International Symposium
Qualification of dynamic analyses of dams and their equipments
and of probabilistic assessment seismic hazard in Europe
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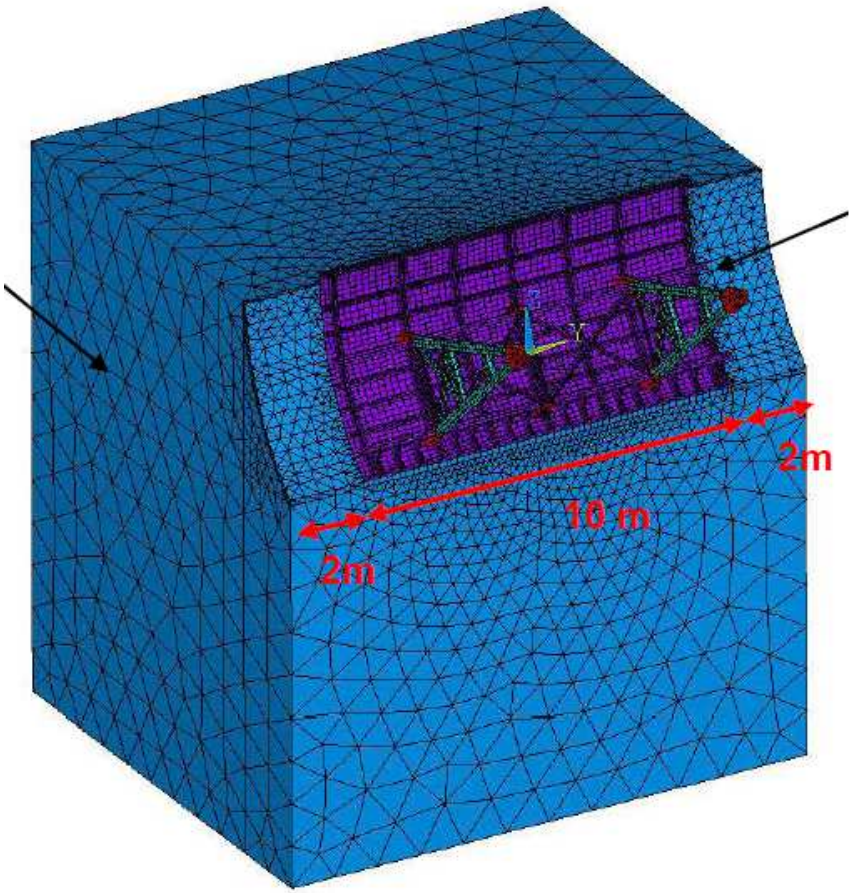
Session 7 : Qualification of equipment

MODAL ANALYSIS OF GATES
FEM Coupled with FSI Analysis Compared to On-Field Measurements

SUMMARY

1. Introduction

- This work is an extension of the work presented in 2014 and 2015 on the **"Spillway Gates at Top of Dam : Evaluation of Mechanical Resistance to Earthquakes"**
- **Focus on study case "segment gate H72"**
- Checking the **integrity** of structure
- Earthquake = accidental load case (**SES spectra**)
- Analysis criteria
  - Ultimate limit state analysis
  - Rules : DIN 19704 (Hydraulic Steel Structures Design Analysis)



2. Calculation Method including Seismic Loads

- **CONVENTIONAL APPROACH (STATIC EVALUATION)**

  Considered Loads :
  - Self weight (**P**)
  - Hydrostatic pressure (**Q1**)
  - Hydrodynamic pressure (**A1**)
    -> using Westergaard's formula
    (hydrodynamic pressure acting on gates due to dams behavior – gates considered as a **rigid body**)

- **MORE REALISTIC APPROACH (INCLUDING DYNAMIC RESPONSE OF DAM & GATE)**

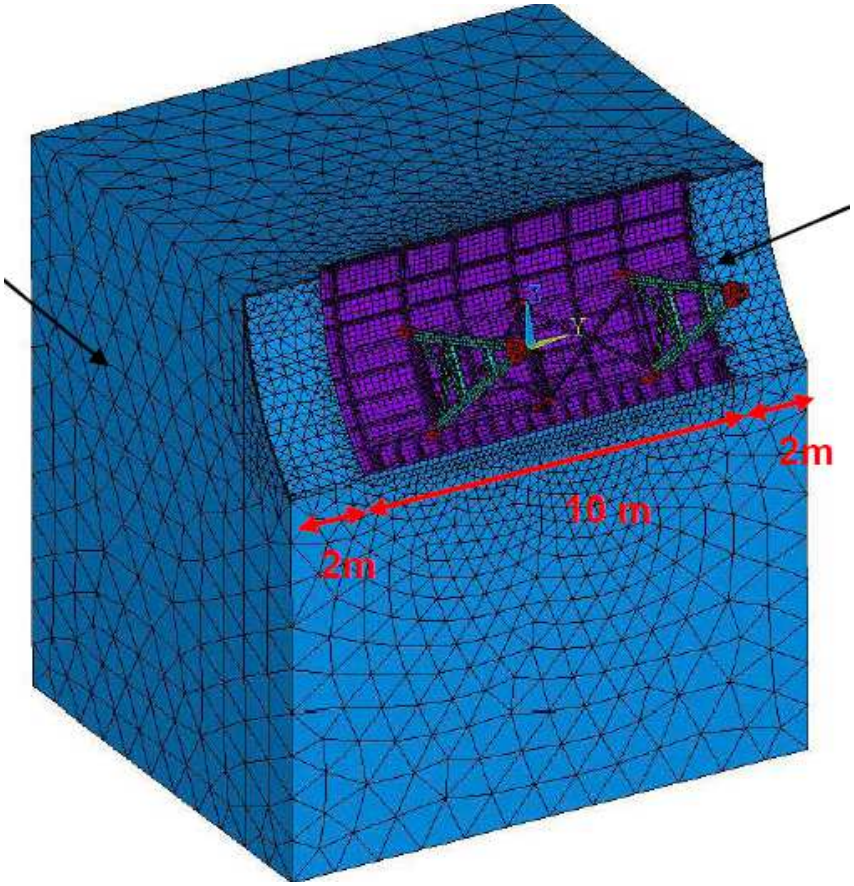
  Considered Loads :
  - Self weight **(P)**
  - Hydrostatic pressure **(Q1)**
  - Hydrodynamic pressure **(A1)**
    -> using Westergaard's formula (hydrodynamic pressure acting on gates due to dams behavior)
  - Dynamic response of immerged gates **(A2)** – spectrum analysis with FSI analysis

- **LOADS COMBINATION (ACCIDENTAL LOAD CASE):**

$$1.35 \times P + 1.35 \times 0.8 \sum (Qi + Ai)$$

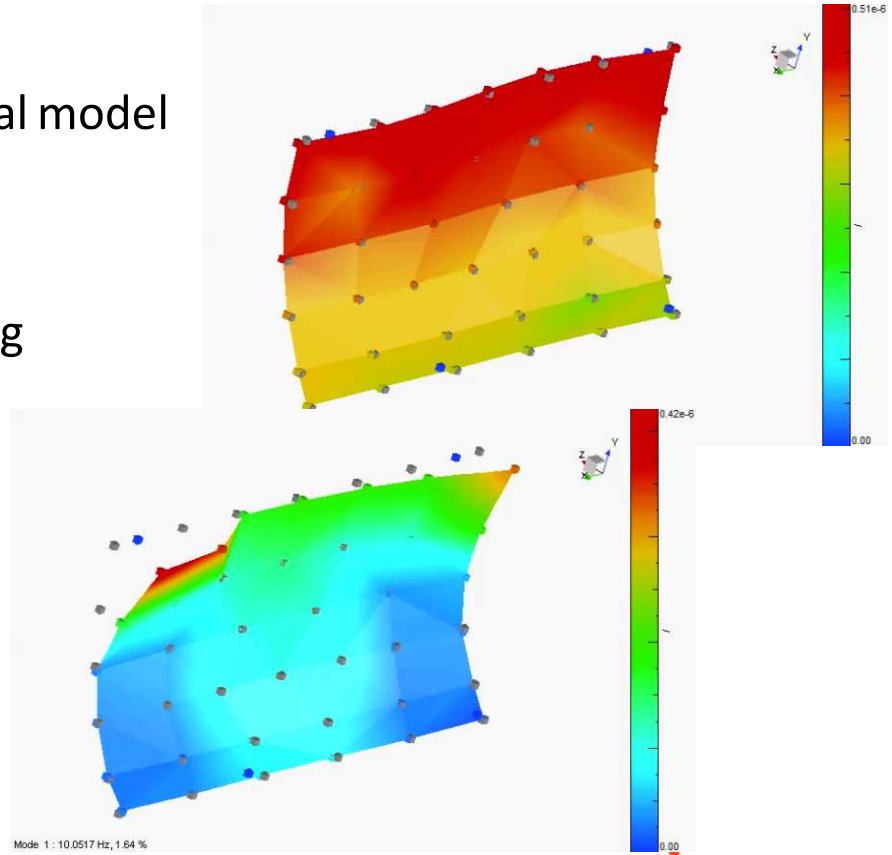
3. Dynamic Behavior of Gate : Qualification of the Numerical Approach

- **FEM modal analysis including Fluid Structure Interaction calculation**
  - **Gate** : Beam and shell structural elements
  - **Fluid** : 3-D Acoustic Fluid elements
  - **Boundary conditions:**
    - **Gate**
      Blocking displacements at trunnions & lower edge
    - **Fluid**
      - Symmetry
      - Free surface (P = Patm)
      - Absorption



3. On-field Measurements

- **Method**
  - For one set of accelerometer locations => transfer functions measurement from impact hammer (load cell) to accelerometers
  - Perform measurements for every impact locations and accelerometer locations
  - Once all measurements are done
  - ➡ synthetize TF to build an experimental model
    - Eigen frequencies
    - Eigen vectors
    - Estimation of the modal damping
- **Comparisons with numerical models**
  - MAC matrix
  - Build cost functions to tune models
- **Two types of modes**
  - Structural modes
  - Rigid body modes

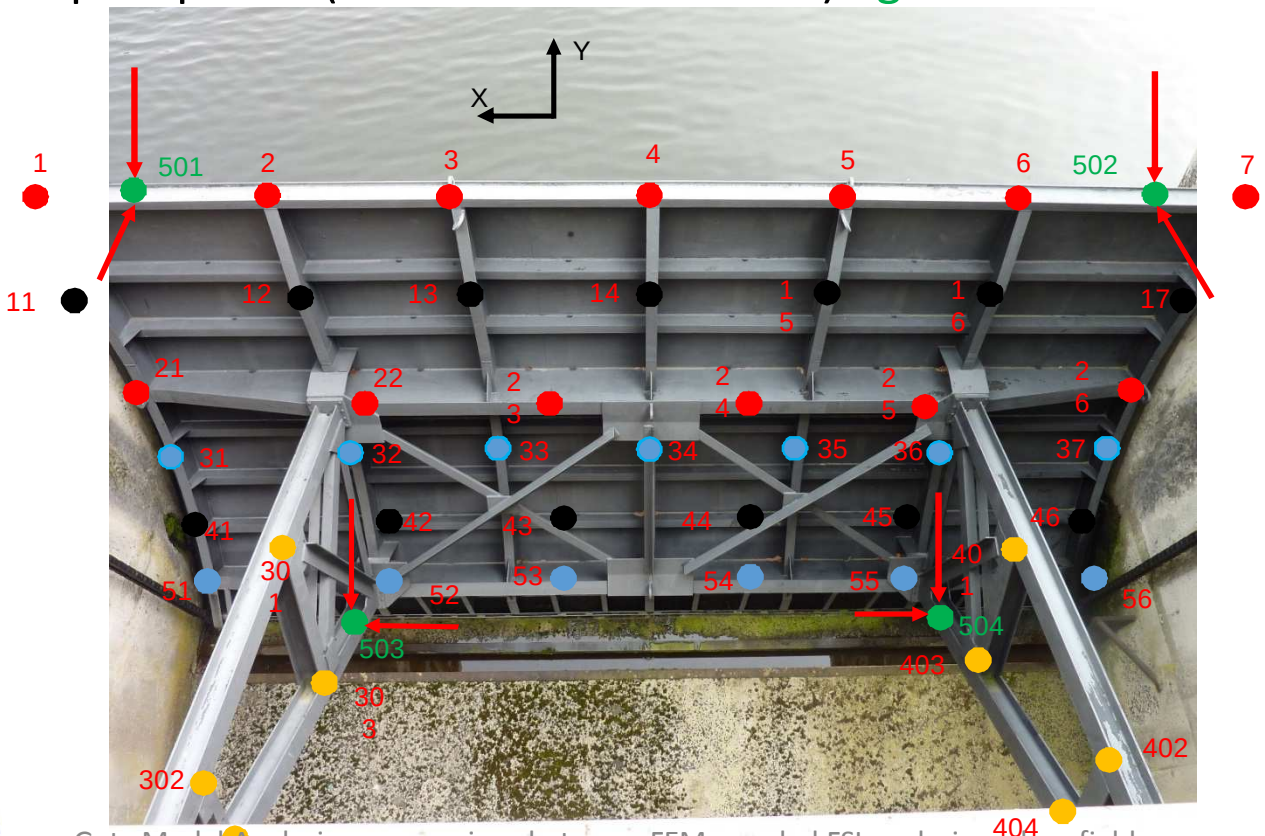


3. On-field Measurements

- **Equipment and Set Up**
  - Sensors - impact hammer - Data acquisition
  - 13 accelerometers – PCB 356A17
  - Hammer PCB type 086D20 (1Kg)
  - Siemens LMS SCADAS SCM05 – 40 inputs
- **Studied configurations**
  - Gate opened and suspended by its chains
  - Gate closed – no water
  - Gate closed – water at mid-level
  - Gate closed – water at high-level
- **Organization**
  - 1 day for install
  - 2,5 days - measurements
  - 0,5 day – deinstall
- **Measurement team**
  - Installation: 2 rope access technicians
  - Measurements: 1 engineer + 1 technician

3. On-field Measurements

- **Sensors and impact points**
  - 39 points on the gate (3 sets of 13 locations) – Red – Black - Cyan
  - 10 points on the arms (1 set of 10 locations) - yellow
  - 4 impact points (2 directions each time) - green

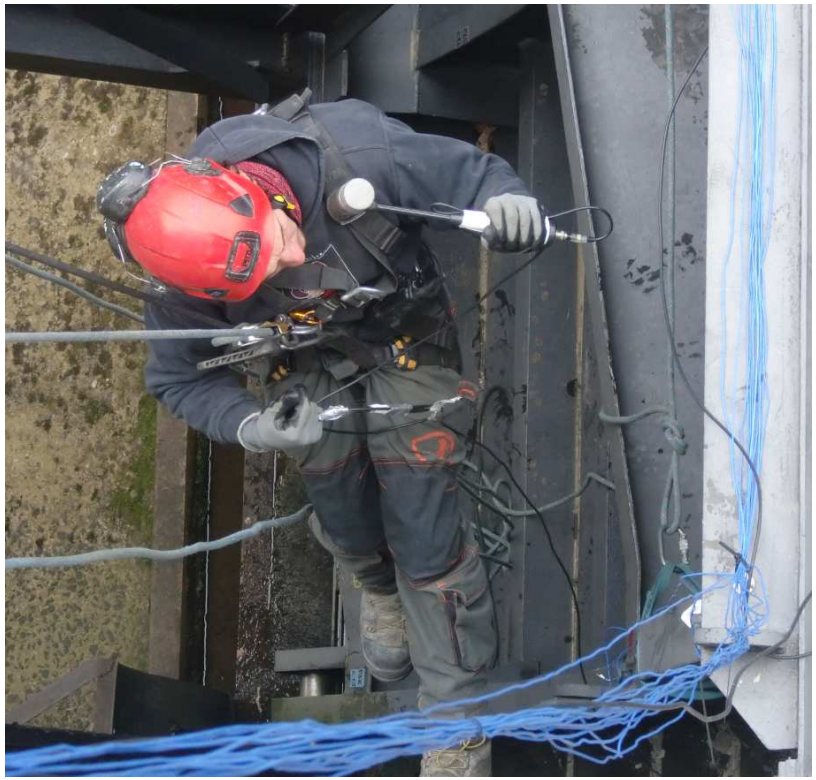


3. On-field Measurements

- **Install**
  - Install by 2 rope access technicians

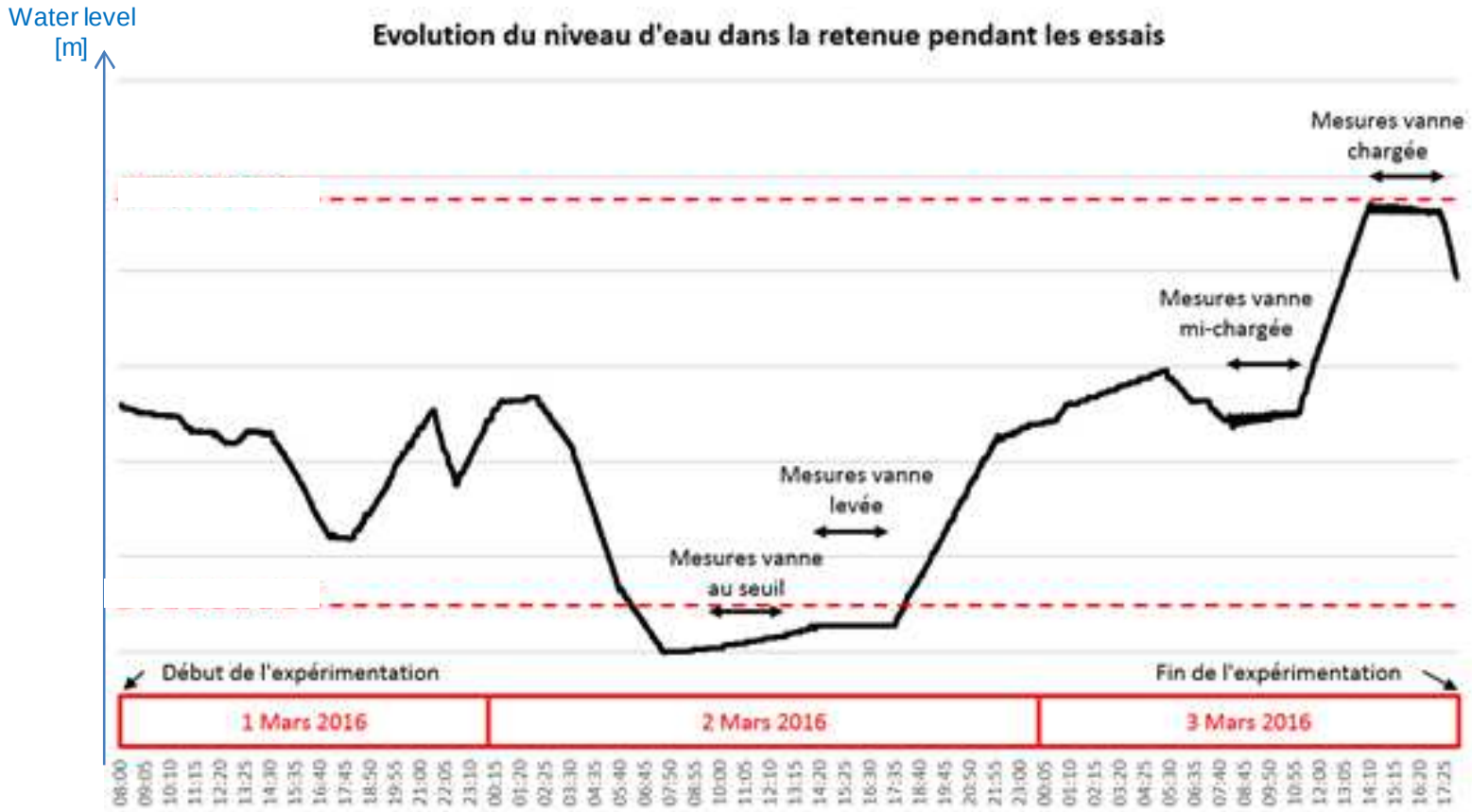
3. On-field Measurements

- **Measurements**
  - Measurements by 2 rope access technicians

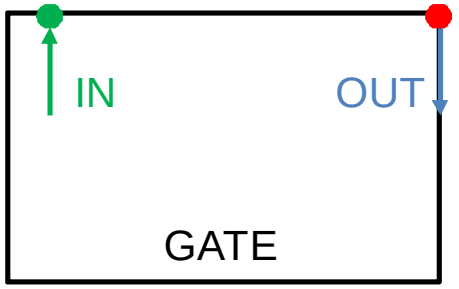


3. On-field Measurements

- **Set Up**
  - Water level stability during measurements

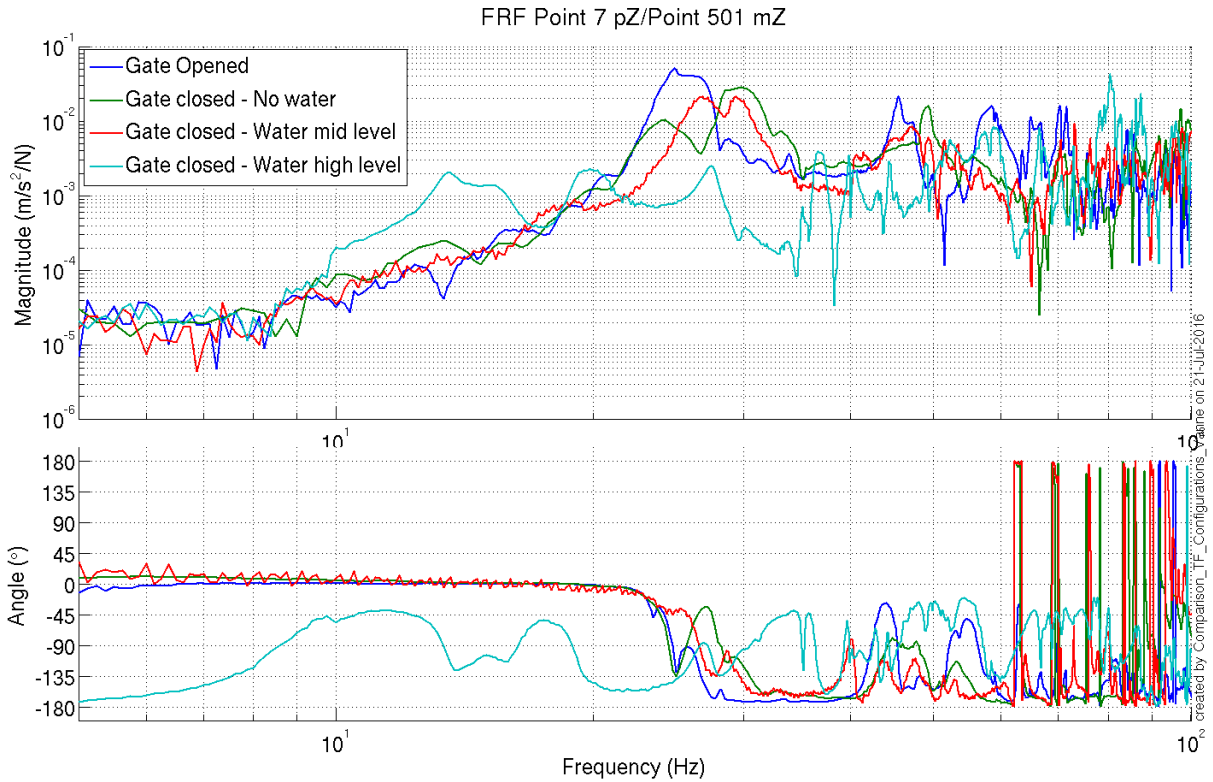


3. On-field Measurements



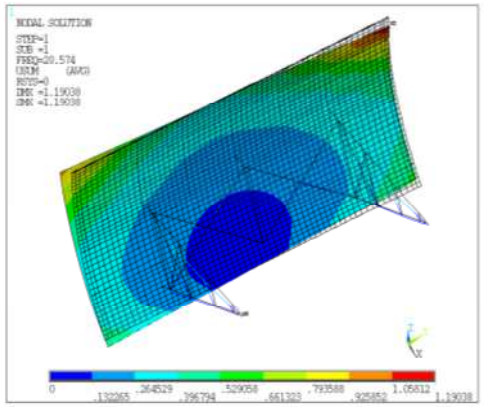
- **Dynamics changes vs configuration**
  - Transfer functions measurements
    - Frequency
    - Damping
    - Amplitude

→ Dynamic changes with water level

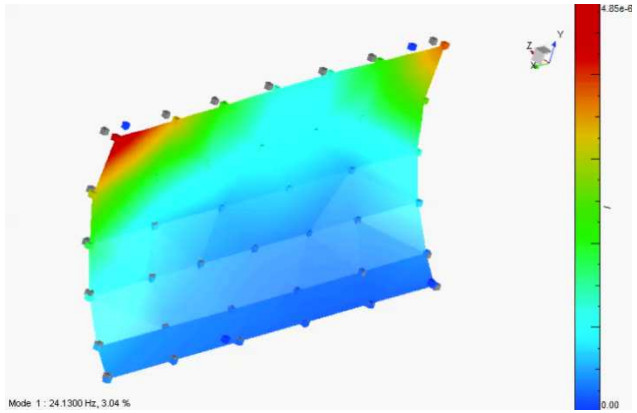


3. On-field Measurements

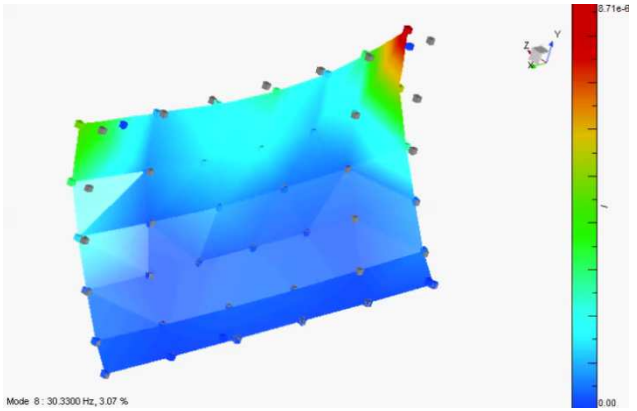
- **Results – Gate closed – No water**
  - **Comparison with numerical model**
    - Similar mode shapes



Model - Mode 1 – 20,6Hz



Measurements - Mode 1 – 24,1Hz – 3,4%



Measurements - Mode 8 – 30,3Hz – 3%

  - **Boundary conditions**
    - **Model**: simply supported at the lower edge of the gate
    - Need to consider :
      - the preload at the lower edge
      - Lateral seals

    → Increase the eigen frequencies of the first modes
  - **Modal damping**
    - From 1% to 3%

Mode - Frequency (Hz) – error (%) vs measurements	
Identified modes	**Simulations vs Meas (error)**
Mode 1 - 24.1Hz	**Mode 1 - 20,6Hz – 17%**
Mode 2 - 24.6Hz	Mode 2 - 21,2Hz – 14%
	Mode 3 - 25,6Hz
	Mode 4 - 26,4Hz
	Mode 5 - 28,6Hz
Mode 4 - 27.8Hz	Mode 6 - 29,1Hz – 5%
Mode 8 - 30.3Hz	**Mode 7 - 30,6Hz – 1%**

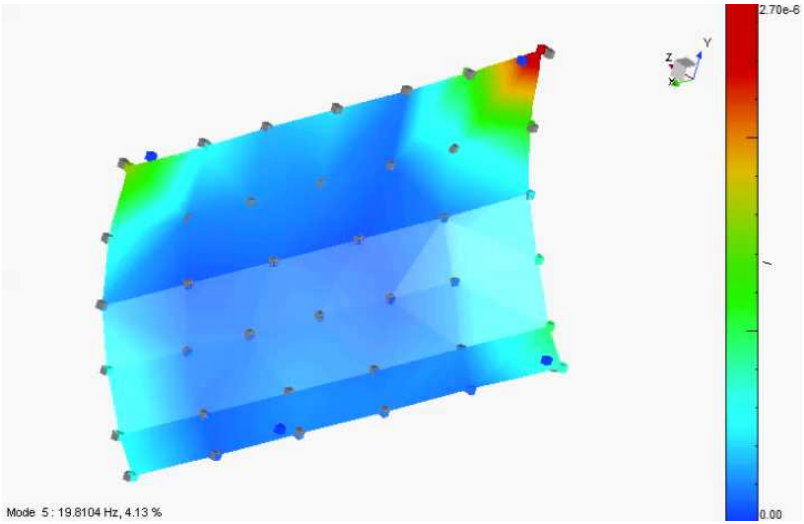
3. On-field Measurements

- **Results – Gate closed – High Water Level**
  - **Comparison with numerical models –** Westergaard vs FSI FEM analysis
    - Overestimation of the added mass by the Westergaard approach
    - Better estimation of modal behavior with the Fluid-structure interaction model

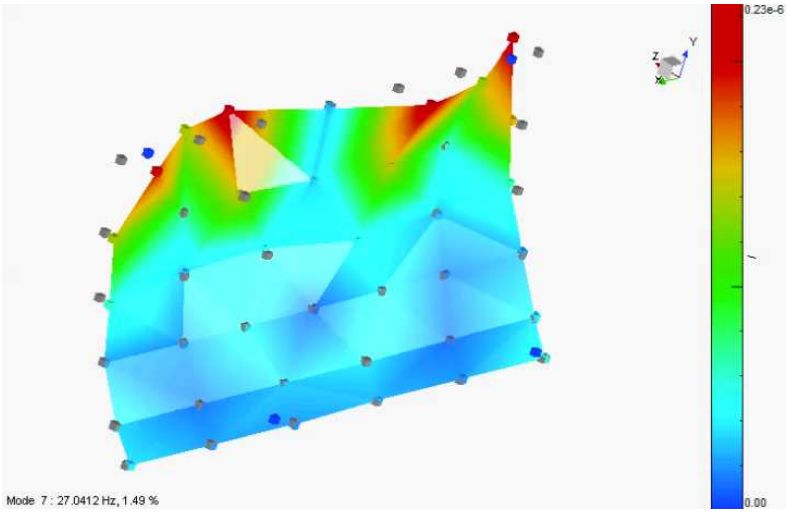
Measurements	Westergaard	Fluid-structure
Mode 1 - 10.1Hz	4.0Hz	10.0Hz
Mode 2 - 13.3Hz		
Mode 3 - 15.2Hz	4.5Hz	14.4Hz
Mode 4 - 19.0Hz		23.0Hz
Mode 5 - 19.8Hz	6.7Hz	
Mode 6 - 23.4Hz		
Mode 7 - 27.0Hz		
Mode 8 - 29.8Hz		

3. On-field Measurements

- **Results – Gate closed – High Water Level**
  - **Modal damping ratios**
    - From 1,6% and 4,5% for structural modes
    - Above 10% for suspension modes
    - Overall increase with water level
    - Modal damping ratios depend on mode shapes



Measurements - Mode 5 – 19,81Hz – 4,1%



Measurements - Mode 7 – 27,04Hz – 1,5%

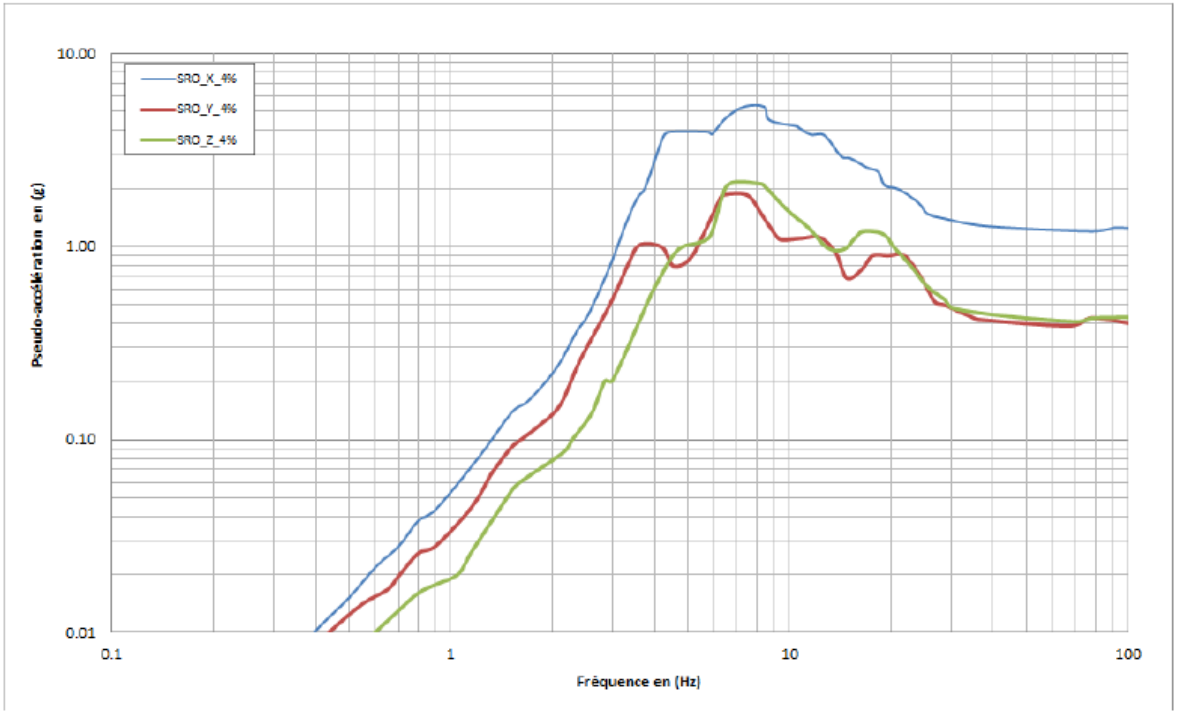
3. On-field Measurements

- **Conclusions experiments**
  - 1-week experiment
  - 4 configurations tested
  - **Comparison model vs experiments**
    - **Gate closed – no water**: need to improve the boundary conditions at the lateral and lower edges of the gate (seals and preload)
    - **Gate closed – high water level**:
      - Westegaard approach overestimates the added mass
      - Fluid-structure interaction model gives eigen frequencies in good agreements with measurements

        ➡ Tuning the model might be necessary
  - **Damping ratios**
    - From 1 to 3% when gate « in air »
    - From 1,5% to 4,5% when gate is « in water ». Modal damping seems to depend on mode shapes
    - Above 10% for suspension modes

4. Summary of the Main Results of FEM Modal-Spectrum analysis with FSI Calculation

- **Seismic load**
  - Soil spectra : Earthquake Safety Assessment
  - Floor spectra : calculated at the dam-gate interfaces



Floor Spectra		« H72 »
X	Peak (f)	**5.31 g** (8.0 Hz)
	Rigid (f)	**1.30 g** (30.0 Hz)
Y	Peak (f)	**1.85 g** (7.0 Hz)
	Rigid (f)	**0.49 g** (30.0 Hz)
Z	Peak (f)	**2.12 g** (7.0 Hz)
	Rigid (f)	**0.48 g** (30.0 Hz)

4. Summary of the Main Results of FEM Modal-Spectrum Analysis with FSI Calculation

- **Reaction forces**

		« H72 »
Reaction Forces	PP (**P**)	91 kN
	Pstat (**Q1**)	1 053 kN
	P hydrodyn. (**A1**)	927 kN
	Spectrum analysis (**A2**)	± 2 620 kN
	r (*) =	**≈ 3.5**

(*) : r = ratio (accidental situation / normal situation) for weighted values

- **Structural strain – Stress**
  - « Classical Elastic criteria » are not respected,
  - Local plastifications
  - Buckling criteria are not respected (gate arms)

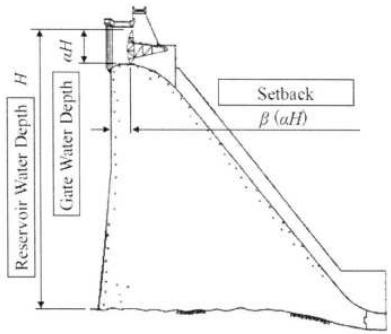
⇒ **Need to conduct an elastoplastic analysis to conclude on the mechanical strength of the gate (rate of plastic deformation seems acceptable)**

⇒ **Need to determine which mode of instability has to be considered : buckling or excess of plastic deformation**

5. Conclusion and Further Works

- **MODAL ANALYSIS**
  - Gate **does not have a rigid behavior** within the bandwidth of an earthquake
    $f_{gate\ in\ air} \approx 24$ Hz $f_{gate\ in\ water} \approx 10$ Hz (≈ peak of floor spectra)
  - **FSI analysis is better suited than analysis with added masses** : mass of water and distribution must be adjusted (as fair as possible) for each natural frequencies
  - Fluid-structure interaction model gives eigen frequencies in **good agreements with measurements.**

- **STRESS ANALYSIS**
  - Complexity of stress analysis (elastic vs elastoplastic) and design criteria must be **adapted to the amplitude of the considered earthquake**.
  - For the studied gate, **seismic stresses (SES spectra) do not seem acceptable**. Some mechanical reinforcements should be considered.
  - This study was conducted on a unit case. It must be extended to other test cases to qualify the proposed calculation method.
  - Some ways have to be still studied as the use of the “set back” (cf publication of Y. NAKAYAMA)




THANK YOU FOR
YOUR ATTENTION