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

Jorge P. Gomes, José V. Lemos
LNEC, Lisboa, Portugal

Session 5 : Qualification of seismic analyses of concrete dams

Characterization of the dynamic behavior of an arch dam by means of forced vibration tests

SUMMARY

1. Introduction

Dynamic characterization of concrete dams

Forced vibration tests

2. The Baixo Sabor project

Arch dam

Dynamic testing and monitoring systems

3. Modeling approach

DEM modeling with 3DEC

Modeling of the forced vibration tests

4. Comparison of experimental and numerical results

Dynamic characterization of concrete arch dams

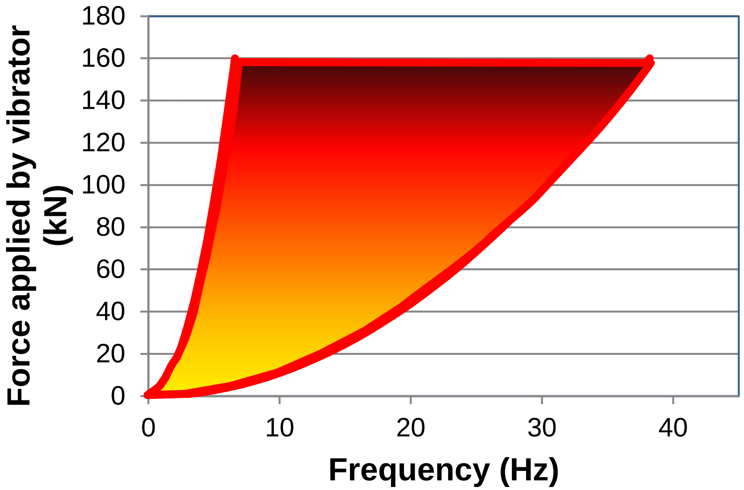
- **Continuous dynamic monitoring**
  - Ease of application; provides continuous response
  - Low level of environmental excitation

- **Forced vibration tests**
  - Higher level of excitation; known action
  - More costly and time consuming

- **Seismic monitoring**
  - Triggered by seismic events
  - Characterizes seismic action and structural response

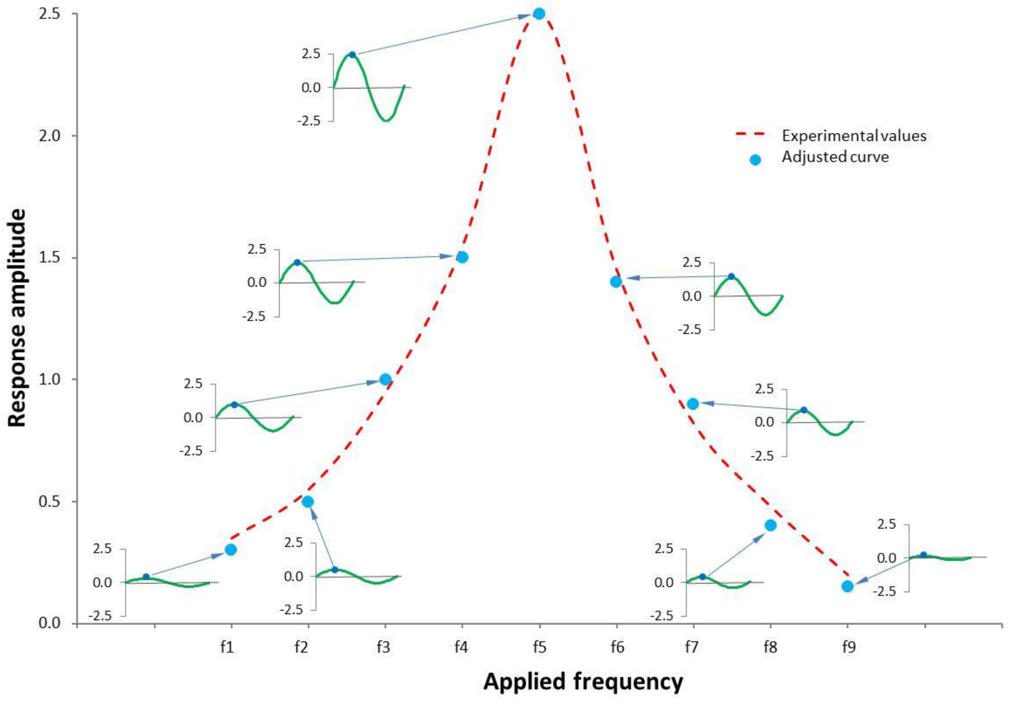
Forced vibration testing

- **Methodology**
  - Application to the structure of a dynamic action with a prescribed amplitude and frequency
  - Action usually applied with eccentric mass vibrator which imposes a sine wave force
  - Structural response measured at representative locations
  - Identification of model parameters (frequencies, shapes, damping, …)



Discrete frequency scanning

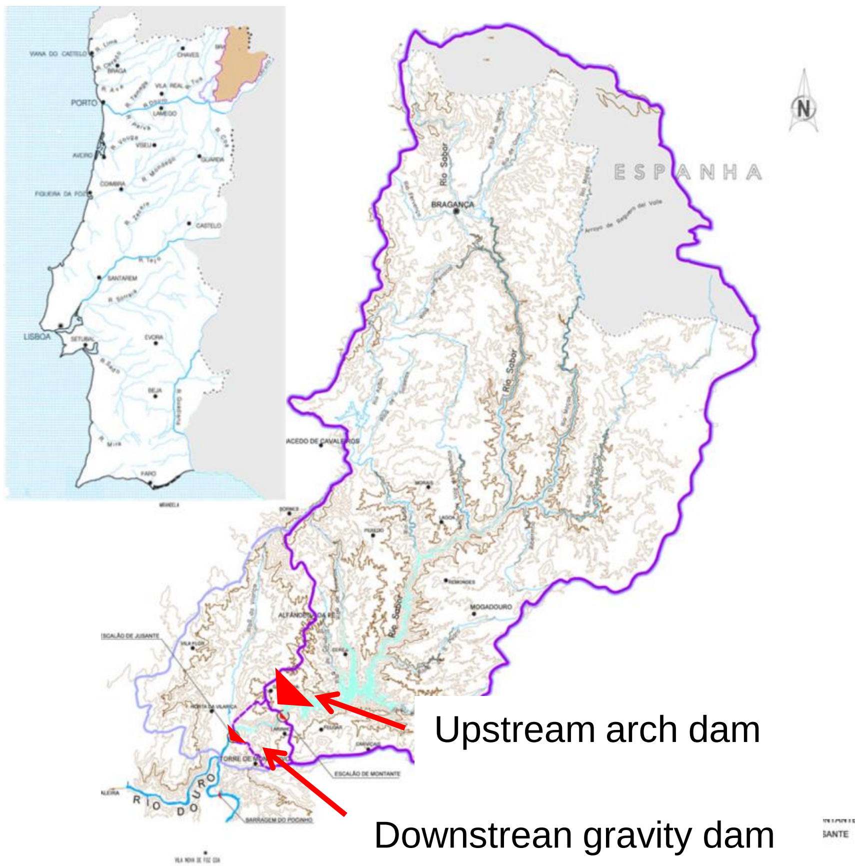
Frequency response function for a measurement point of the structure obtained by discrete frequency scanning



Displacement/force transfer function for MDOF system

$$H_{ij}(w)=\sum_{k=1}^{N}\frac{(\phi_i)_k\,(\phi_j)_k}{(w_k^2-w^2)+\mathrm{i}(2\xi_k\,w_k\,w)}$$

Baixo Sabor project (EDP)

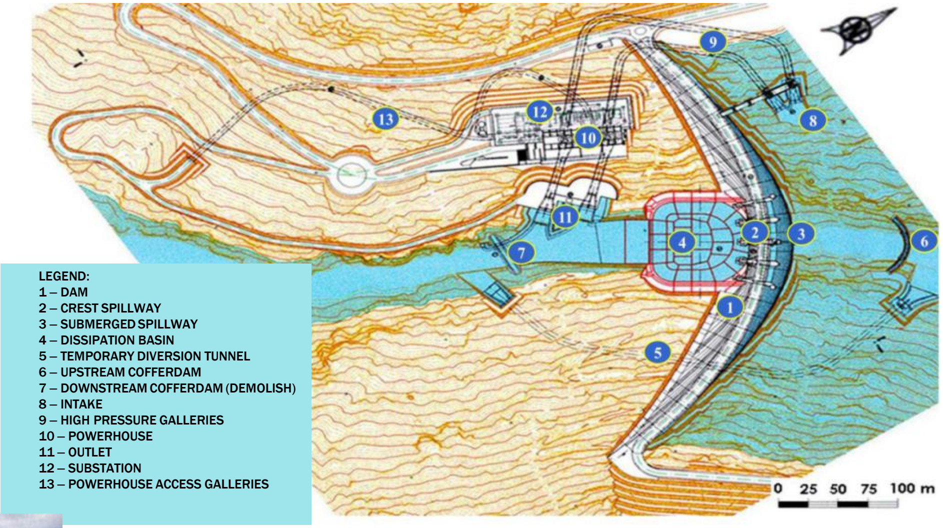


Owner: EDP
Construction started: July 2008
First filling completed (arch dam): April 2016

Arch dam – General layout

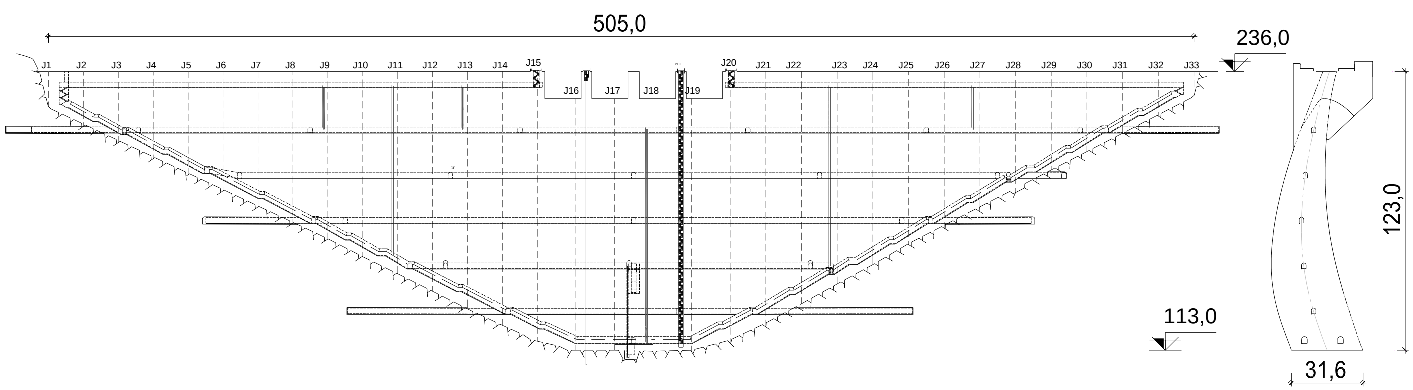
- **Arch dam**
  - 2 reversible groups
  - Power : 2x70 MW
  - Net energy production : 230 GWh

- **Design by EDP**



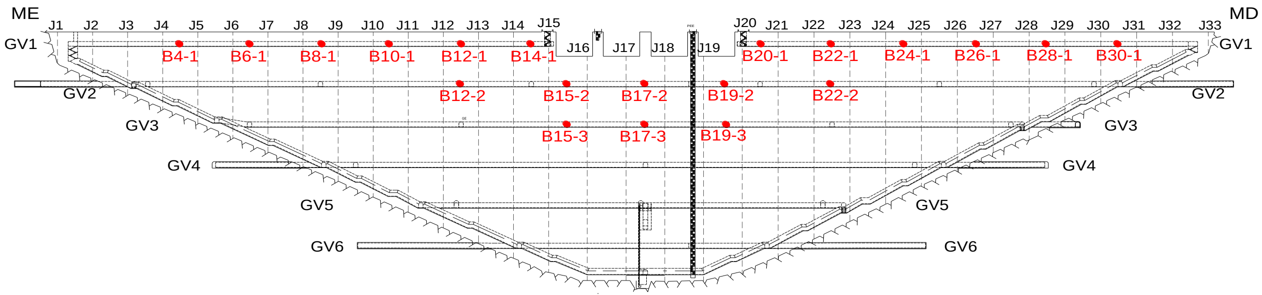
Arch dam

- **Dimensions**
  - Height 123 m
  - Crest length 505 m
  - Central cantilever thickness
    - Min. 6 m
    - Max. 31.6 m
  - Reservoir
    - Max. volume 1275 hm^3
    - Max. area 3100 ha

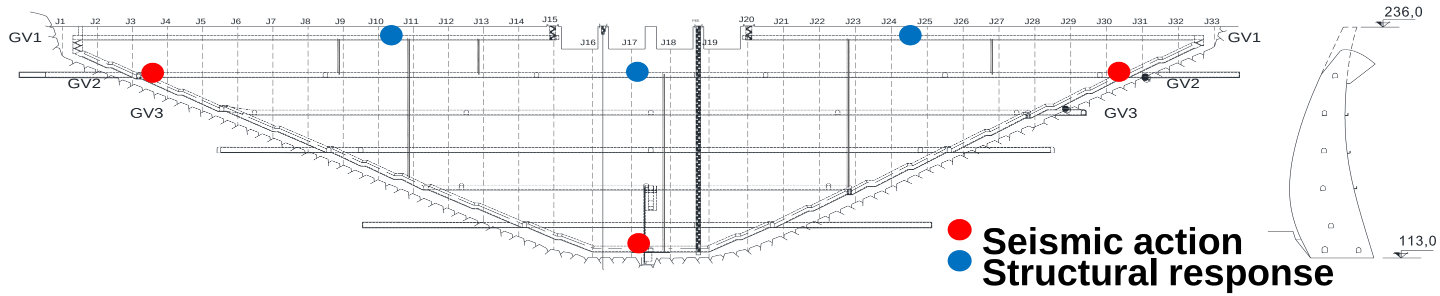


Dynamic monitoring systems
(currently being installed and tested)

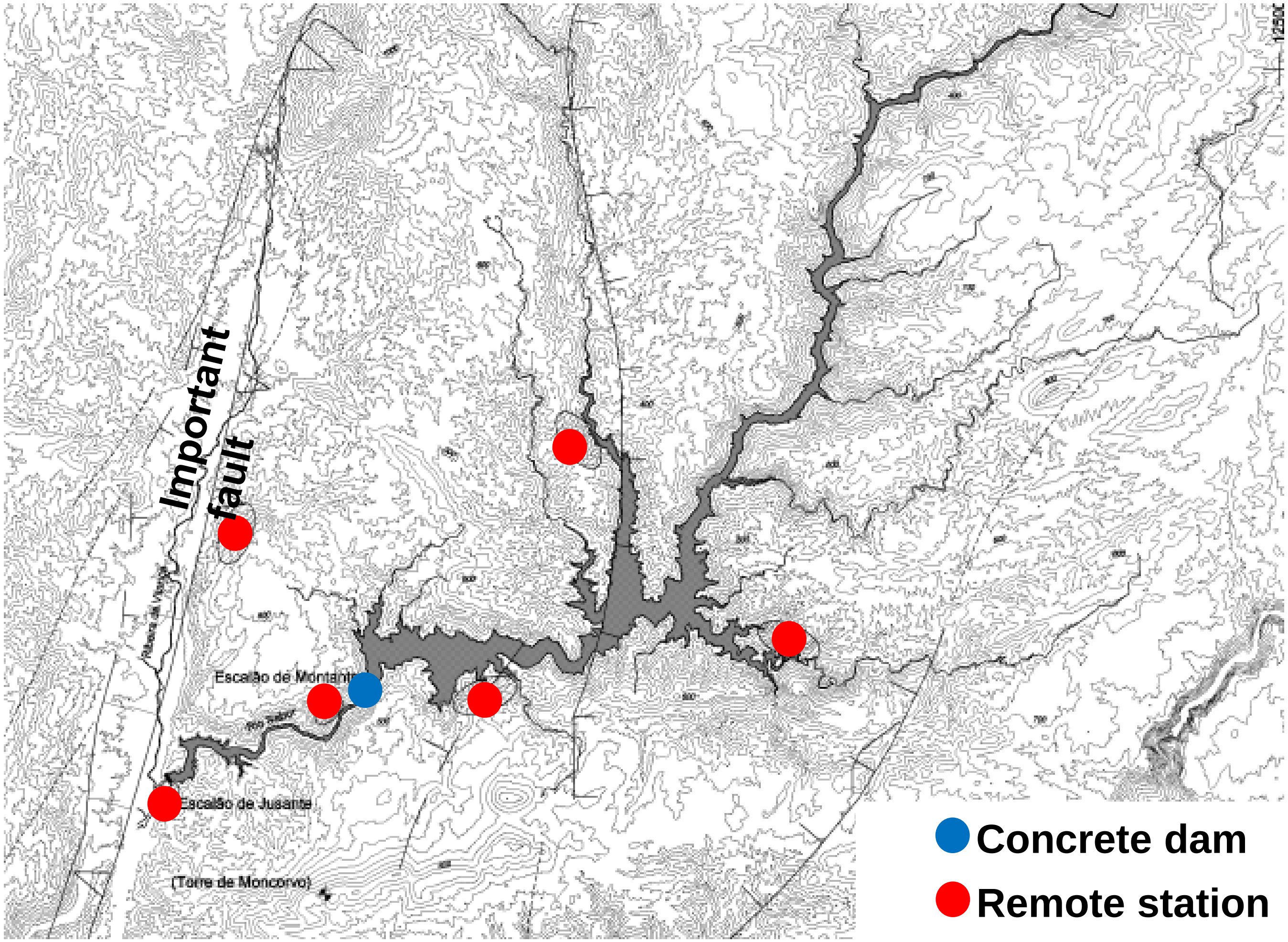
- **Continuous dynamic monitoring**
  - 20 radial accelerometers for continuous dynamic monitoring



- **Seismic monitoring system**
  - 3D accelerometers to be triggered in case of earthquake

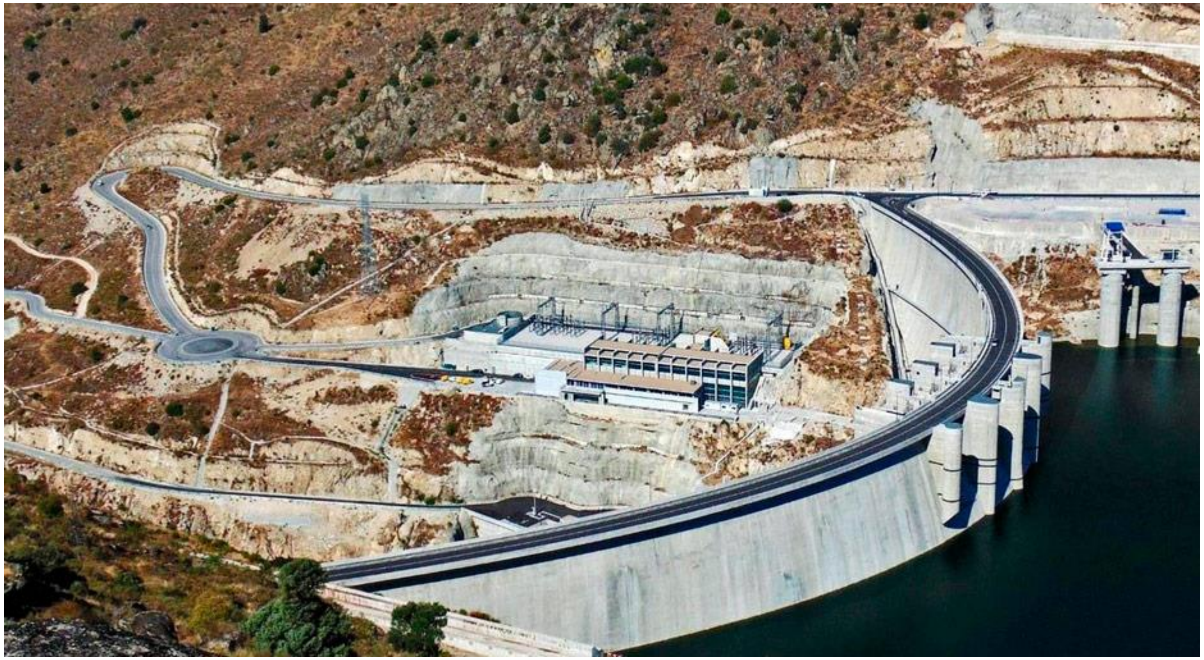


Seismic monitoring system – Remote stations



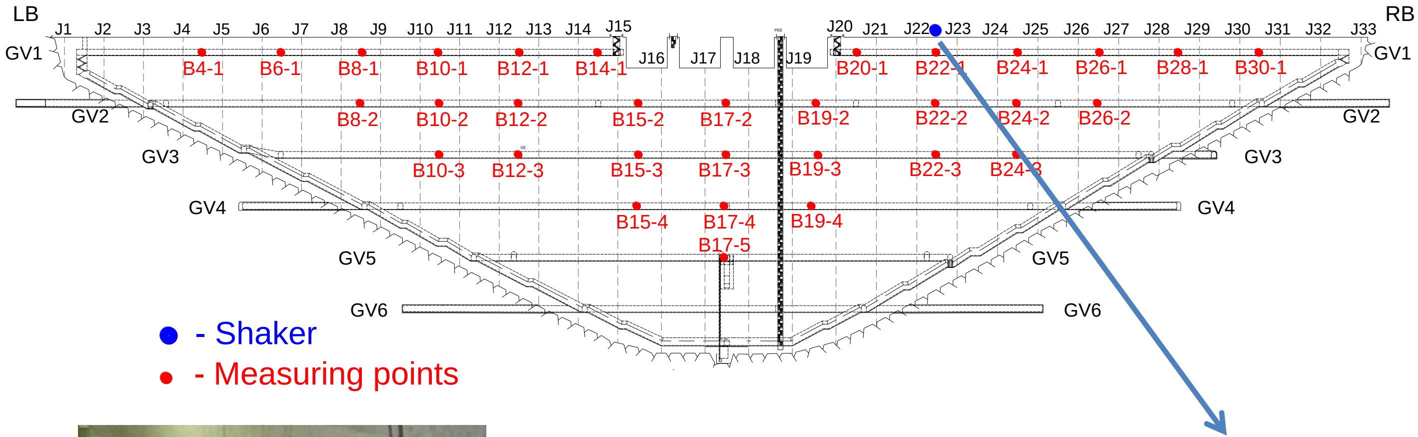
Arch dam – Forced vibration tests

- Forced vibration tests to be performed before and after reservoir filling
- First set of tests performed in Jan 2015 for a reservoir level 38.5 m below crest (about 70% of max. water height)
- Reservoir filling completed in April 2016; second set of tests recently performed



Water level during first set of tests (Jan 2015)

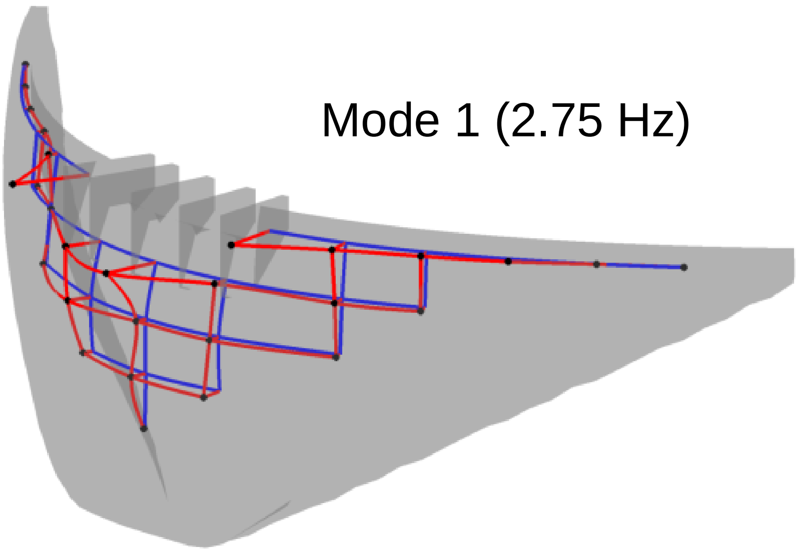
Plan of installed equipment during forced vibration tests



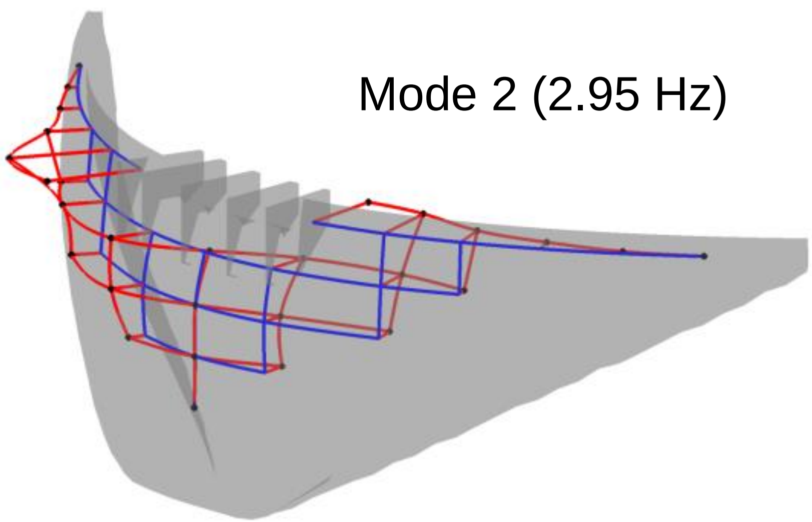
● - Shaker

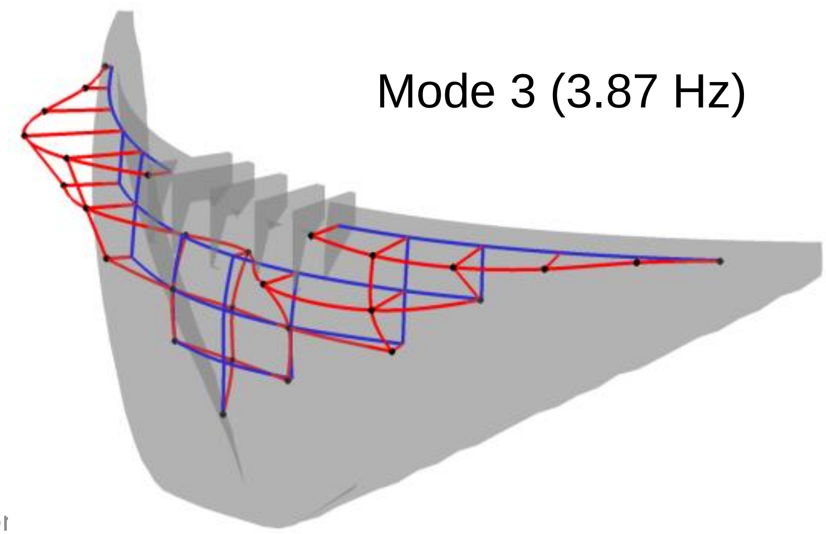
● - Measuring points

Experimental results – First set of forced vibration tests



Mode	Freq. (Hz)	Modal damping (%)	Modal configuration
1	2.75	1.0	≈ Symmetric
2	2.95	1.0	≈ Anti-symmetric
3	3.87	1.1	≈ Symmetric
4	4.46	0.6	≈ Anti-symmetric
5	5.26	0.6	≈ Symmetric
6	5.88	1.0	≈ Anti-symmetric
7	6.22	1.4	≈ Anti-symmetric
8	6.69	0.6	≈ Symmetric
9	7.81	0.9	≈ Anti-symmetric
10	8.42	1.8	≈ Anti-symmetric





Numerical modeling

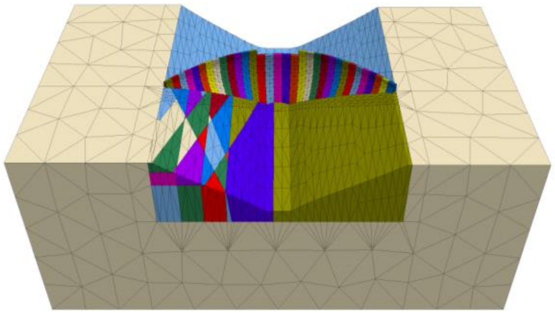
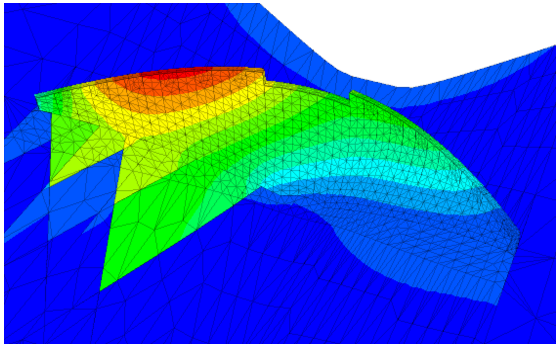
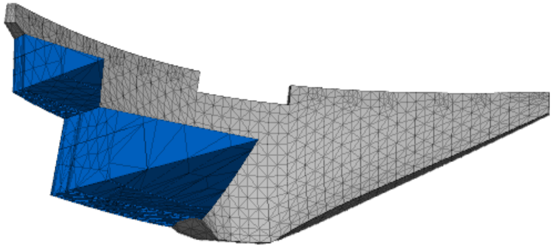
- **3DEC code**
  - 3DEC a DEM code mostly used in rock mechanics modeling
  - At LNEC, it is used in
    - Analysis of dam foundation failure modes
    - Earthquake analysis of dams
    - Masonry block dynamics

- **Arch dam model**
  - Cantilever blocks represented by 20-node FE brick elements
  - Contraction joints (with nonlinear behavior)

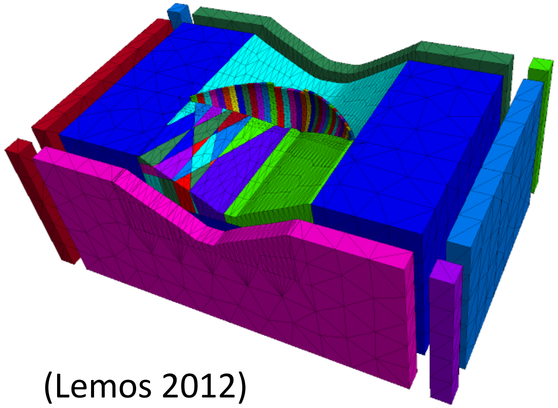
- **Rock mass (if represented)**
  - Polyhedral deformable blocks with internal tetrahedral FE mesh

Typical applications of 3DEC

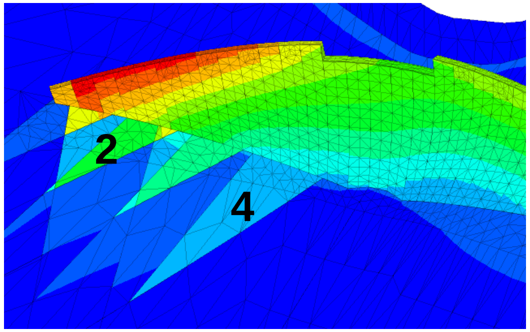
- **Failure modes involving rock mass (static analysis)**

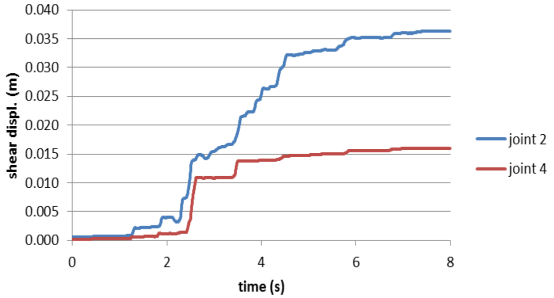
- **Earthquake analysis considering rock mass joints (time domain explicit dynamic analysis)**



(Lemos 2012)



Permanent displacement contours (max. 0.12 m)

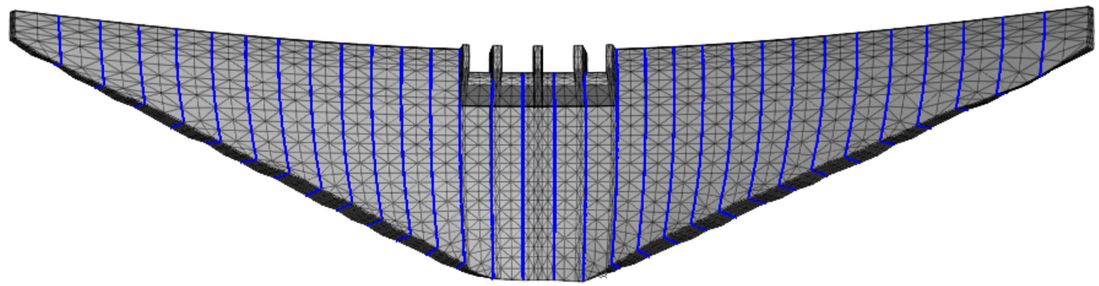


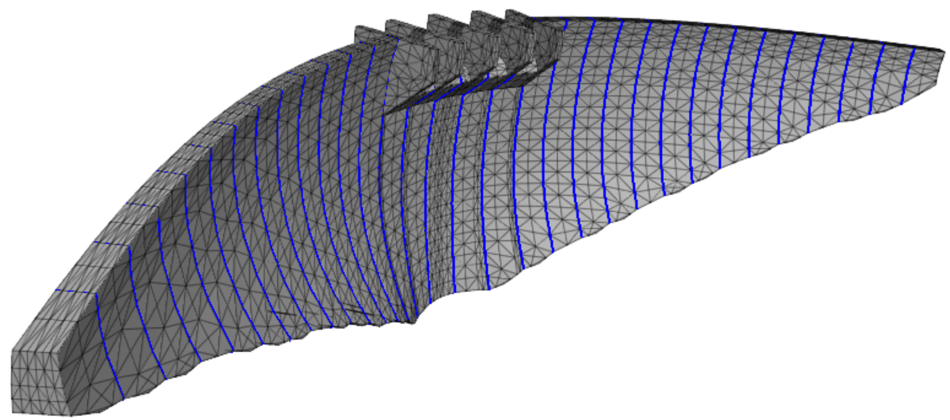
Time evolution of slip on rock joints

Numerical model for first set of forced vibration tests

- **Dam**
  - Elastic blocks
  - 20-node FE elements
  - Elastic contraction joints
  - Foundation nodes fixed

- **Reservoir effect**
  - Added mass technique
  - For the low water level, the hydrodynamic effect is not very significant



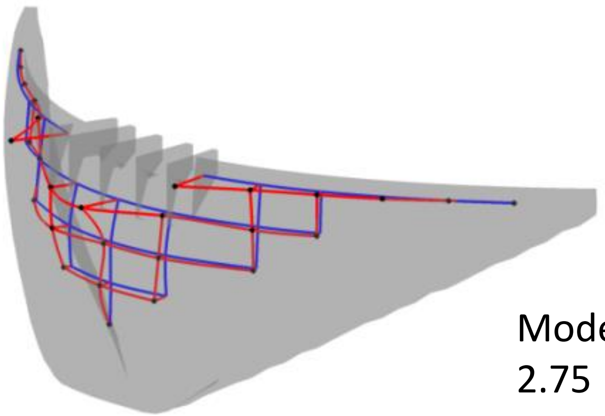


Dam material		Contraction joints	
Young's modulus	35.0 GPa	Normal stiffness	25.0 GPa/m
Poisson's ratio	0.20	Shear stiffness	10.0 GPa/m
Density	2400 kg/m3		

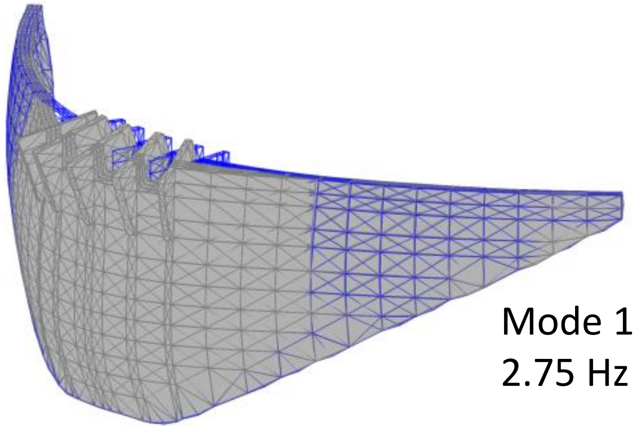
Comparison of experimental and numerical results (i)

- **MAC matrix**
  (Modal Assurance Criterion)

Numerical Mode (Hz)	Experimental modes (Hz)					
	2.75	2.95	3.87	4.46	5.26	5.88
2.75	0.77	0.00	0.05	0.02	0.07	0.03
2.96	0.03	0.95	0.02	0.14	0.00	0.05
3.96	0.09	0.02	0.90	0.00	0.01	0.01
4.46	0.10	0.05	0.02	0.79	0.01	0.04
5.15	0.01	0.00	0.03	0.00	0.21	0.00
5.39	0.07	0.00	0.01	0.00	0.88	0.02
6.07	0.06	0.04	0.01	0.00	0.03	0.86

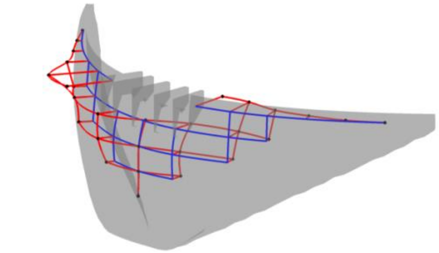


Mode 1 exp.
2.75 Hz

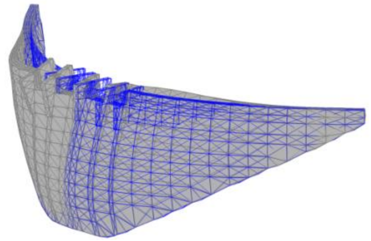


Mode 1 num.
2.75 Hz

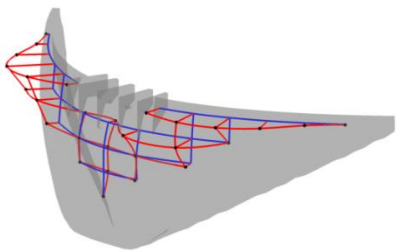
Comparison of experimental and numerical results (ii)



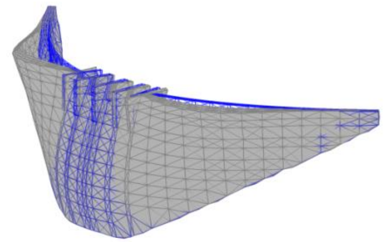
Mode 2 exp.
2.95 Hz



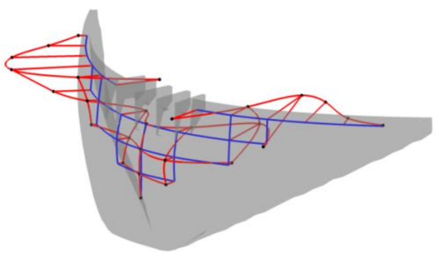
Mode 2 num.
2.96 Hz



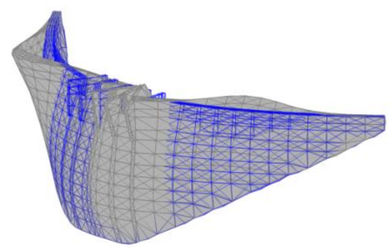
Mode 3 exp.
3.87 Hz



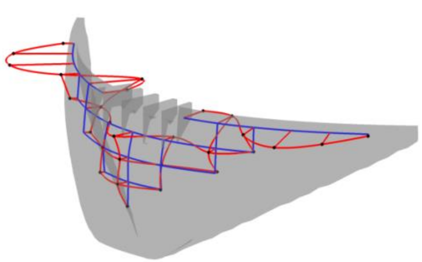
Mode 3 num.
3.96 Hz



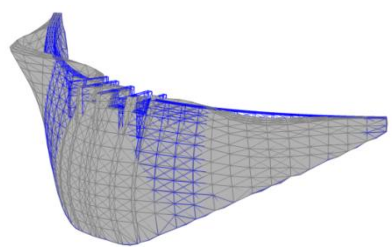
Mode 4 exp.
4.46 Hz



Mode 4 num.
4.46 Hz

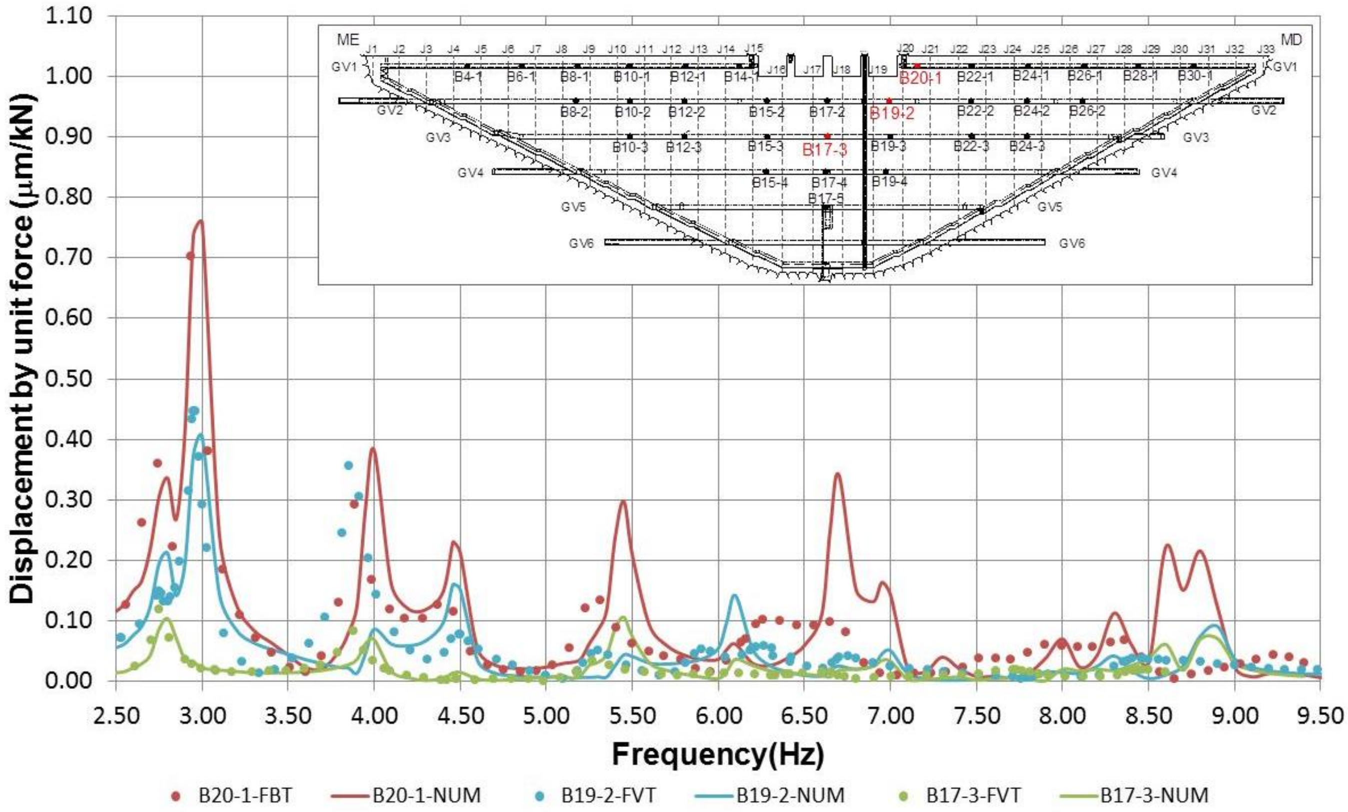


Mode 5 exp.
5.26 Hz



Mode 5 num.
5.39 Hz

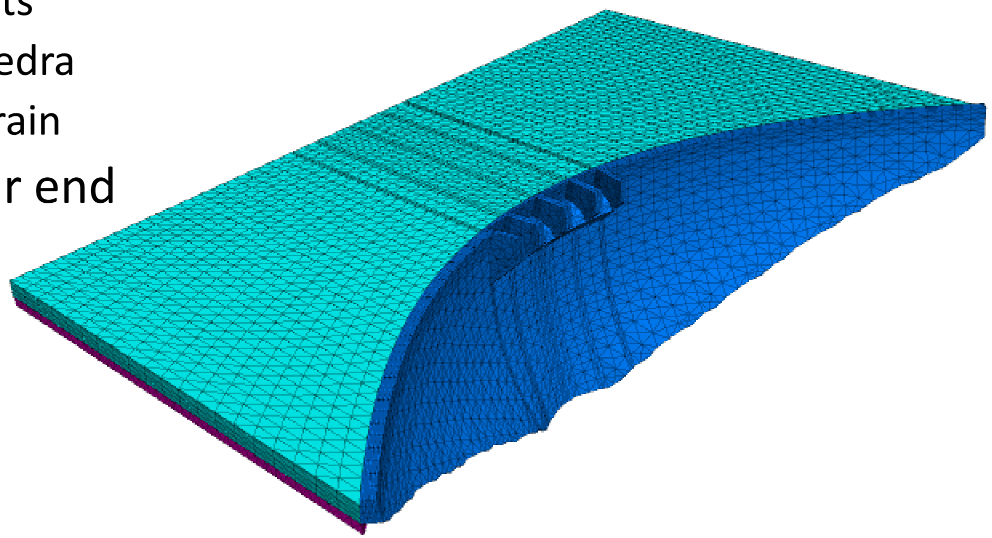
Comparison of frequency response functions obtained from the forced vibration testing (EVF) and the numerical model (NUM)



- Numerical results obtained by time domain analysis reproducing the test procedure (assumed mass-proportional viscous damping, 1.1% at 2.95 Hz)

Second set of tests – Full resevoir
Numerical model with representation of reservoir

- **3DEC reservoir model**
  - Cundall’s mixed discretization elements
    - similar to FLAC-3D elements
    - double overlay of 5 tetrahedra
    - averaging of volumetric strain
  - Absorbing boundaries at far end



- **Determination of numerical frequencies and mode shapes**
  - Random vibration applied to the dam
  - Identification of frequencies and mode shapes from response time records at the measurement points

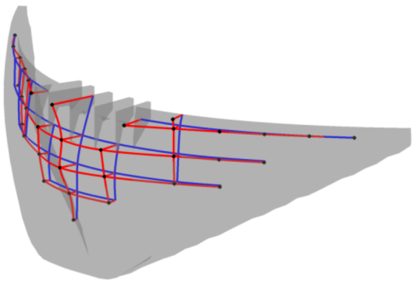
Second set of test – Full resevoir
Comparison of experimental and numerical frequencies

Mode		Experimental	Numerical Reservoir model	Numerical Added-masses (50%)
1	symmetric	2.44	2.48	2.50
2	skew-sym.	2.57	2.65	2.78
3	symmetric	3.34	3.46	3.71
4	skew-sym.	3.94	3.96	4.20
5	symmetric	4.78	4.77	4.88

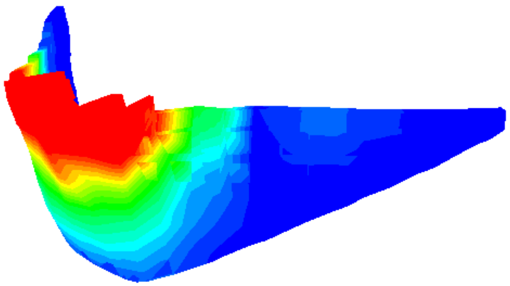
- **Numerical models for full reservoir**
  - Reservoir model with water elements
  - Dam only with added-masses
    - reduction factor of 0.5 applied to the added-masses

Second set of test – Full resevoir

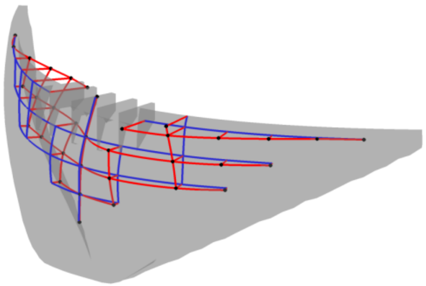
Experimental and numerical (reservoir model) mode shapes



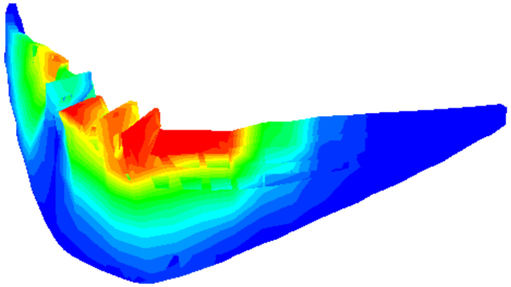
Mode 1 exp.
2.44 Hz



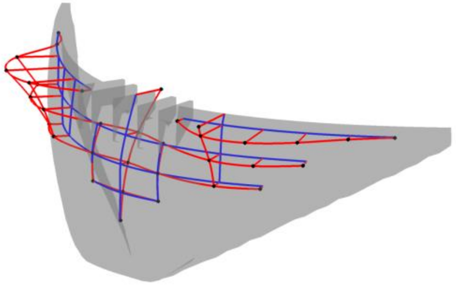
Mode 1 num.
2.48 Hz



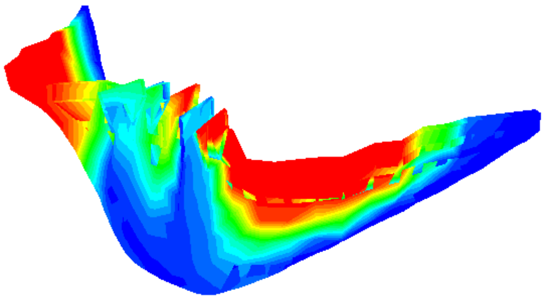
Mode 2 exp.
2.57 Hz



Mode 2 num.
2.65 Hz



Mode 3 exp.
3.34 Hz



Mode 3 num.
3.46 Hz

Concluding remarks

- The Baixo Sabor arch dam has been equipped with dynamic monitoring systems which are intended to provide data for the characterization of the dynamic behavior under environmental and seismic actions
- Forced vibration tests were performed with a low reservoir level, and, recently, after the first filling
- The analysis of the first set of tests by means of a numerical model showed a good agreement with the frequencies and mode shapes obtained in the experiments
- As data from the dynamic monitoring systems becomes available, it will allow a full comparison with the forced vibration test results and the numerical representations


THANK YOU FOR
YOUR ATTENTION