ICOLD
INTERNATIONAL COMMISSION ON LARGE DAMS

ICOLD-BW 2019
9th-11th September
MILANO
Numerical analysis of dams

ICOLD COMMITTEE ON COMPUTATIONAL ASPECTS OF ANALYSIS AND DESIGN OF DAMS

15th INTERNATIONAL BENCHMARK WORKSHOP ON NUMERICAL ANALYSIS OF DAMS

Theme A - Formulation

SEISMIC ANALYSIS OF PINE FLAT CONCRETE DAM

September 9, 2019, Milan, Italy

Benchmark Formulation - Presentation

ICOLD Benchmark Workshops on Numerical Analysis of Dams

- 12th ICOLD Benchmark Workshop, Graz 2013
- 13th ICOLD Benchmark Workshop, Lausanne 2015
- 14th ICOLD Benchmark Workshop, Stockholm 2015

2019 ICOLD Workshop - Background

2016 USSD Workshop, Denver

Monticello Blind Prediction Study

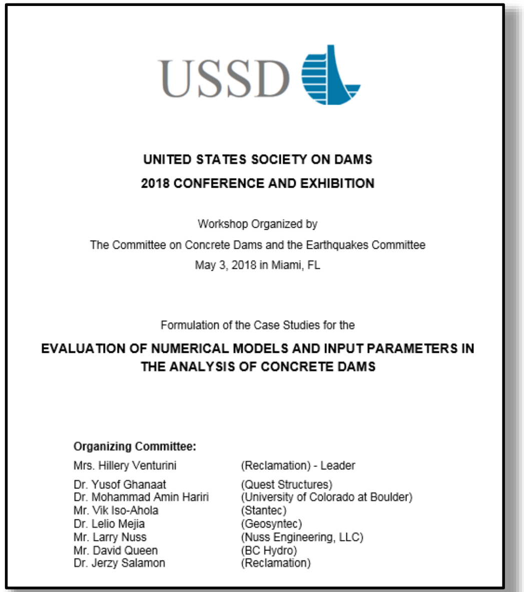
Performed in an arbitrary manner, have not produced desired results or clear conclusions for advancement

2018 USSD Workshop, Miami

Evaluation of Numerical Models and Input Parameters in the Analysis of Concrete Dams for Pine Flat Dam

The ultimate goal was to identify key uncertainties causing differences in results, determine research needs and develop best practices in the advanced analysis of concrete dams

https://www.usbr.gov/ssle/damsafety/TechDev/DSOTechDev/DSO-2019-13.pdf



USSD

UNITED STATES SOCIETY ON DAMS
2018 CONFERENCE AND EXHIBITION

Workshop Organized by
The Committee on Concrete Dams and the Earthquakes Committee
May 3, 2018 in Miami, FL

Formulation of the Case Studies for the
EVALUATION OF NUMERICAL MODELS AND INPUT PARAMETERS IN THE ANALYSIS OF CONCRETE DAMS

Organizing Committee:

Mrs. Hillery Venturini	(Reclamation) - Leader
Dr. Yusof Ghanaat	(Quest Structures)
Dr. Mohammad Amin Hariri	(University of Colorado at Boulder)
Mr. Vik Iso-Ahola	(Stantec)
Dr. Lelio Mejia	(Geosyntec)
Mr. Larry Nuss	(Nuss Engineering, LLC)
Mr. David Queen	(BC Hydro)
Dr. Jerzy Salamon	(Reclamation)

2019 ICOLD Benchmark Study

15^{TH} INTERNATIONAL BENCHMARK WORKSHOP ON NUMERICAL ANALYSIS OF DAMS

Theme A

SEISMIC ANALYSIS OF PINE FLAT CONCRETE DAM

- Continuation of the 2018 USSD Benchmark study for Pine Flat Dam
- Formulation based on the lesson learned
- New case studies: non-linear material , massless foundation, eccentric-mass vibration generator simulation, analysis for impulsive stress excitations

2019 ICOLD Benchmark Study
Theme A Formulators

Dr. Jerzy Salamon (U.S. Bureau of Reclamation)

Mr. Christopher Wood (U.S. Bureau of Reclamation)

Dr. M. Amin Hariri-Ardebili (University of Colorado at Boulder)

Dr. Richard Malm (KTH Royal Institute of Technology)

Mrs. Giorgia Faggiani (RSE S.p.A)

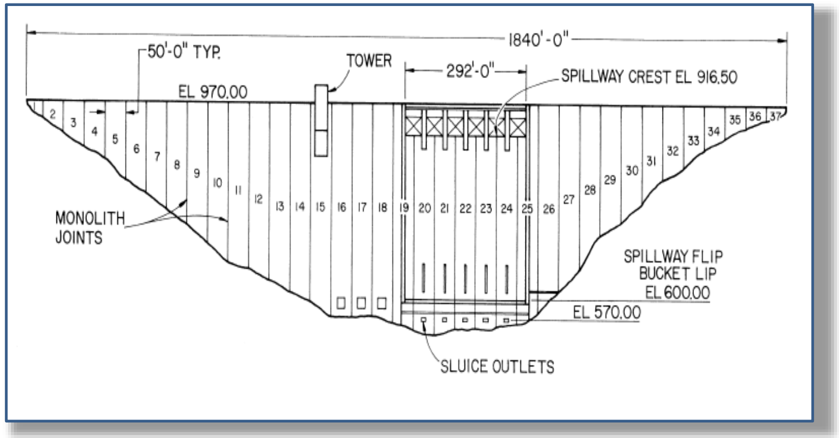
Appreciation to the *Committee Team Formulating Theme A* for the effort of formulating, organizing and presenting this benchmark study results

Acknowledgments

Appreciation to the *U.S. Bureau of Reclamation* for supporting the effort

Dam Selection for the Study

- **Pine Flat Dam** was selected for the case study
- The dam was constructed in 1954
  by the United States Army Corps of Engineers
- The Dam consists of thirty-six *15.24 m* wide
  and one *12.2 m*-wide monoliths
- The length of the straight gravity dam is 561 m
- The tallest non-overflow monolith is *121.91 m* high



Reasons for the selection Pine Flat Dam in the study

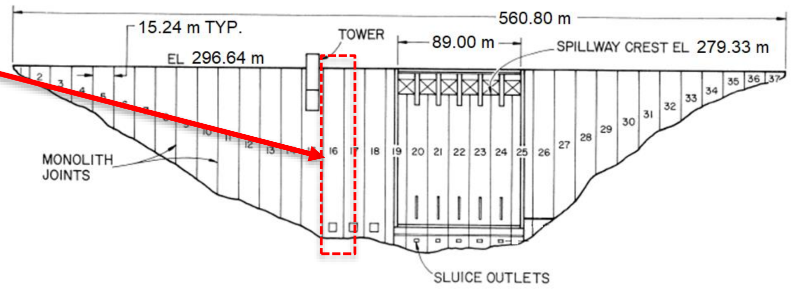
- Relatively simple geometry
- Project information and data publicly available
- Extensive studies performed at the University of California at Berkeley in the 70's & 80's
- Pine Flat Dam model used as an example in several technical publications and studies

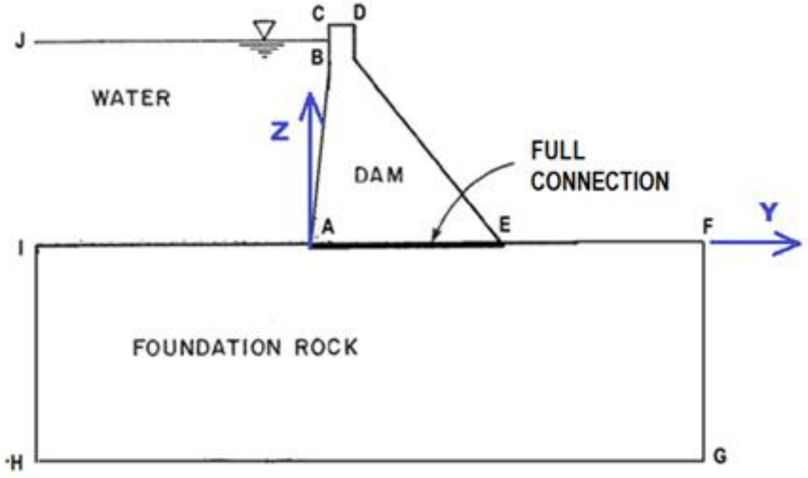
Purpose of Theme A Benchmark Study

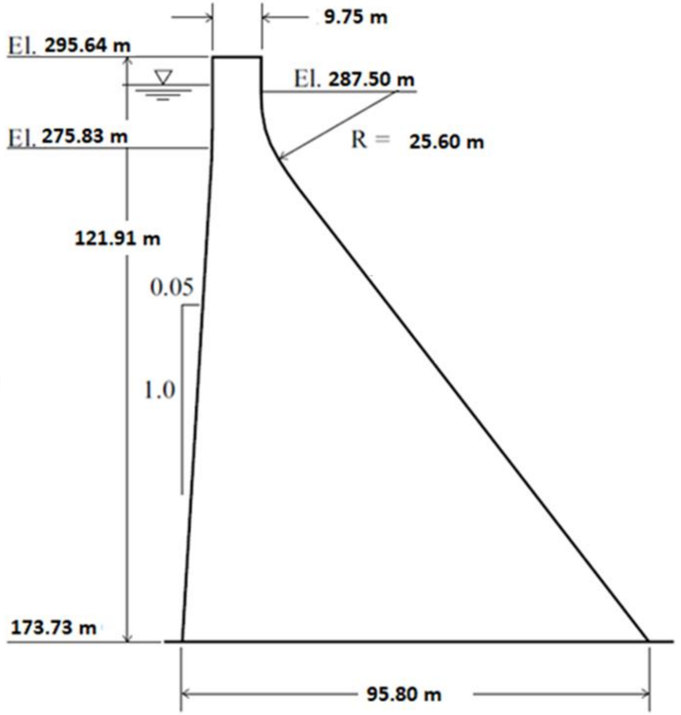
- The **purpose** is to identify key uncertainties causing differences in analysis results
- Establish a common understanding regarding the sensitivity of the results in numerical analyses of concrete dams
- Verify the efficiency of the non-reflecting boundary conditions in seismic analyses of concrete dams
- The **ultimate goal** is to develop the best practices for advanced analyses of concrete dams

Benchmark Study Formulation

- Analysis of the tallest non-overflow dam monolith 16 at Pine Flat Dam
- **“Base Model” Configuration**
  - The model consists of the 15.24-m-wide dam monolith and a corresponding strip of the foundation and the reservoir
  - Foundation length: *H-G = 700 m*
  - Foundation depth: *I-H = 122 m*
  - Dam heel location: *I-A = 305 m*







Material Properties

Concrete and foundation rock materials are assumed to be homogeneous, isotropic, and elastic (except for Case E)

Elastic properties are the same for concrete and rock materials

Dam Concrete Properties	SI Units
Modulus of Elasticity	22 410 MPa
Density	2 483 kg/m^3
Poisson’s Ratio	0.20
Compressive Strength	28.0 MPa
Tensile Strength	2.0 MPa
Fracture energy	250 N/m
Compressive strain at peak load	0.0025
Tensile strain at peak load	0.00012

Foundation Rock Properties	SI Units
Modulus of Elasticity	22 410 MPa
Density	2 483 kg/m^3
Poisson Ratio	0.20
Shear Wave Velocity	1 939 m/s
Compressional Wave Velocity	3 167 m/s

Water is considered to have a unit weight of 1000 kg/m^3 and compression wave velocity of 1439 m/sec.

Benchmark Study Cases

- **Case A – EMVG Test Simulation**

  Simulation of the eccentric-mass vibration generator (EMVG)
- **Case B – Foundation Analysis using Impulsive Loads**

  Foundation block using the Impulsive Stress Records
- **Case C – Dynamic Analysis using Impulsive Loads**

  Dam-foundation-reservoir system using the Impulsive Stress Records
- **Case D – Dynamic Analysis for Various Reservoir Levels**

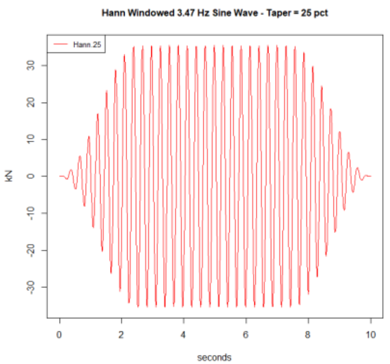
  Effects of reservoir water levels for a dam-reservoir-foundation model and 1952 Taft Earthquake record.
- **Case E – Non-linear Dynamic Analysis**

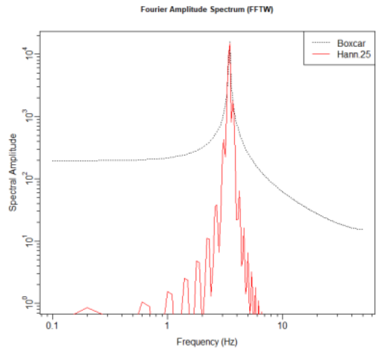
  Dam-reservoir-foundation system with non-linear properties for concrete considering the 1952 Taft Earthquake record and the Endurance Time Acceleration Function (ETAF)
- **Case F – Massless Foundation**

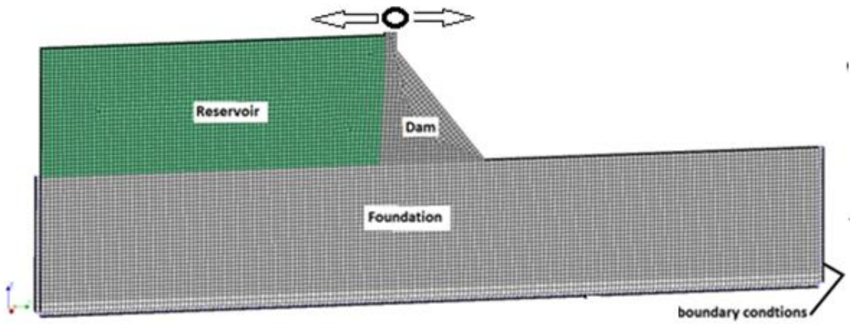
  Dam-reservoir-foundation system with the modified massless foundation properties and 1952 Taft Earthquake record

Case A – EMVG Test Simulation

- **In Case A**, the "Base Model" is investigated.
  - Natural frequencies and shape modes are determined
  - Dynamic linear analysis of the dam-foundation-reservoir system for the harmonic force record exerted by an eccentric-mass vibration generator (EMVG) positioned at the dam crest is considered
- Analysis corresponds to the 1971 tests conducted on Monolith 16
- Model assumptions:
  - 2% viscous damping for the dam and foundation
  - EMVG harmonic-force time history record applied at the middle of the dam crest in the upstream /downstream direction
  - The signal amplitude of 35.4 kN at a frequency of 3.47 Hz
  - The signal windowed with 25 % Hann taper to reduce artifacts
- Static load for two reservoir levels
  - Winter El: *268.21 m* and Summer El: *278.57 m*

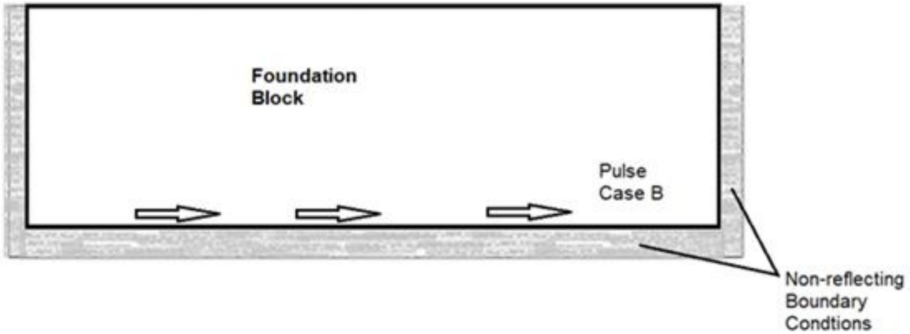


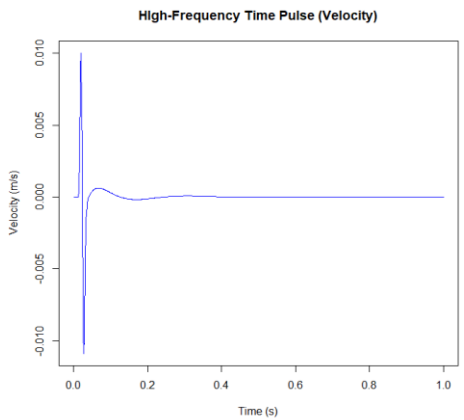


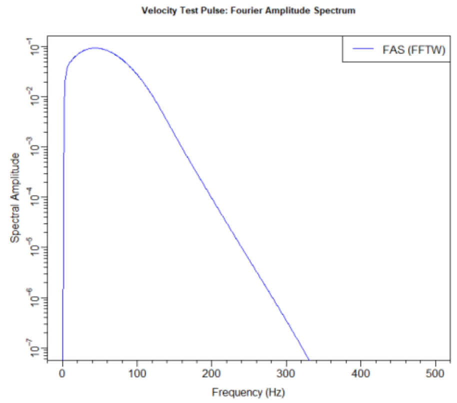


Case B – Foundation Block Analysis using Impulsive Signal

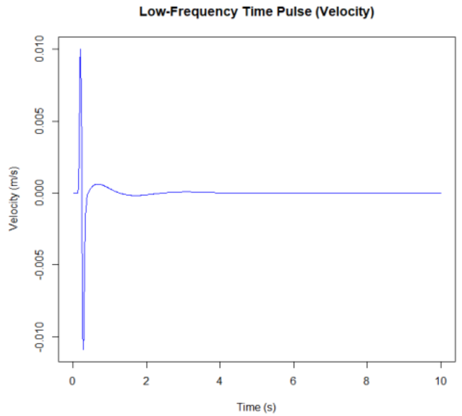
- Foundation block from the "Base Model": *700-m*
- Extended block model: length *3,700-m*
- Pulse excitation applied at the base of the block for
  - High and low frequency pulses
- Zero viscous damping
- Contributors selecting boundary conditions and the analysis method
- **Results:** determine velocities in selected points

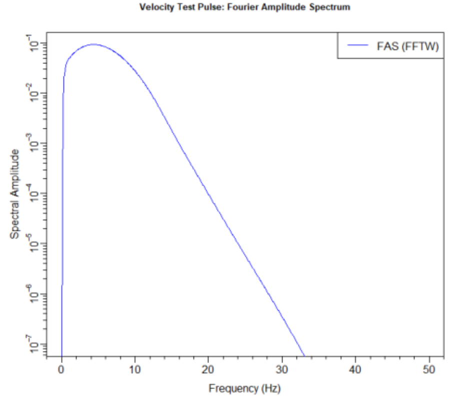






δt (s)	$F_{Nyquist}$ (Hz)	F_N (Hz)	F_{lo} (Hz)	F_{hi} (Hz)	Impulse Amp. (m/s)	Impulse Dur. (s)	Zero-pad
0.001	500	40	5	80	0.01	2.0	10

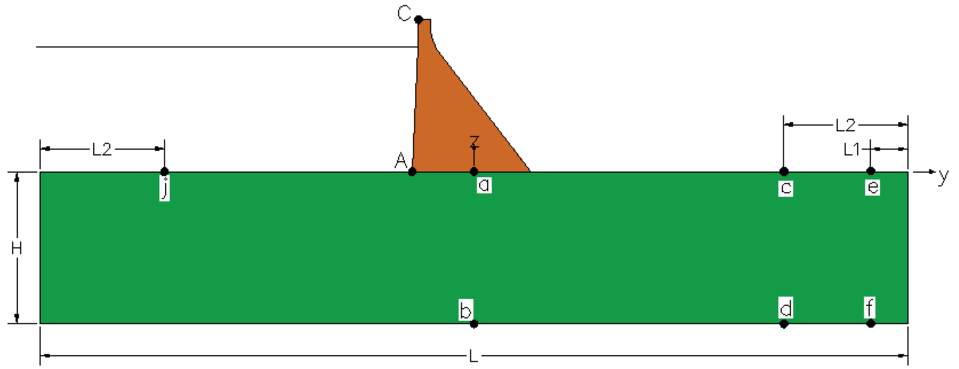




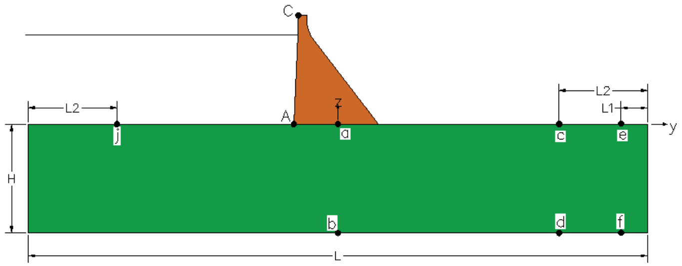
δt (s)	$F_{Nyquist}$ (Hz)	F_N (Hz)	F_{lo} (Hz)	F_{hi} (Hz)	Impulse Amp. (m/s)	Impulse Dur. (s)	Zero-pad
0.01	50	4.0	0.5	8.0	0.01	20	10

Case C – Dynamic Analysis using Impulsive Load

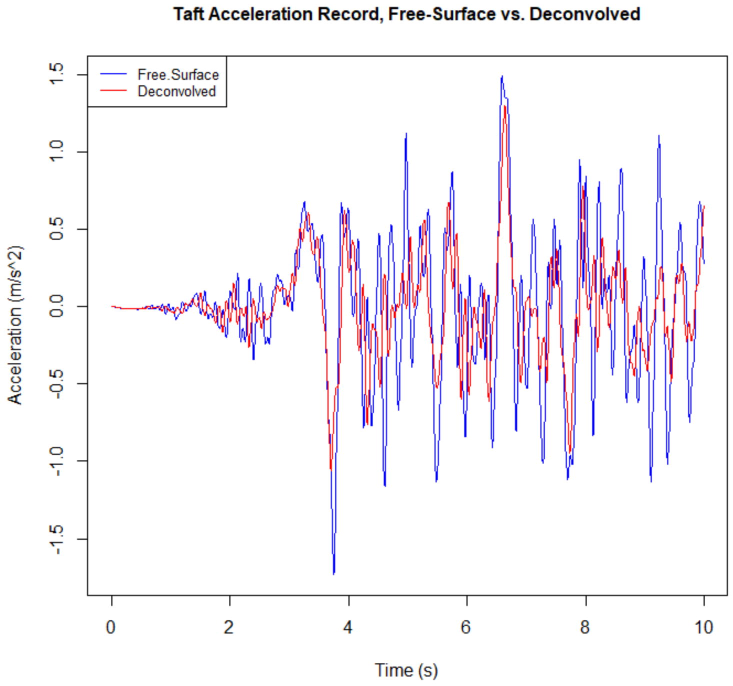
- **In Case C**, the "Base Model" configuration is considered
- **Purpose:** determine influence of the dam presence in seismic wave propagation (comparison to Case B)
- Pulse excitation applied at the base of the foundation block as in Case B
  - High and low frequency pulses
- Zero viscous damping
- Contributors selecting boundary conditions and the analysis method
- **Case studies:** with and without reservoir
- **Results:** determine velocities in selected points

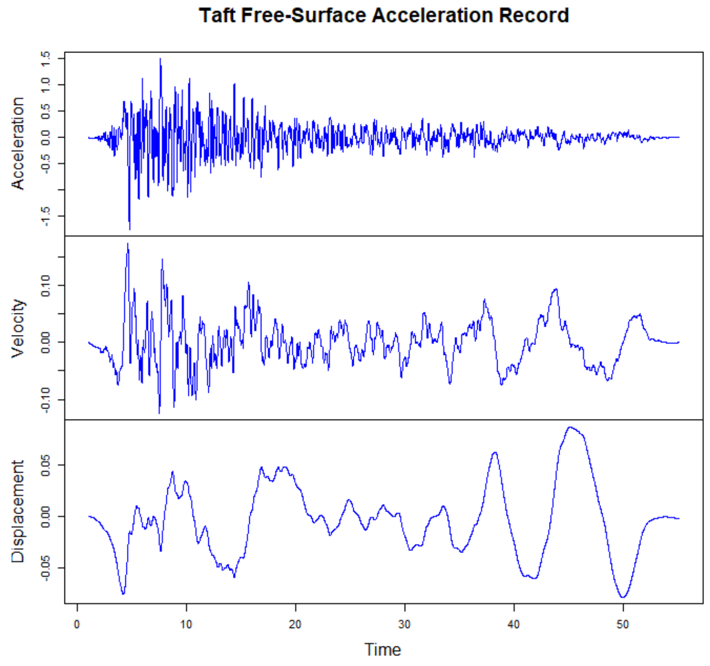


Case D – Dynamic Analysis for Various Reservoir Levels



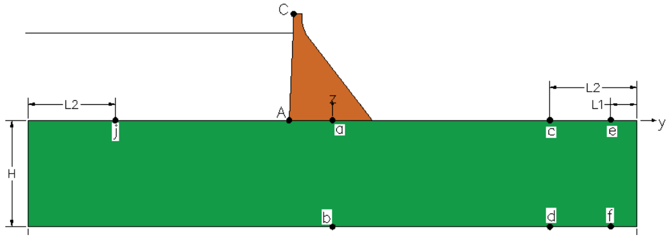
- **In Case D**, the "Base Model" configuration as in Case C
- Model excitation at the base of the foundation
  - Taft deconvolved (by Formulators) acceleration time history
  - or Taft stress time history
- 2 % viscous damping
- **Case studies:** reservoir levels
  - Winter El: *268.21 m*
  - Summer El: *278.57 m*
  - Normal El: *290 m*
- **Results:** displacements, accelerations, hydrodynamic pressure at selected points

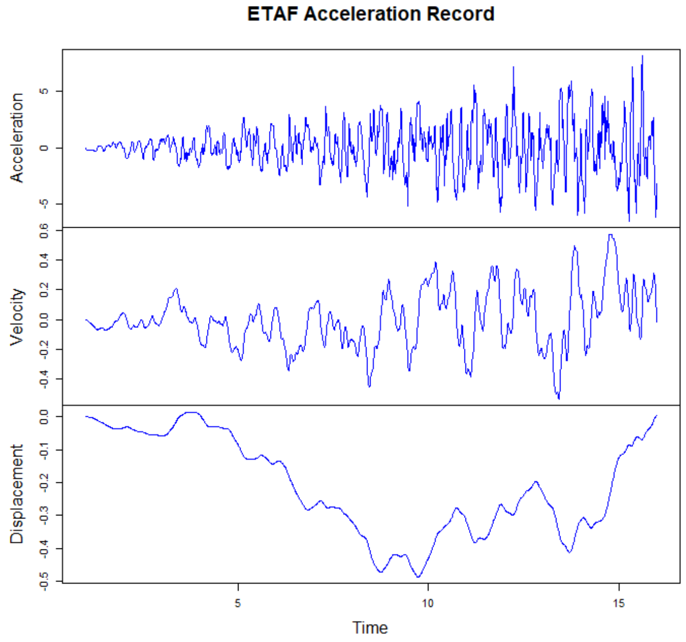


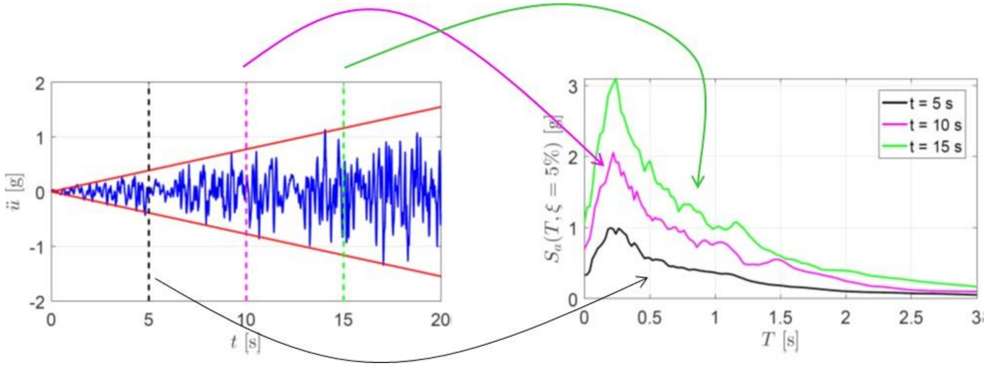


Case E – Non-linear Dynamic Analysis

- **In Case E**, the “Base Model” configuration as in Case D
- Static load for winter reservoir level at El *268.21 m*
- Model excitation at the base of foundation as in Case D
  - **Taft** (time history for deconvolved acceleration or stress record)
  - **Endurance Time Acceleration Function** (ETAF) - artificially designed intensifying acceleration time history record
- 2 % viscous damping
- **Results:** displacements, accelerations, hydrodynamic pressure at selected points and the extended damage in the dam

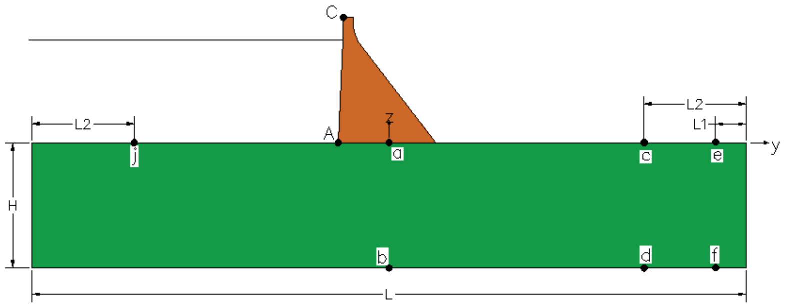






Case F – Massless Foundation

- **In Case E**, the "Base Model" configuration as in Case D except <u>massless</u> foundation is considered
- Model excitation at the base of foundation
  - Taft record (free-surface acceleration time history by Formulators)
  - 2 % viscous damping
- Static loads for three reservoir levels
  - Winter El: *268.21 m*
  - Summer El: *278.57 m*
  - Normal El: *290 m*
- **Results:** displacements, accelerations, hydrodynamic pressure at selected points of the dam



Summary of Required Analyses

Case	Analysis Type			
	1	2	3	4
A	**Obligatory**	**Obligatory**	**Obligatory**	**Obligatory**
B	Optional	Optional	Optional	Optional
C	Optional	Optional	Optional	Optional
D	**Obligatory**	**Obligatory**	Optional	
E	**Obligatory**	Optional		
F	Optional	Optional	Optional	

Information on Workshop Contribution

Submitted analysis results

- **24** contributions with more than 3 studied cases and
- Additional **8** analysis results provided for Case B only

28 Contributors are participating in the benchmark study

- **Kudos to 6 contributors** who provided results for all 6 study cases
- 4 Contributors provided two sets of results

Most interesting study case voted by Contributors:

- 1^{st} chose: A(8), B(5), D(4), E(4)
- 2^{nd} chose: B(1), C(2), D(8), E(6), F(2)

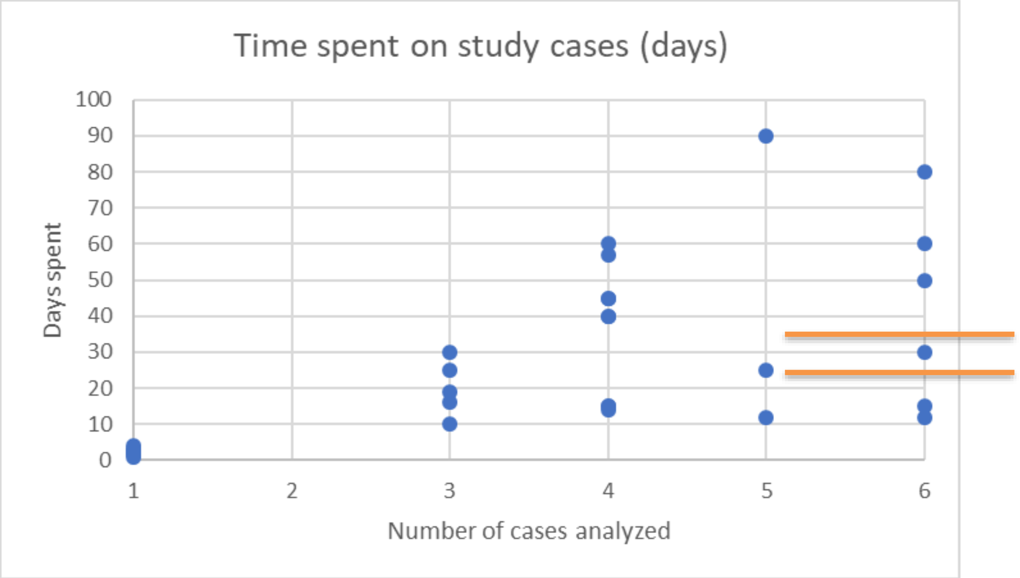
Estimation of Analysis Effort

Formulators estimations:

- Obligatory part is *10-15* staff days
- Optional part is *15-20* staff days
- **Total** *25-35* staff days

Contributors input:

- **Total** *10-90* staff days (for 3 and more cases)



Who are the Contributors

Contributors Information:

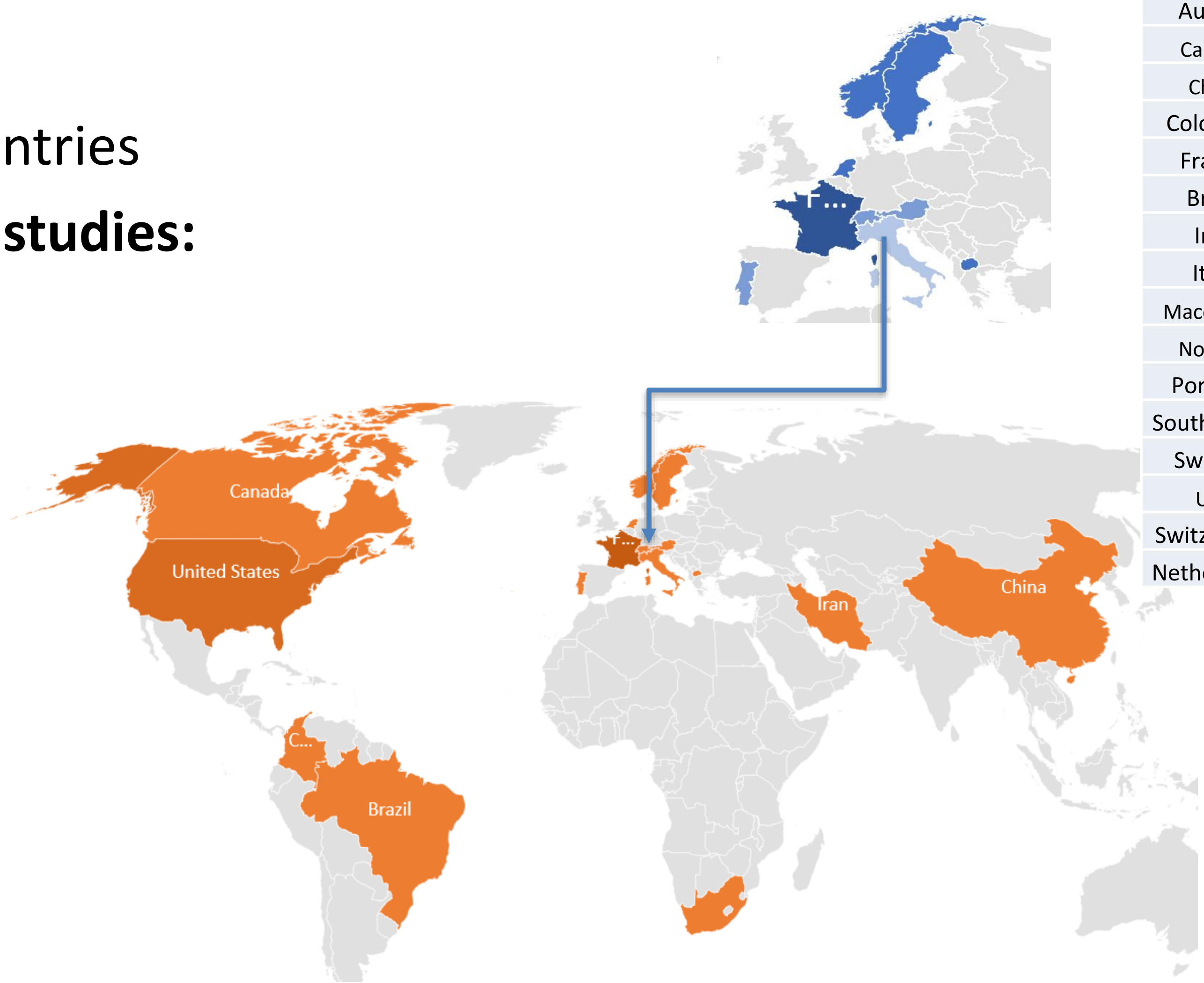
- **28** Contributors representing 16 countries

Contributing to the ICOLD benchmark studies:

- First time: **8 (+ 4** Case B only)
- One time: **9**
- Two times: 3
- Three times: **4**
- <u>Eight times</u>: (RCE, Italy)

Contributor association:

- Universities: **8**
- Consulting & government: **20**



- Austria
- Canada
- China
- Colombia
- France
- Brazil
- Iran
- Italy
- Macedonia
- Norway
- Portugal
- South Africa
- Sweden
- USA
- Switzerland
- Netherlands

Analysis Software and Methods

Software Name	No. of contributions
ABAQUS	9
ADINA	1
ANSYS	3
Code_Aster	2
DIANA	5
EDF	1
FLAC3D	1
LSDYNA	5
Parmac	2
Real ESSI	1
SAP2000	1
SOFiSTiK	1

Time integration method:

- Benchmark Study
  - Implicit: 19
  - Explicit: 5
- Case B only
  - Implicit: 3
  - Explicit: 5

Boundary conditions:

- Benchmark Study
  - Free field: 9
  - Other: 15
- Case B only
  - Free field: 3
  - Other: 5

Contributor's Interest in the Benchmark

Software validation and advance modeling	Learn	Other
keep up with the best approaches	improve knowledge	*continue the tradition of our work group that has been participating since the first edition of the benchmark workshop !!!*
verify and improve the accuracy	expand and share expertise	
explore new modelling features	gaining knowledge	
workshop served as a test case for using the software	train our own staff	meeting other specialists, enhancing visibility and keeping up to date
validate the code	exchange experiences	
improve numerical models	improve computational proficiency	promoting and advancing proper numerical modeling for dam safety evaluations

Contributor's Results

- **Preliminary results**

  Formulators compiled the preliminary results and the initial report was available to those Contributors who submitted such results. **Purpose**: model verifications

- **Final results**

  The final results were submitted in an Excel spreadsheet format using templates prepared by Formulators

- **Identification of the contributions**
  - Randomly assigned number *(#99)* identifies each contribution (names of Contributors are not listed)
  - *Numbers **11*** through ***34*** – contributions for the formulated benchmark study
  - Numbers ***51*** through ***58*** – contributions for Case B only

Thank you