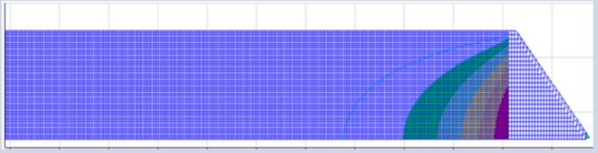
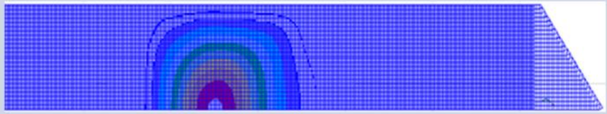
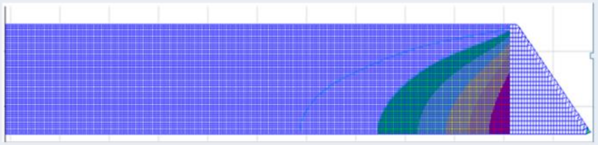
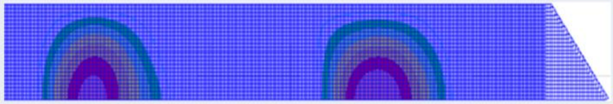
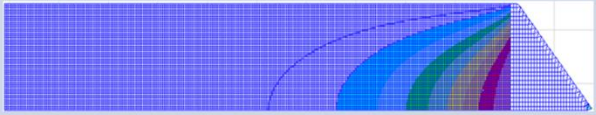
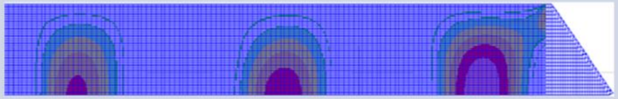
- Nearly incompressible material ($\nu = 0.5$)
  - ❖ Volumetric locking to be avoided with caution
  - ❖ Use of standard linear/cubic elements inaccurate

- A few possible solutions to overcome the overstiffness
  - ❖ Reduced integration (FEM)
  - ❖ Mixed Discretization scheme
  - ❖ …

- Mixed Discretization scheme used in FLAC/FLAC3D
  - ❖ Isotropic and Deviatoric parts of stresses and strains calculated **separately**

Modeling methodology of interactions (2015)

- **Dam / Reservoir interaction – Validation of the numerical model**
  - $R = f_{dam}/f_R$
    - ❖ If R > 1, ~ 2% supplementary damping ratio at low frequencies

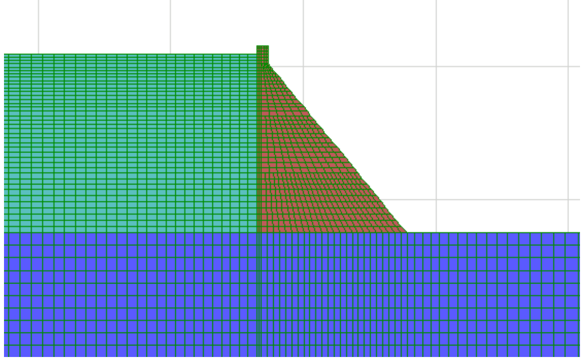
R<1 ⇔Added mass regime		R>1 ⇔Wave propagation regime	
R = 0.28		R = 1.1	
R = 0.56		R = 1.5	
R = 0.65		R = 2	

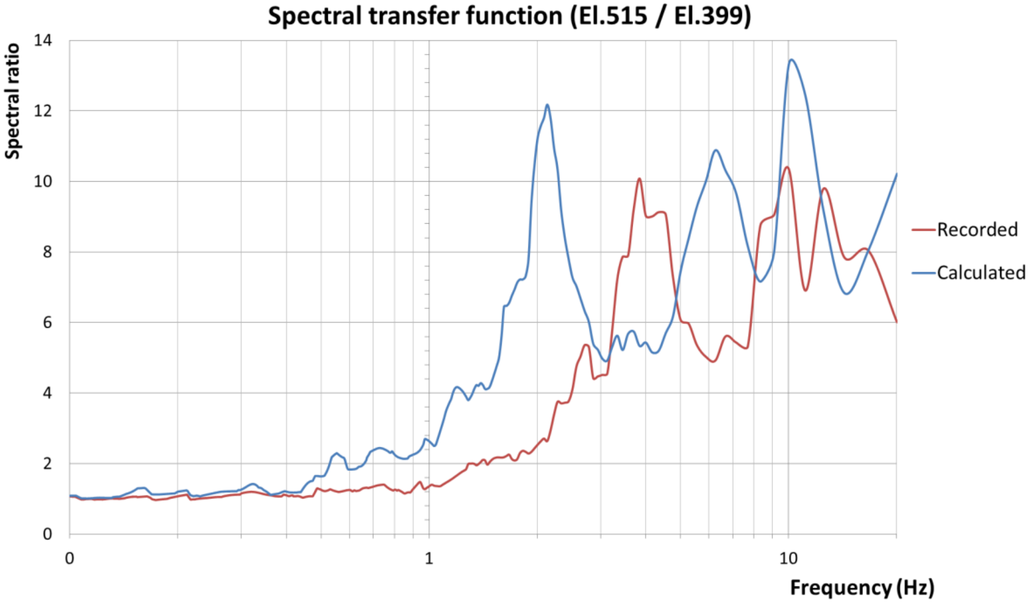
Modeling methodology of interactions (2015)

- **Foundation / Dam / Reservoir interaction – Overall results**
  - Dam / foundation interaction
    - ❖ 10 - 12% supplementary damping ratio
  - Dam / reservoir interaction
    - ❖ $R = f_{dam}/f_R$
    - ❖ If R > 1, ~ 2% - 3% supplementary damping ratio ~ large dams
    - ❖ If R< 1, added masses regime ~ small dams
      - ➢ *Westergaard distribution = very specific case (rigid dam + compressible water)*
      - ➢ *Westergaard distribution = not always the most conservative*
  - Total radiation damping (water + foundation) : ~ 15% for stiff foundation
    - ❖ Consistent with the findings of 2014 work

Calibration of the low frequency response (2016)

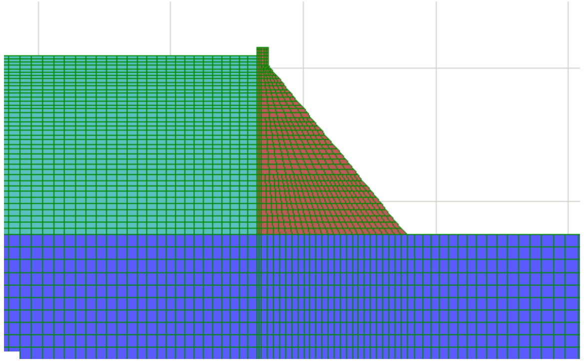
- **2D calculations**
  - 1st step: blind calculation
  - 0 % material damping
  - E_{dam} = 23.04 GPa, E_{found} = 20 GPa (JCOLD data)

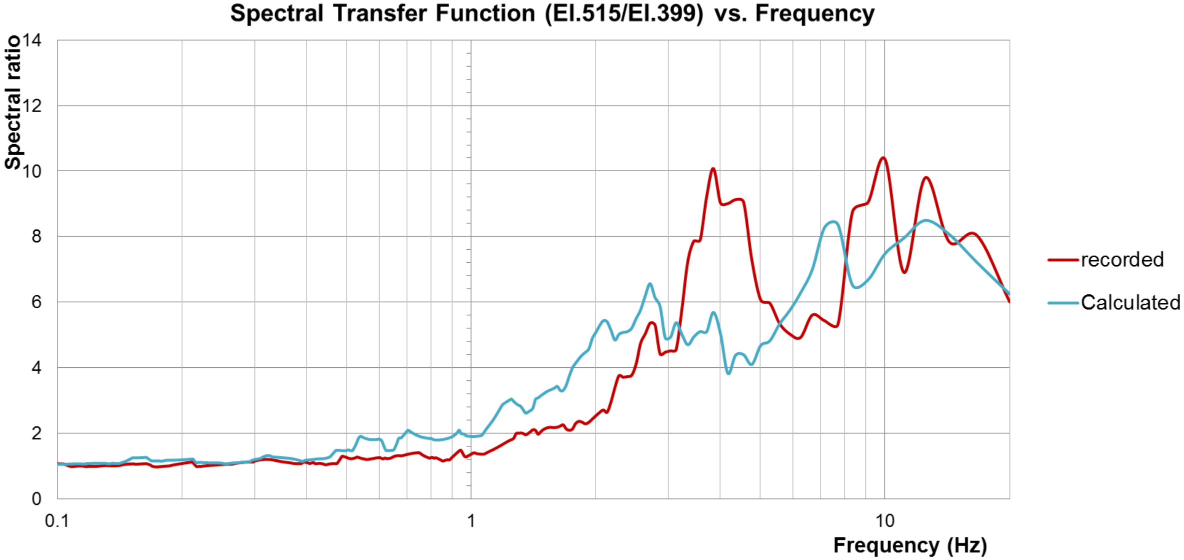




Calibration of the low frequency response (2016)

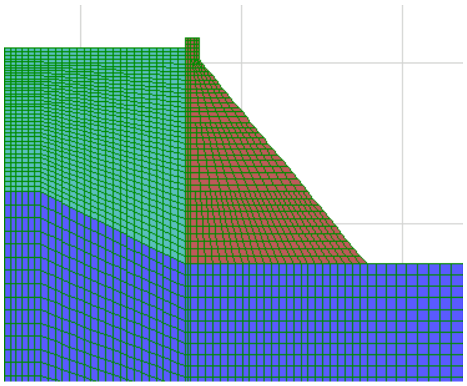
- **2D calculations**
  - 2nd step: Increased moduli (~3D effect)
  - 0 % damping
  - E_{dam} = 40 GPa, E_{found} = 35 GPa

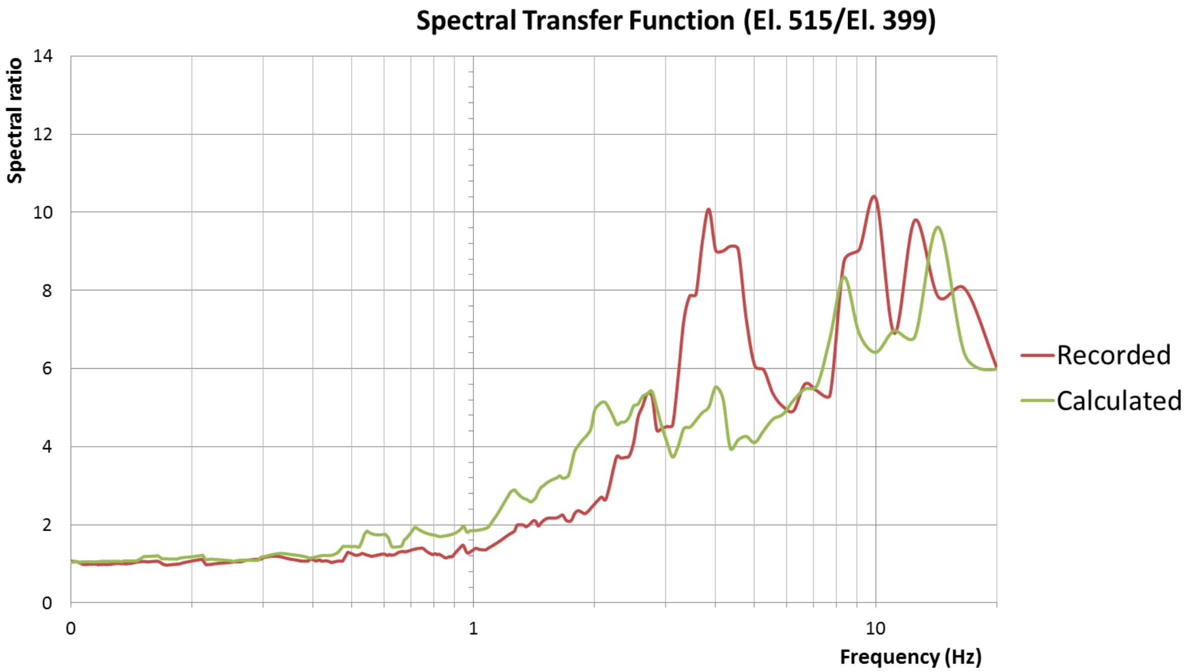




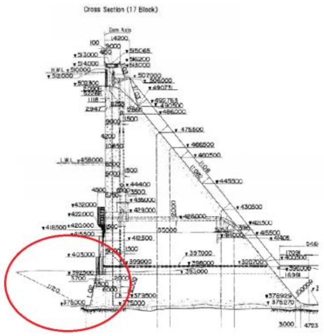
Calibration of the low frequency response (2016)

- **2D calculations**
  - 3rd step: Improvement of reservoir geometry
  - 0 % damping
  - $E_{dam} = 40$ GPa, $E_{found} = 35$ GPa



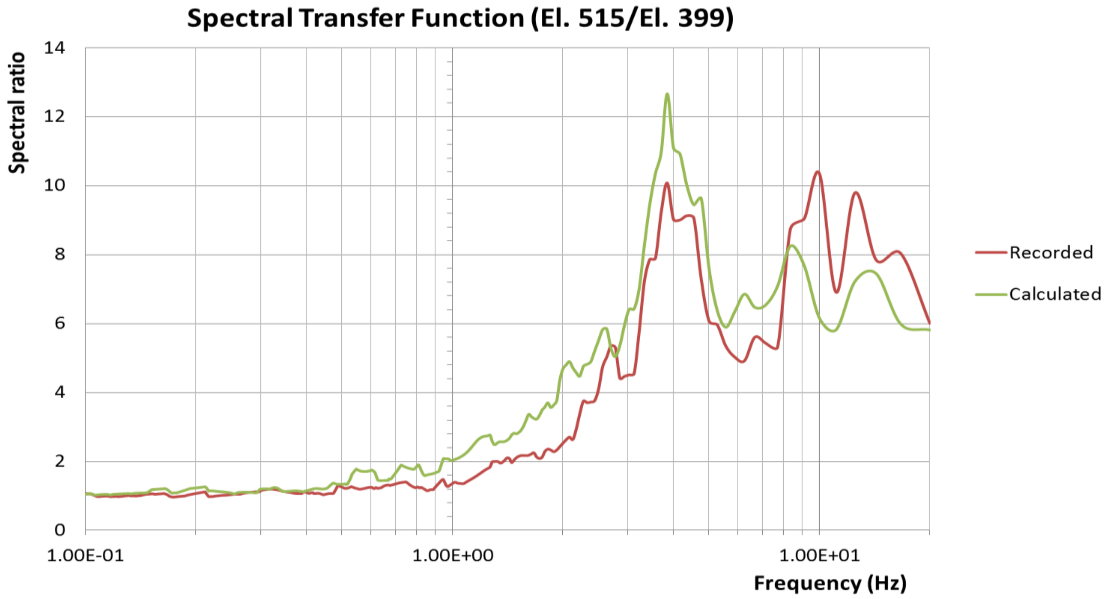


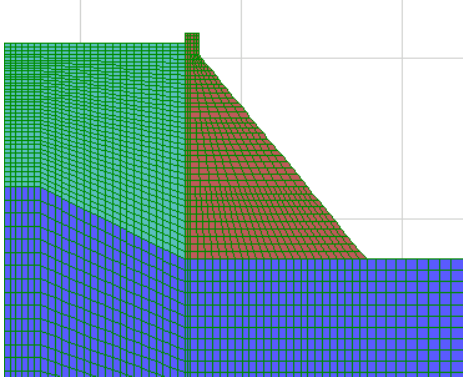
Spectral Transfer Function (El. 515/El. 399)



Calibration of the low frequency response (2016)

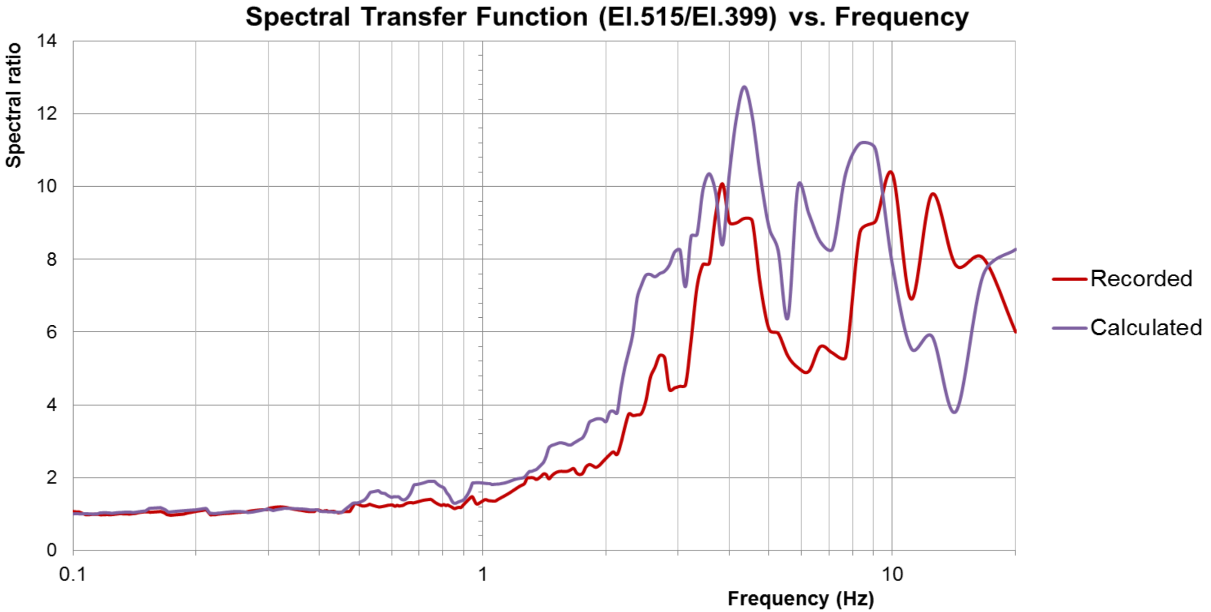
- **2D calculations**
  - 4th step: Horizontal + Vertical input components
    - ❖ Better (best) record fitting : 3.9 Hz frequency due to water vertical oscillation
    - ❖ Effect of reservoir modeling (reservoir attached to foundation)?
    - ❖ Does it work as well with FE-BE method?

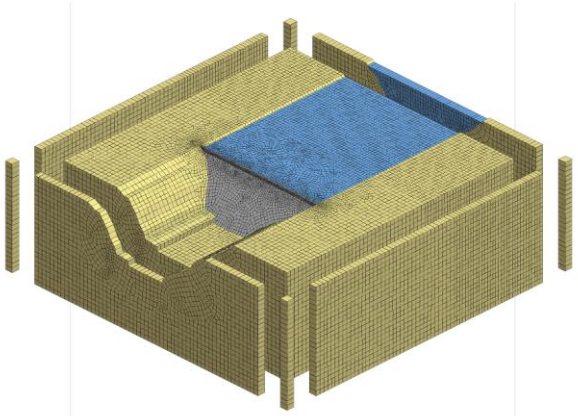

Spectral Transfer Function (El. 515/El. 399)



Calibration of the low frequency response (2016)

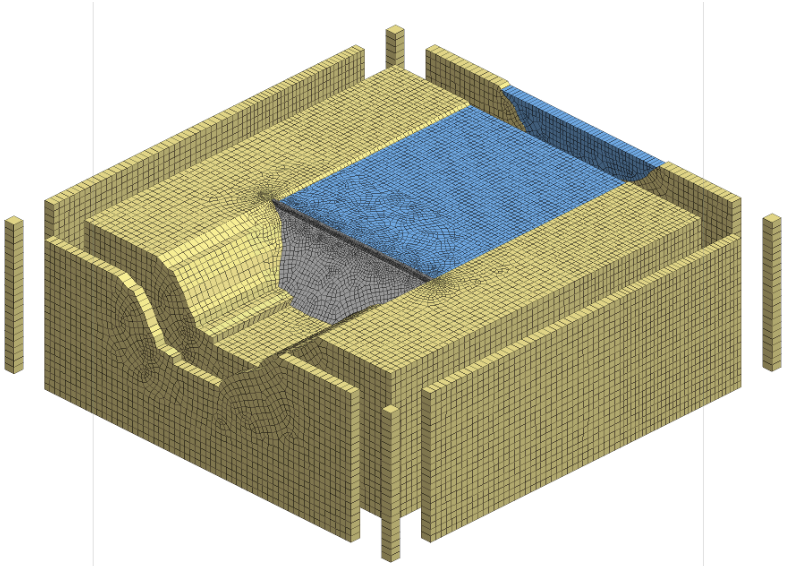
- **3D calculations – Blind results**
  - 0% material damping, 3D input
  - E_{dam} = 23.04 GPa, E_{found} = 20 GPa (JCOLD data)
    - ❖ Satisfactory but less fitting than 2D calculations
    - ❖ Calculated spectrum = 1.10 to 1.30 times the recorded one
    - ❖ Lower calibration quality of the water-related frequency





Calibration of the low frequency response (2016)

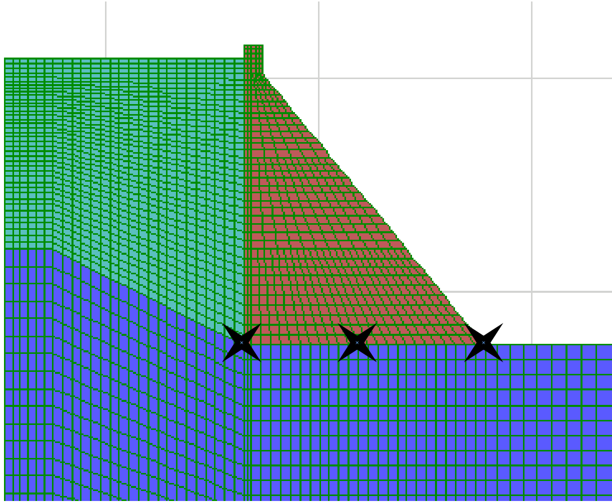
- **3D calculations – Possible explanation of lower calibration quality of 3D analysis**
  - Channel effect of the reservoir (model) vs. Real geometry (left bank)
  - Better representation of the reservoir by the 2D model
    - ❖ Infinite width toward the out-of-plane direction



Qualifications of methods (2016)

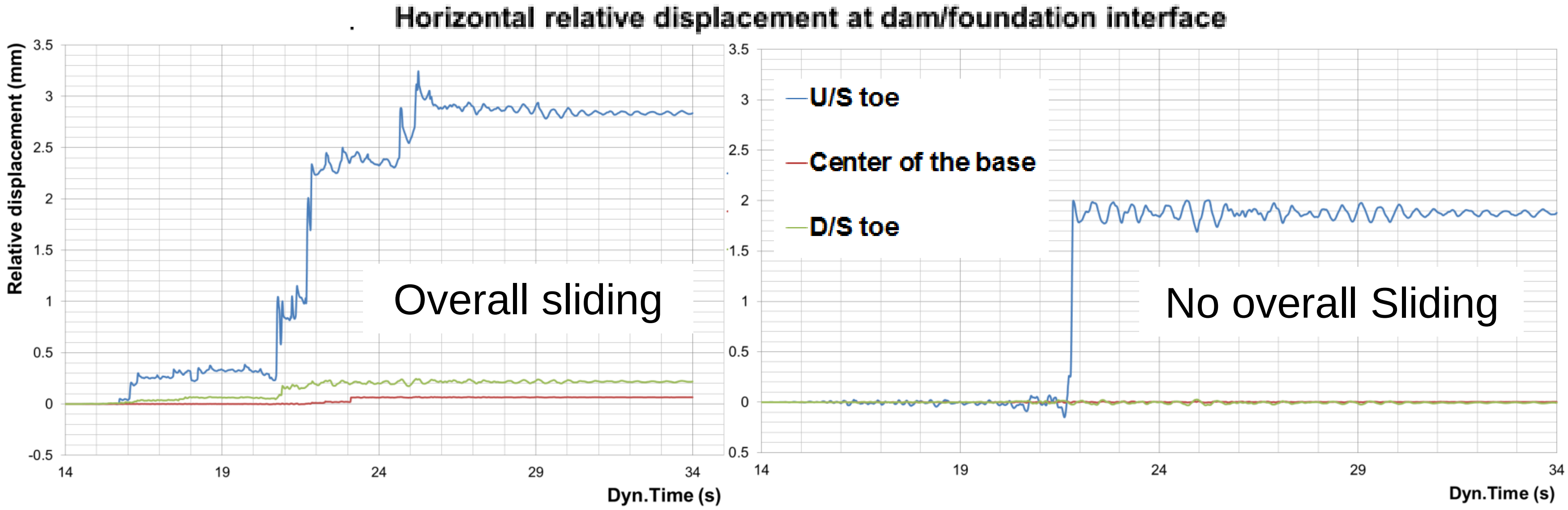
- **Sliding limit PGAs – Non-linear time history 2D analysis**
  - Coulomb friction law at dam / foundation interface
  - Friction angle = 45° + free opening
  - Sensitivity analysis with regards to cohesion
  - Drainage efficiency = 2/3 at the location of galleries
  - 5% material damping (dam only)
  - Input = H + V scaled with an increasing factor until sliding occurs

  - Relative horizontal displacements monitored at three locations
    - ❖ U/S toe
    - ❖ Center of the base
    - ❖ D/S toe



Qualifications of methods (2016)

- **Sliding limit PGAs – Non-linear time history 2D analysis**

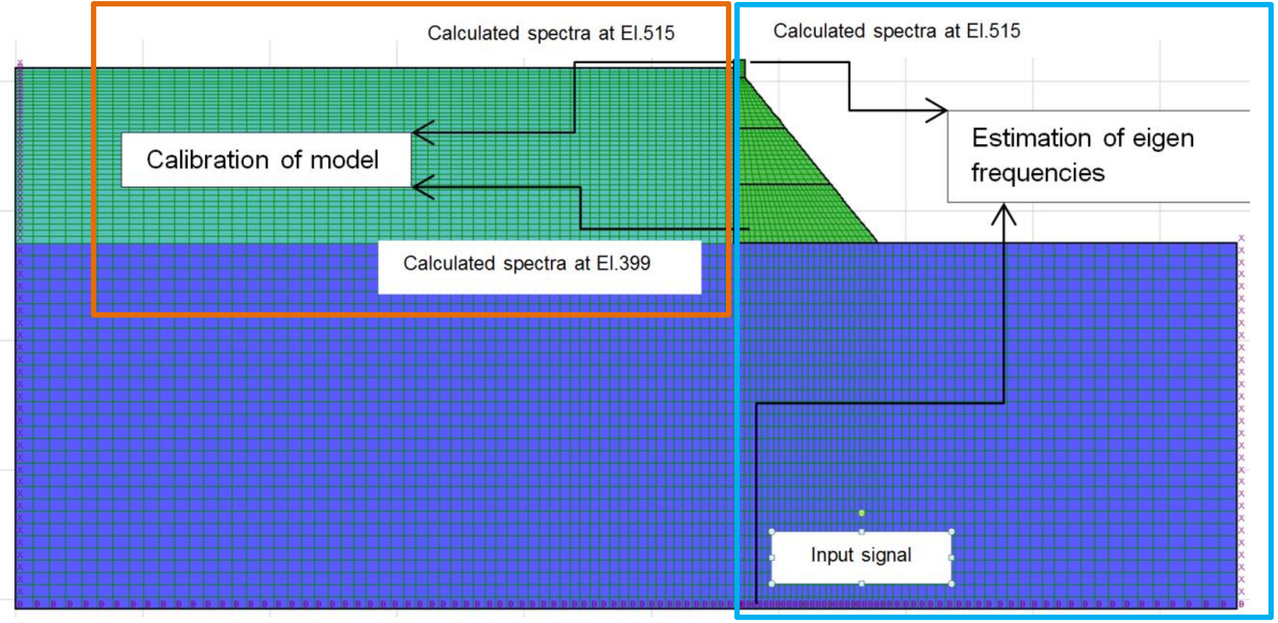


- Sliding limit PGA with pseudo-static analysis = 0.31 g.
    - ❖ pseudo-static coefficients = 2/3 H + 1/5 V
- 9 mm U/S toe relative displacement for PGA = 0.7g phi = 45°

Cohesion (kPa)	Sliding limit PGA (g)
0	0.34
100	0.38
200	0.44
300	0.55

Qualifications of methods (2016)

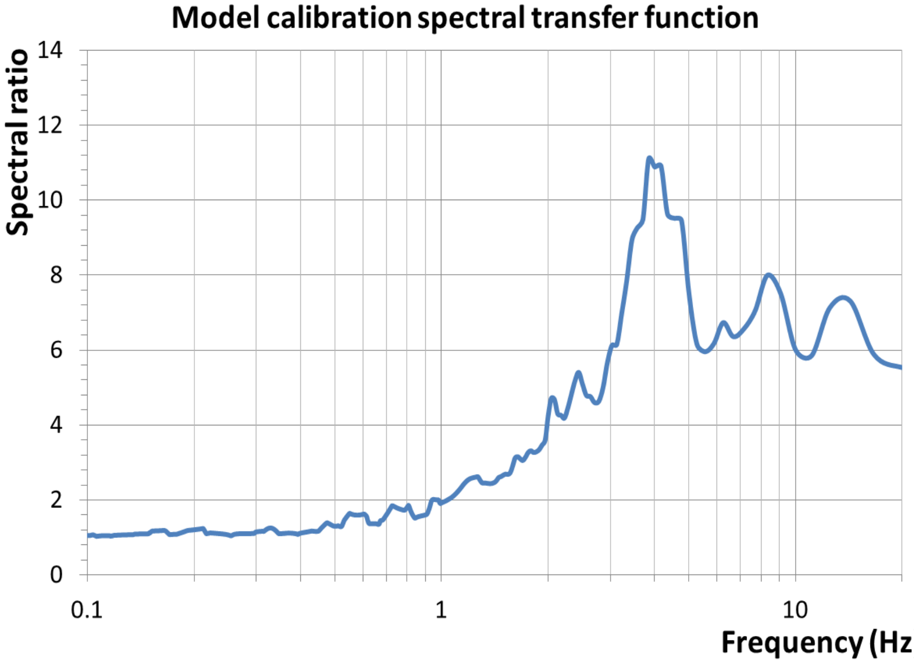
- **Use of spectral transfer functions: qualification of simplified methods**

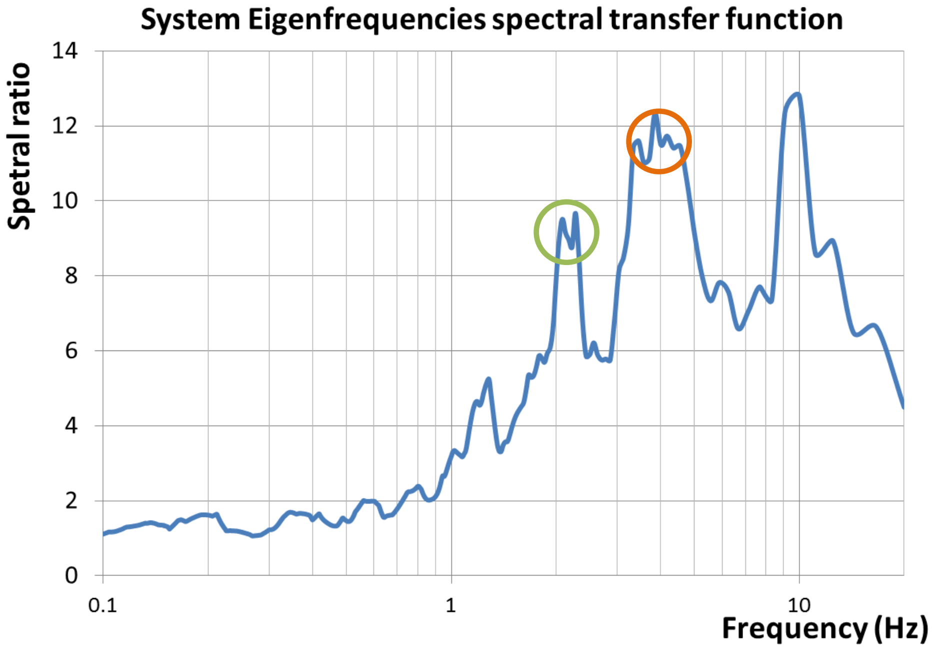


- Left hand spectral transfer function: $\dfrac{Calc.spectrum\ at\ El.515}{Calc.spectrum\ at\ El.399}$
  - ❖ Used for the calibration of the model with the records
- Right hand spectral transfer function: $\dfrac{Calc.spectrum\ at\ El.515}{Input}$
  - ❖ Used for assessment of the Eigen frequencies of the system

Qualifications of methods (2016)

- **Use of spectral transfer functions: qualification of simplified methods**





- First mode: 2.2Hz ≠ Predominant mode: 3.9Hz
- First mode usually used as input for simplified methods

➡ **Is this always relevant?**

Main conclusions (1/2)

- **Validation of the use of radiative boundary conditions by means of recorded data**
  - ❖ Up to 12 % supplementary damping for stiff bedrock
  - ❖ Acknowledgment to JCOLD

- **0-1% required material damping ratio for Tagokura dam with the used input**
  - ❖ Consistent with the magnitude of the input
  - ❖ No need for fictitious (and difficult to calibrate) additional material damping

- **Validation of the reservoir model for dam / reservoir interaction**
  - ❖ Westergaard distribution = very specific case, may not be suitable for large dams and **not necessarily the most pessimistic**

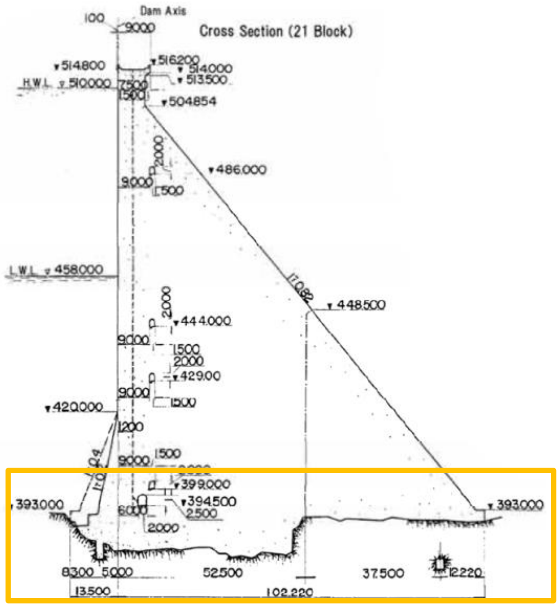
- **Use of vertical component = best calibration results so far (Major finding)**
  - ❖ May depend on reservoir modeling
  - ❖ French guidelines to be updated?

- **Reservoir geometry in 3D analysis to be further investigated**

Main conclusions (2/2)

- **Non-linear analysis**
  - Pessimistic results as the excavation « step » not modeled
  - Still reassuring results as low expected relative displacement if any
  - If sliding, drainage discharge to be assessed as per Tardieu et al.
  - Method to be calibrated with a dam subjected to stronger earthquake (e.g. Kasho dam)

- **Predominant mode ≠ First mode (Major finding)**
  - Due to the effect of the reservoir
  - What about the input of simplified methods?
  - Field of application to be clarified



THANK YOU FOR YOUR ATTENTION