ICOLD
INTERNATIONAL
COMMISSION ON
LARGE DAMS

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

15th INTERNATIONAL BENCHMARK WORKSHOP ON NUMERICAL ANALYSIS OF DAMS

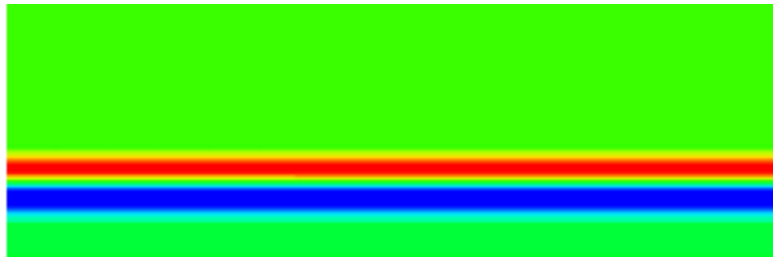
Theme A

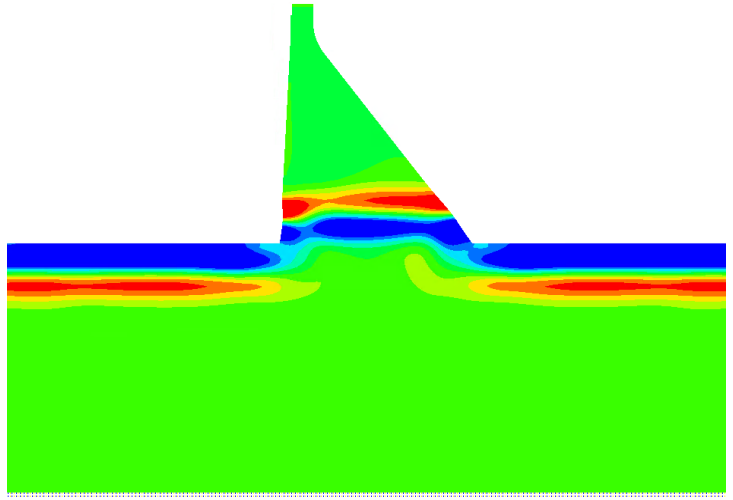
SEISMIC ANALYSIS OF PINE FLAT CONCRETE DAM

9 September 2019, Milan, Italy

Summary of the Benchmark Analysis Results

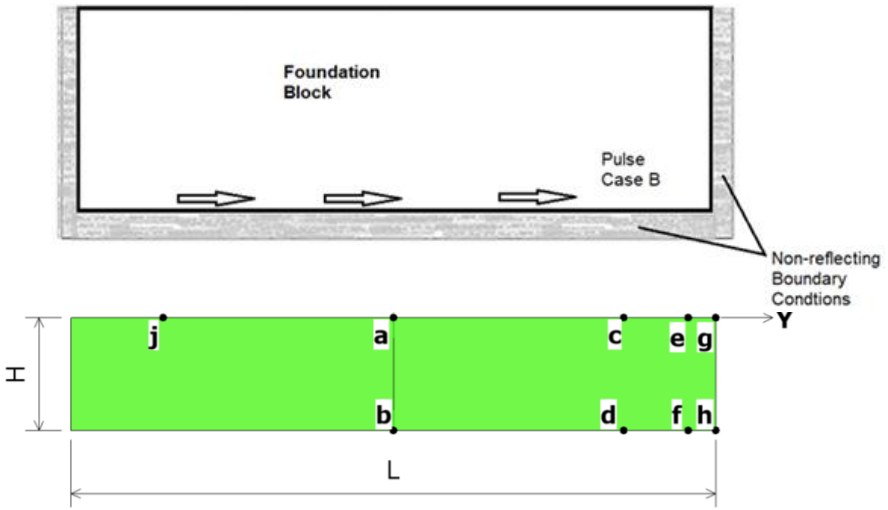
Study Case B and Case C





Case B - Foundation Block Analysis for Impulsive Excitation

- **Purpose** - to verify the efficiency of the non-reflecting boundary conditions in the dynamic analysis of the foundation block and to investigate the effect of the foundation size
- A foundation block is a reduced-domain model for a uniform half-space
- **Expectation** – the applied shear stress pulse at the foundation base should reproduce the free-surface velocity time history if the model provides a good representation of the semi-infinite domain
- **Model definition**
  - High and low frequency excitation records
  - Block configurations (L x H): *700 m x 122 m* and *3700 m by 122 m*
  - Mass type foundation
  - Zero viscous damping
  - Elastic properties
  - The maximum mesh size 1.5 m
- **Investigations**
  - Boundary conditions to be defined and justified by the contributors
  - Results are compared in selected locations defined by points **a** through **j**
- Theoretical solution for a wave propagation in an elastic half space is known
- **Results**: comparison of the benchmark analysis results with the analytical solution

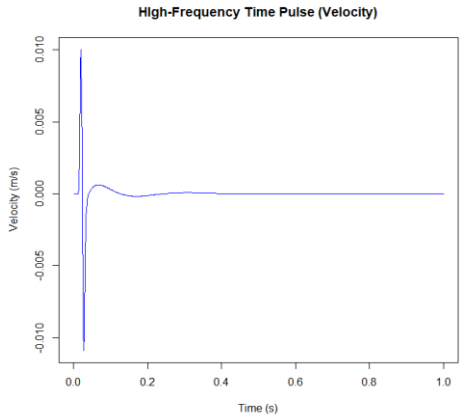


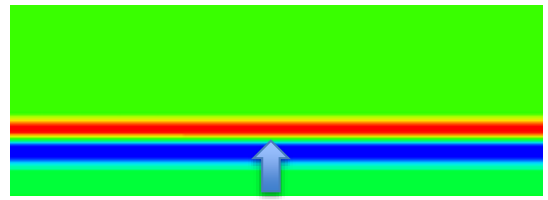
Impulsive Excitation Record

- **Pulse** – base line corrected
- **High and low** frequency time pulses
- Applied in the form of stress excitation at the foundation base

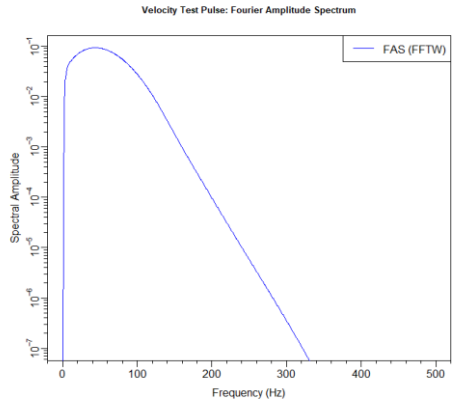
- Case B consists of 4 case studies

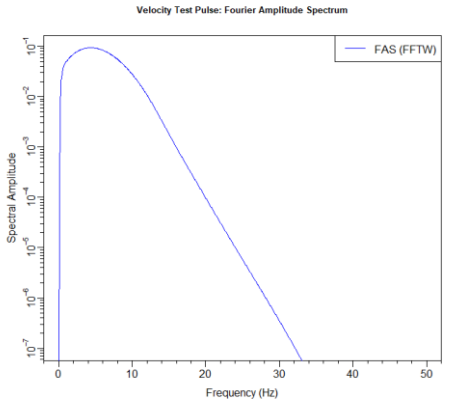
	Case B1	Case B2	Case B3	Case B4
Length (m)	700	700	3700	3700
Pulse freq.	High	Low	High	Low
Number of solutions	22	21	14	14



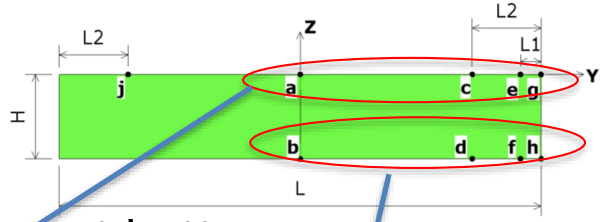


Impulse Frequency	Δt (sec.)	$F_{Nyquist}$ (Hz)	F_N (Hz)	F_{lo} (Hz)	F_{hi} (Hz)	Amplit. (m/s)	Record (sec.)	Zero-pad (samp)
Low	0.01	50	4.0	0.5	8.0	0.01	20	10
High	0.001	500	40	5	80	0.01	2.0	10





Case B1 - Result Summary - High Frequency Pulse

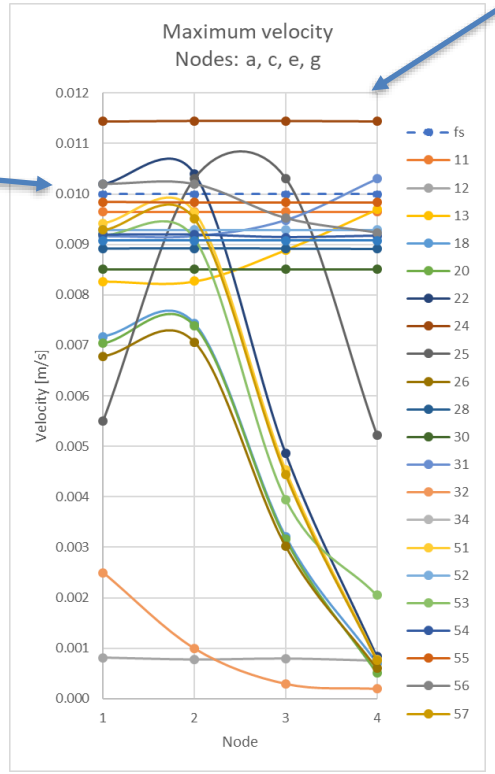


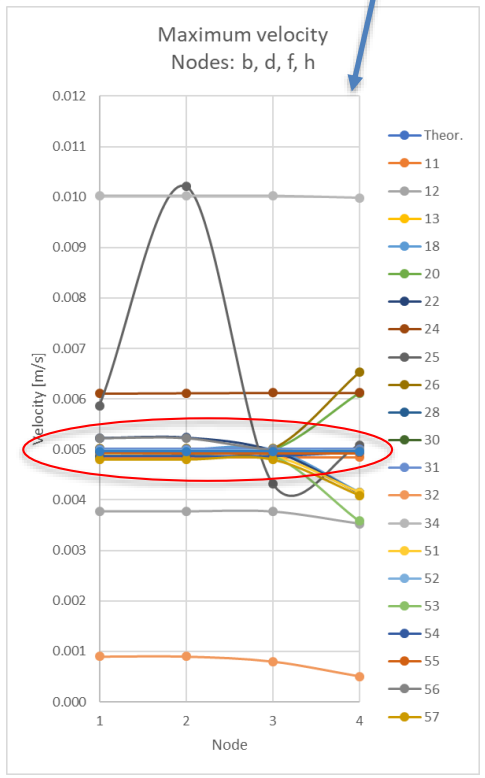
Maximum velocity

➢ All the results

at surface

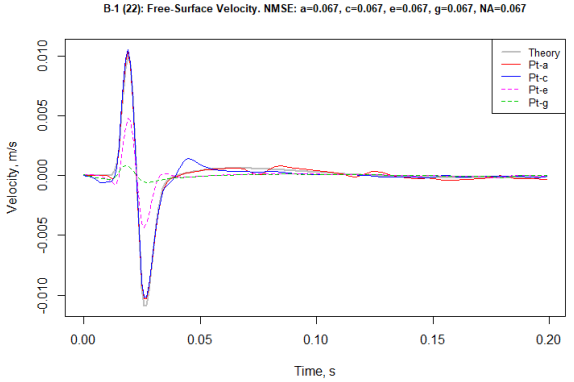
at bottom

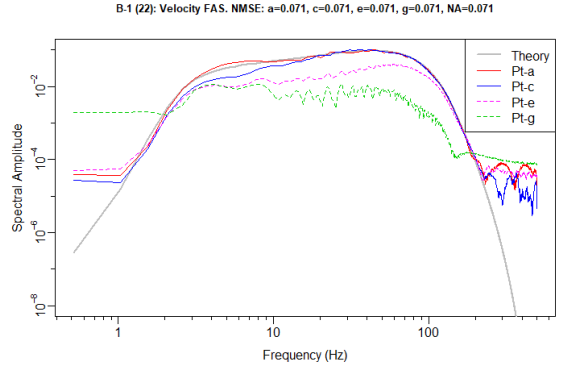


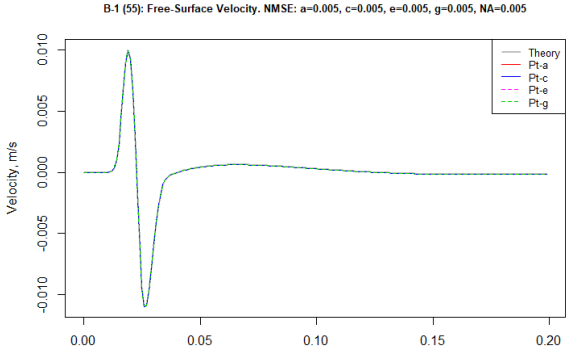


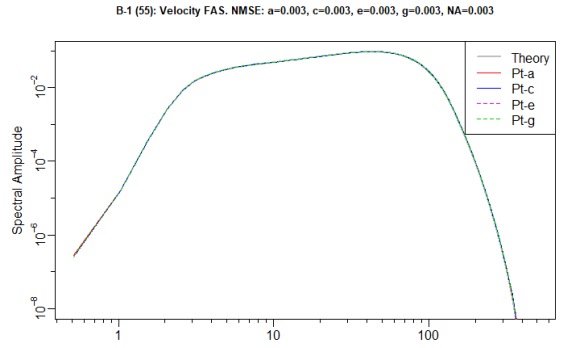
Absorbing boundaries

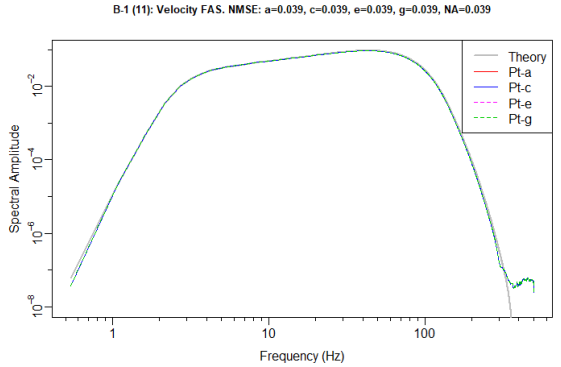
Free-field boundaries

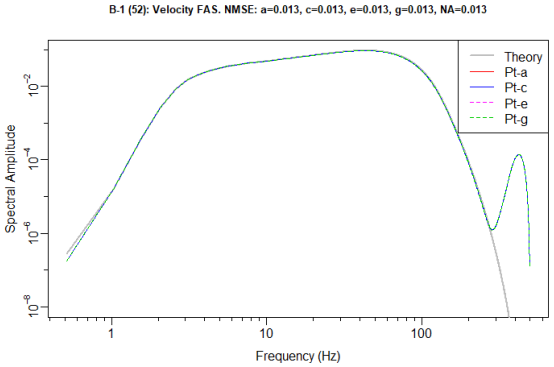












Case B1 - Result Summary - High Frequency Pulse

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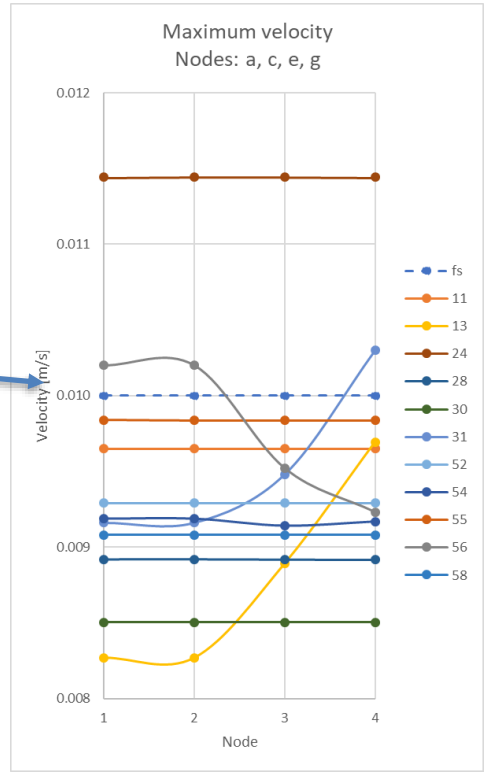
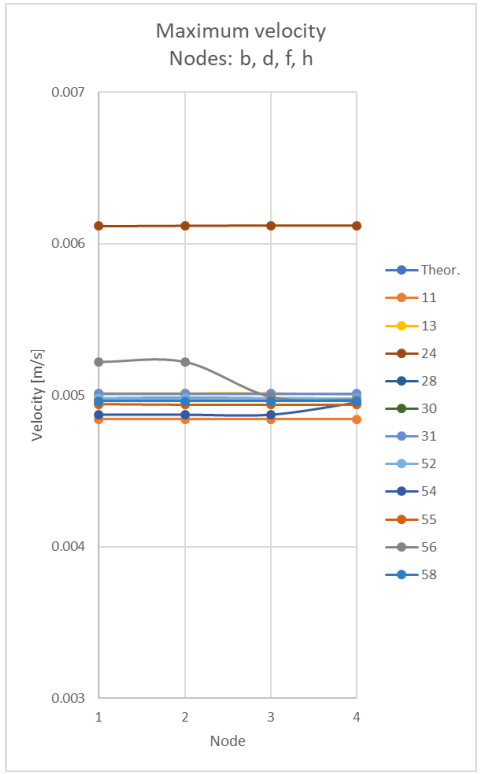
Maximum velocity

➢ Selected results

at surface

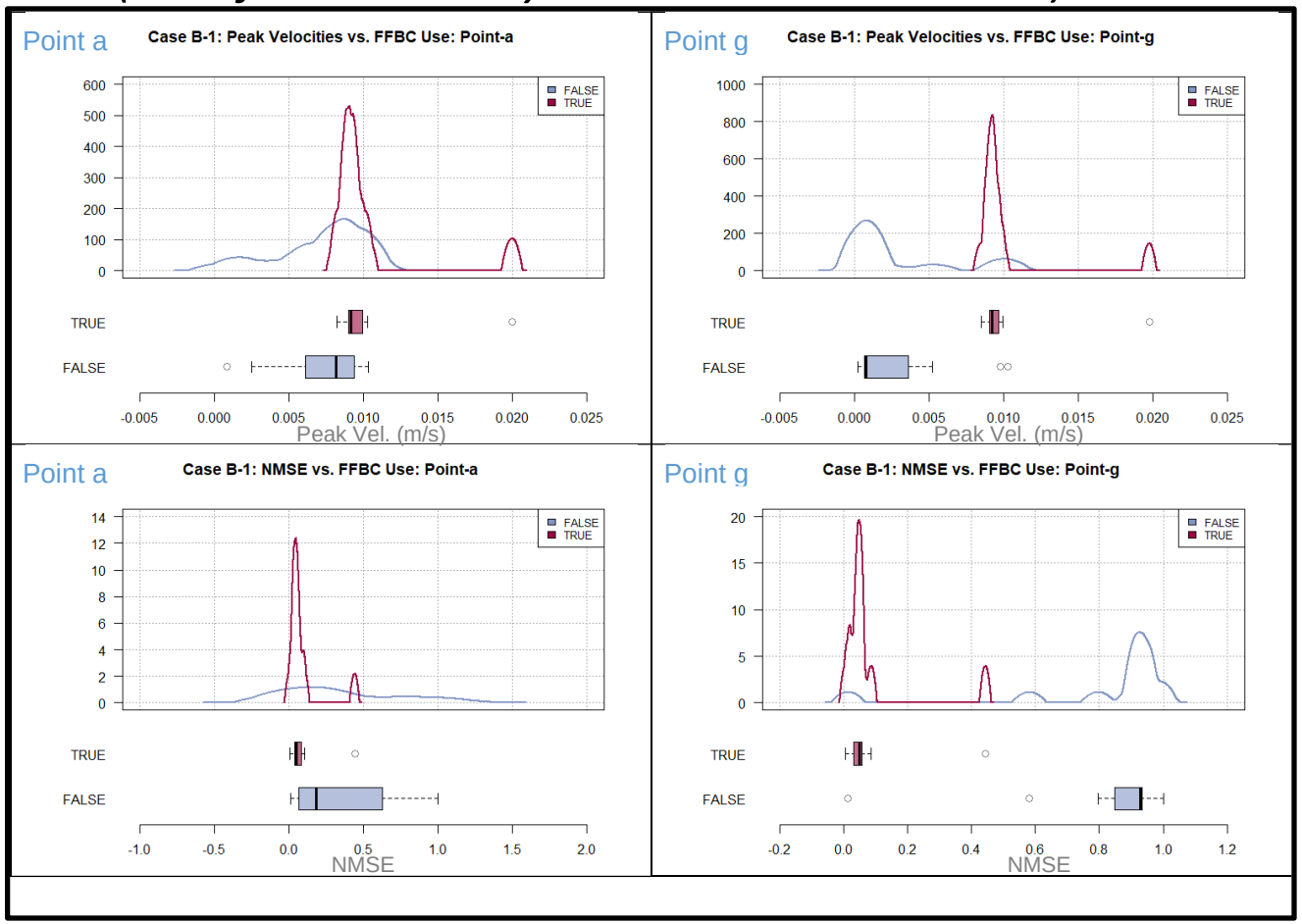


at bottom



Peak time-history values are defined as $A_{peak} = A_{max}$

*(Free-field boundary conditions used = **TRUE**)*

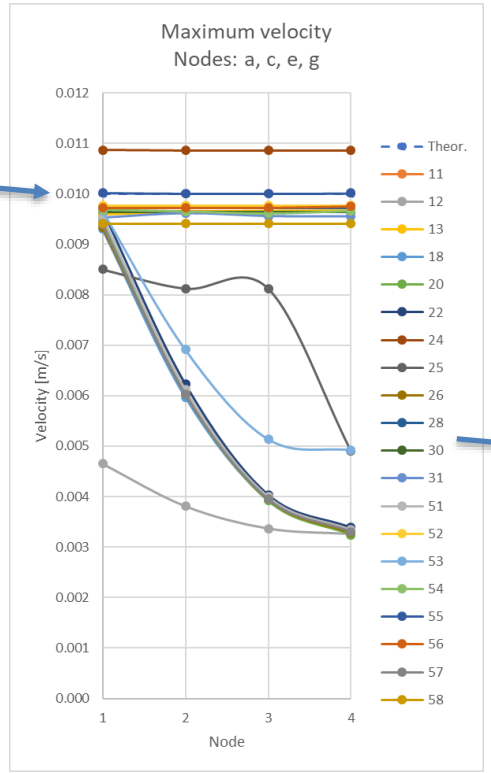


Case B2 - Result Summary - Low Frequency Pulse

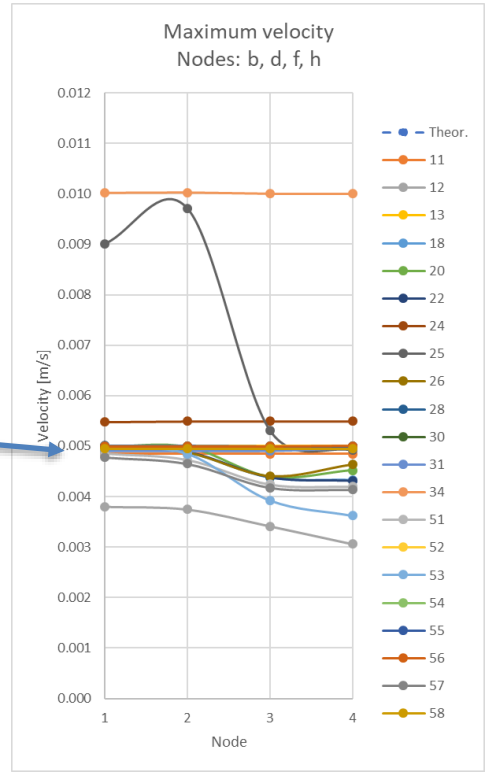
Maximum velocity

➢ All the results

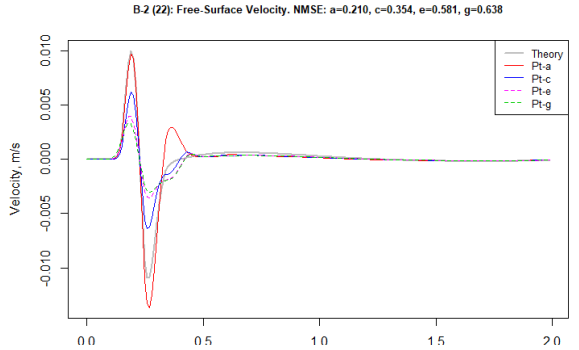
at surface

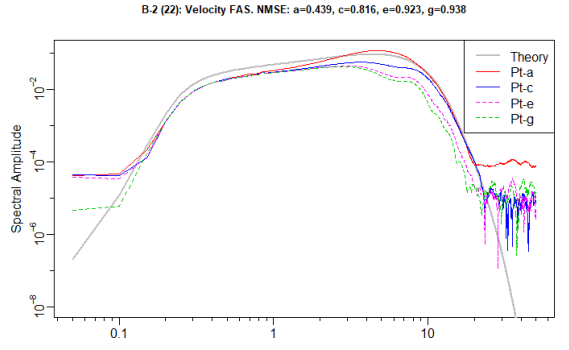


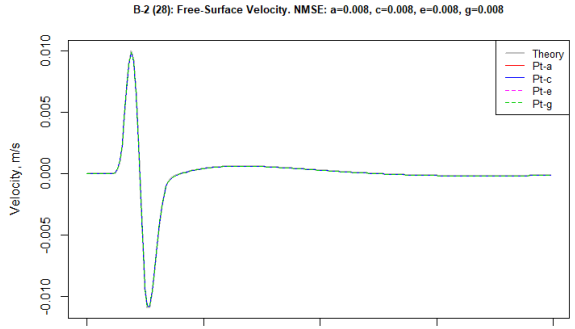
at bottom

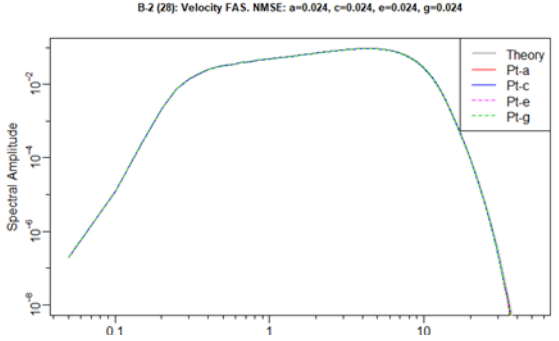


Absorbing boundaries

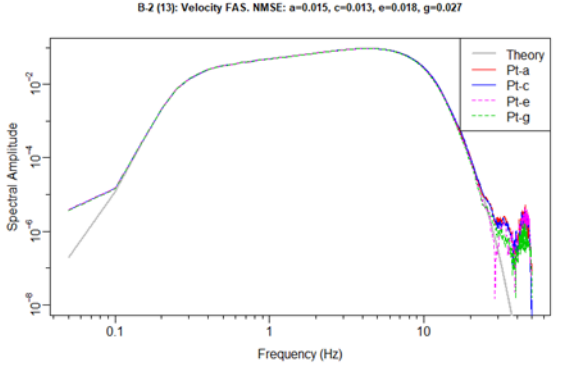


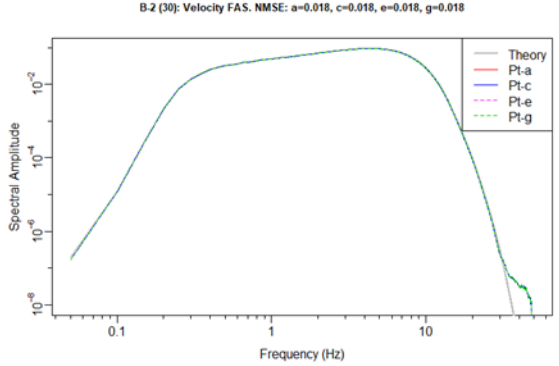






Free-field boundaries



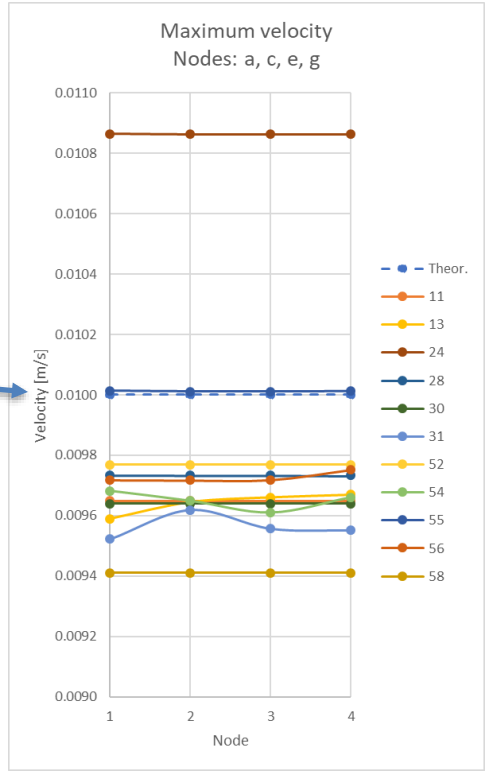


Case B2 - Result Summary - Low Frequency Pulse

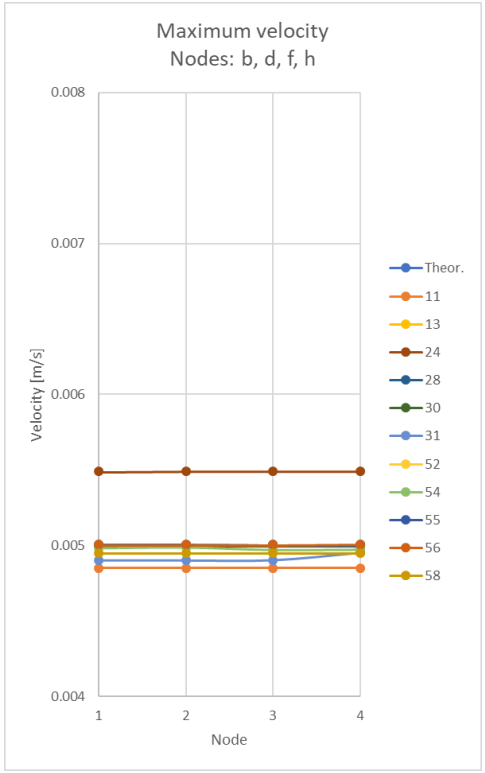
Maximum velocity

➢ Selected results

at surface

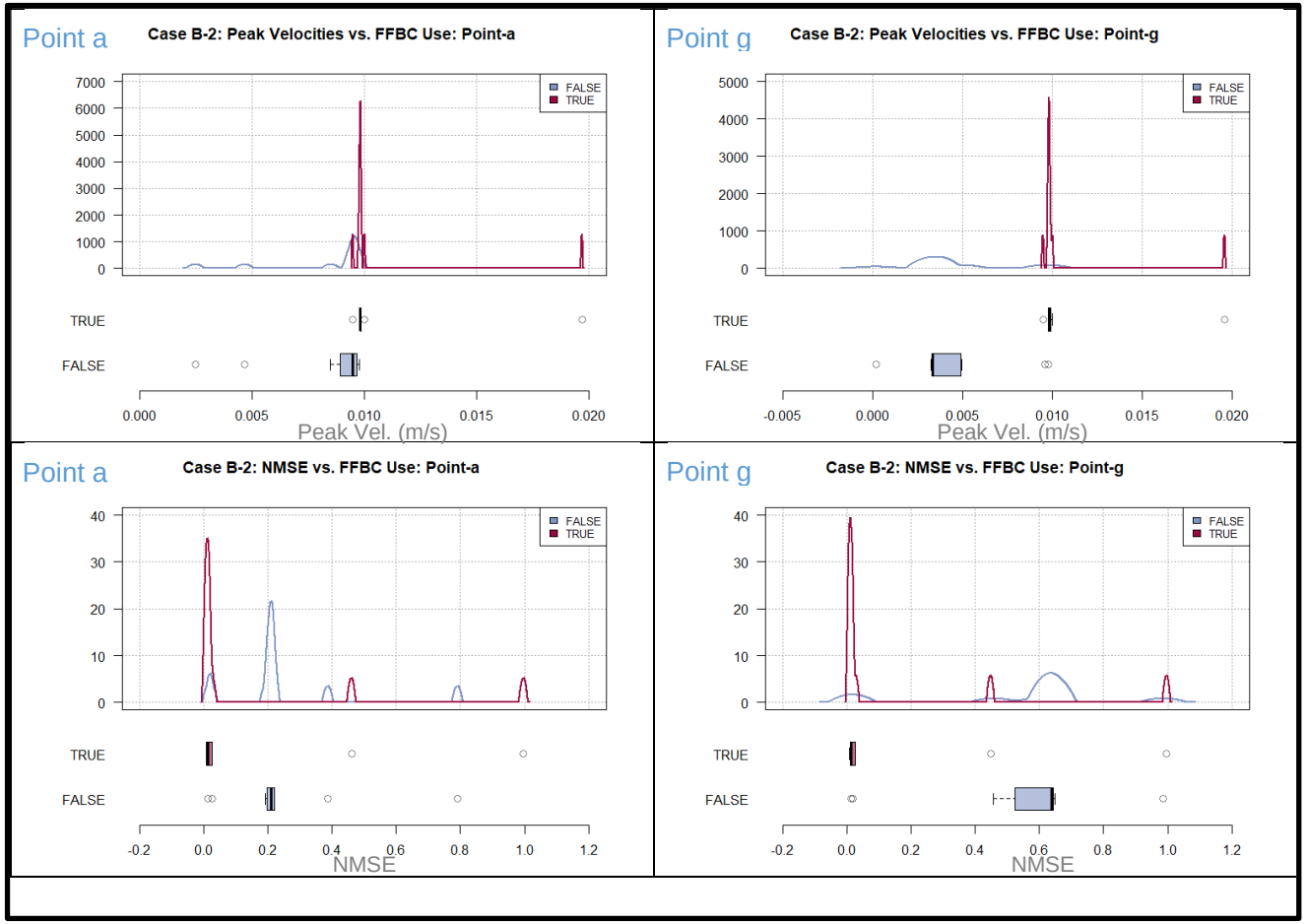


at bottom



Peak time-history values are defined as $A_{peak} = A_{max}$

*(Free-field boundary conditions used = **TRUE**)*

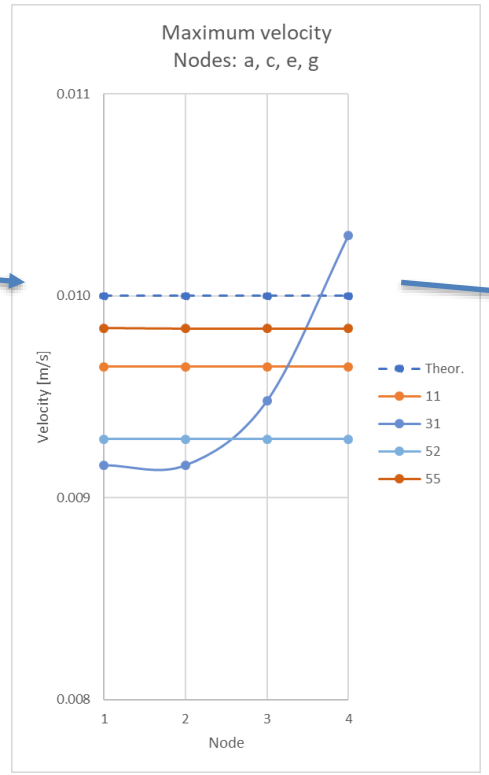


Case B1 and B3 - Result Comparison - High Frequency Pulse

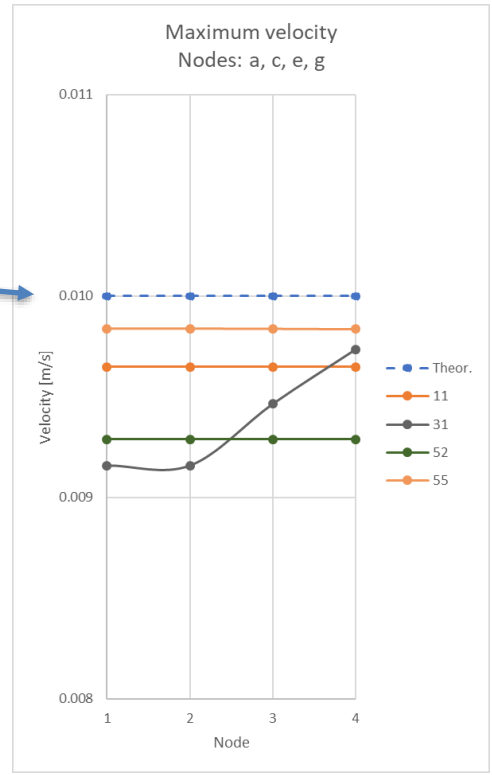
Maximum velocity comparison – size of the foundation block

Free-field boundary conditions

Case B1

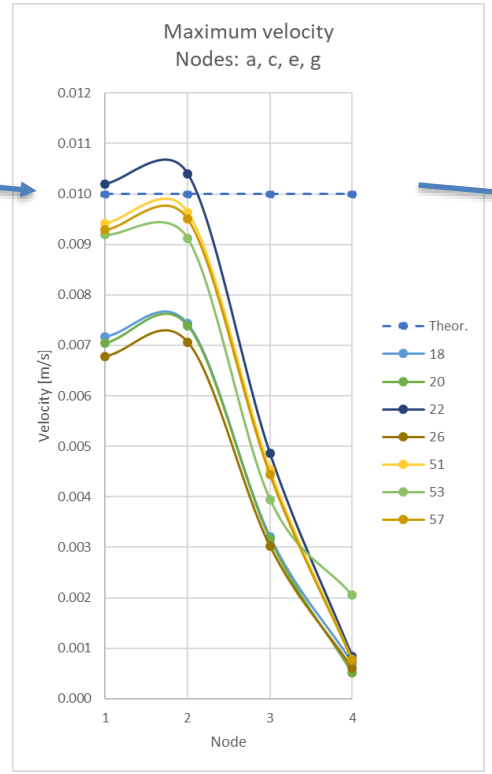


Case B3

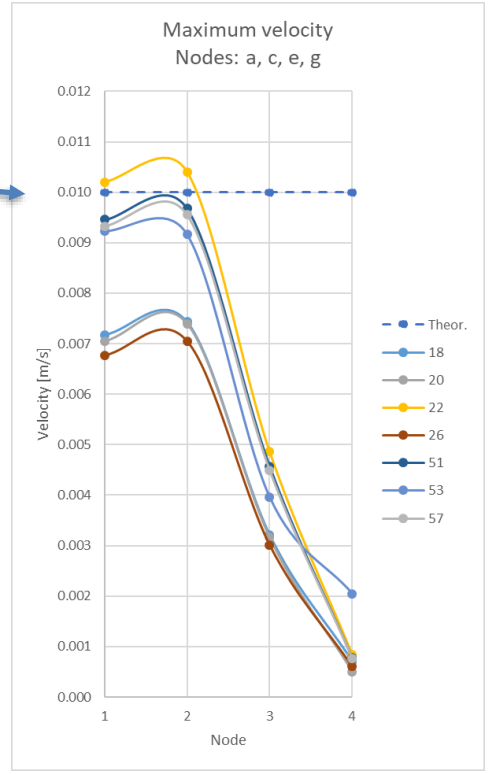


Absorbing boundary conditions

Case B1



Case B3

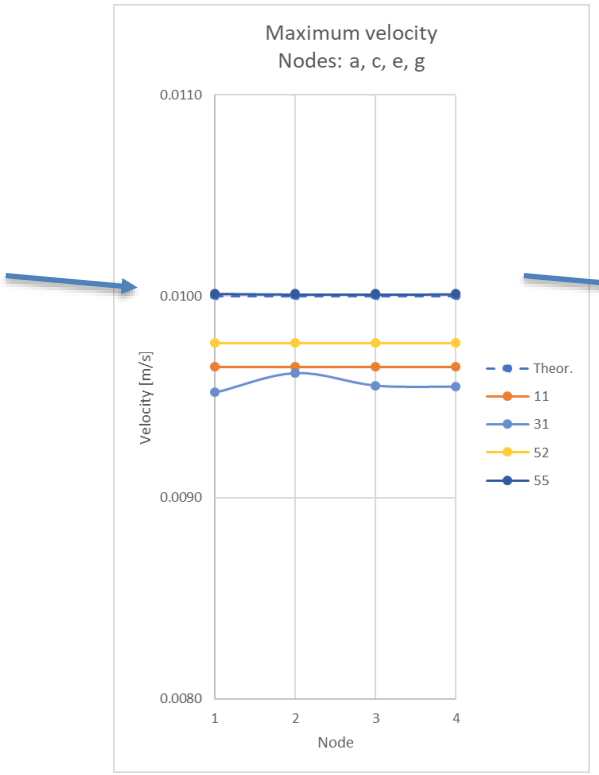


Case B2 and B4 - Result Comparison - Low Frequency Pulse

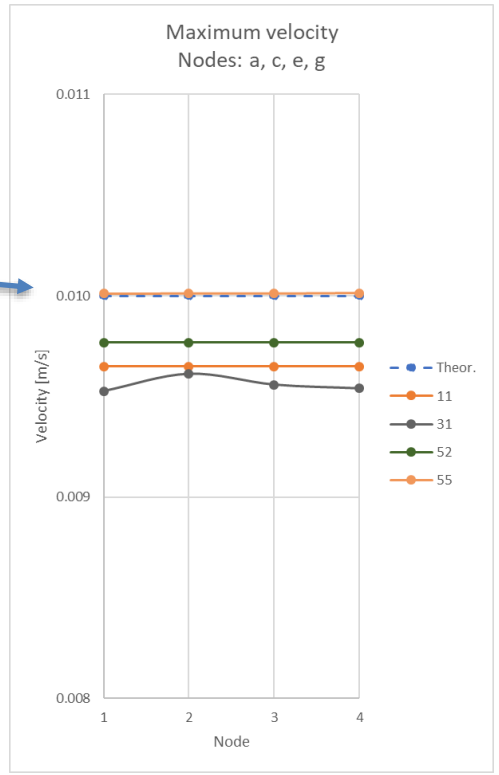
Maximum velocity comparison – size of the foundation block

Free-field boundary conditions

Case B2

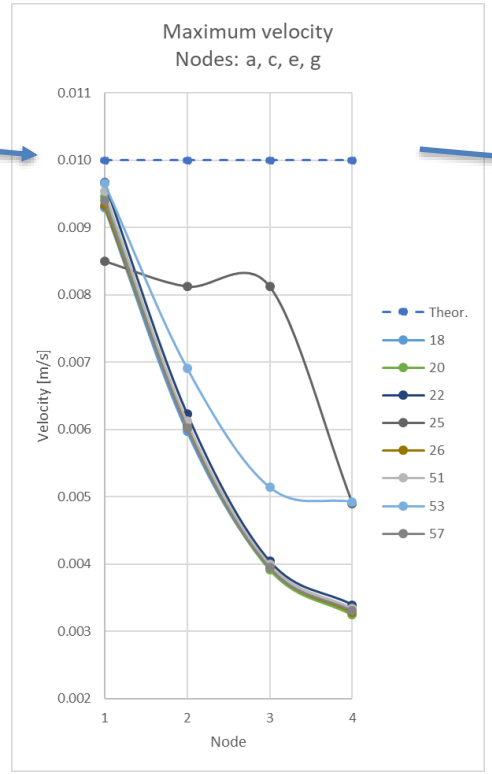


Case B4

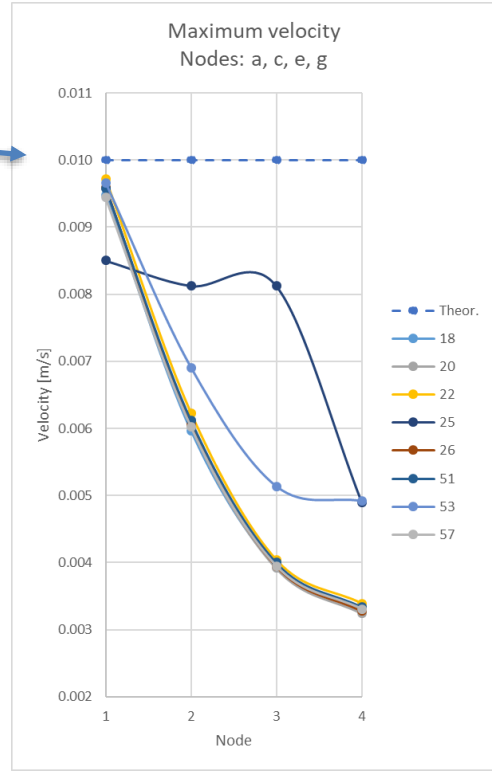


Absorbing boundary conditions

Case B2



Case B4

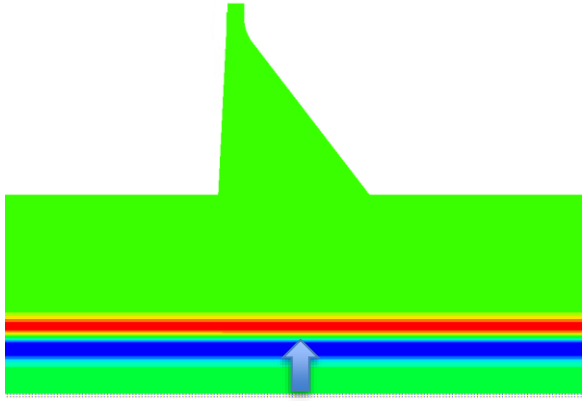


Case B - Observations

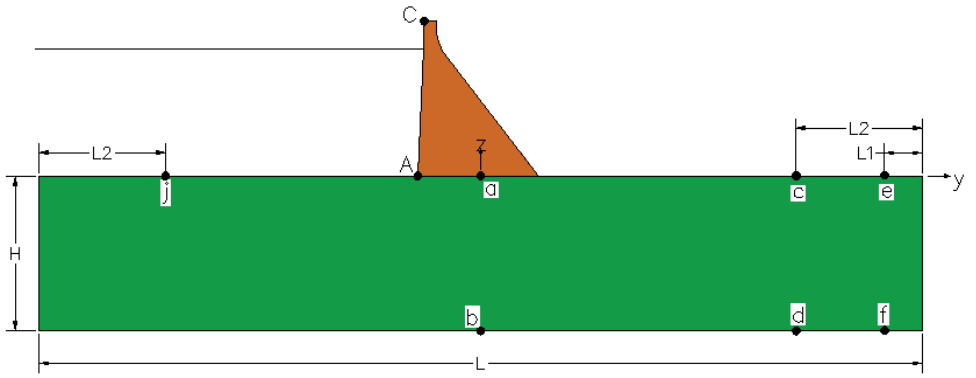
- It is expected that a uniform up-going wave remains uniform at the top surface of the foundation block
- Results obtained from models with free-field boundary conditions are in very good agreement with the theoretical solutions

Case C – Dynamic Analysis of Dam-Foundation System for Impulsive Excitation

- **Purpose** - to investigate seismic wave propagation in the model with the presence of a concrete dam and reservoir
- **"Base Model" configuration**
  - Dam, reservoir and mass foundation block *700 m x 122 m*
  - High and low frequency excitation records
  - Zero viscous damping
  - Elastic properties
  - The maximum mesh size 1.5 m
- **High and low** frequency time pulse as in Case B
  - Applied in the form of stress excitation at the foundation base
- **Investigations**
  - Boundary conditions to be defined and justified by the participants
- **Results**:
  - Comparison of the analysis results at Points **a** through **j** and **A** and **C**
  - Comparison between Case C and Case B results



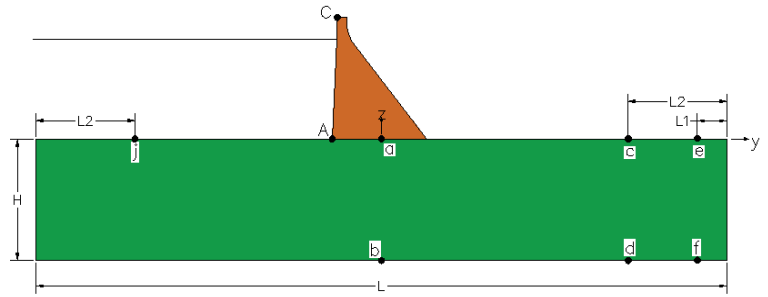
Impulse Frequency	Δt (sec.)	$F_{Nyquist}$ (Hz)	F_N (Hz)	F_{lo} (Hz)	F_{hi} (Hz)	Amplit. (m/s)	Record (sec.)	Zero-pad (samp)
Low	0.01	50	4.0	0.5	8.0	0.01	20	10
High	0.001	500	40	5	80	0.01	2.0	10



Case C - Dynamic Analysis of Dam-Foundation System for Impulsive Excitation

➢ Case C consists of 4 studies

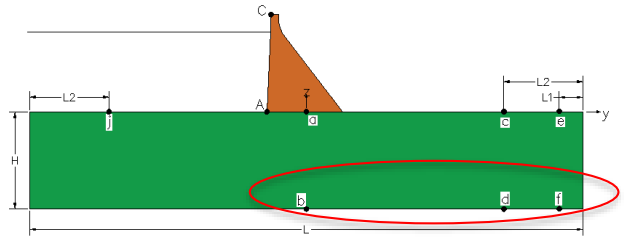
	Case C1	Case C2	Case C3	Case C4
Model	Dam – foundation - reservoir	Dam – foundation - reservoir	Dam - foundation	Dam - foundation
Pulse frequency	High	Low	High	Low
Number of solutions	11	11	11	11



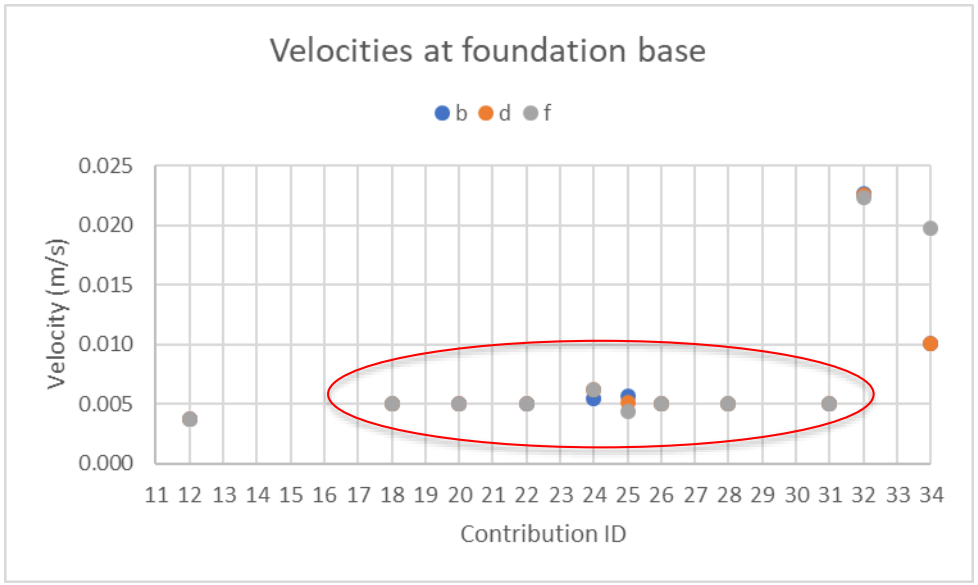
➢ Solution method

Contributor ID	Time step (sec)	Mesh size (m)	Implicit time step	Free-field BC	Code
12	1.00E-03	1.5	Implicit	-	Diana
18	1.00E-03	1.5	NA	-	Diana
20	1.00E-03	11.5	Implicit	-	Abaqus
22	1.00E-03	1.5	Implicit	-	Diana
24	3.85E-05	1.5	Explicit	Free-field	FLAC3D
25	2.00E-04	1.5	Implicit	-	Diana
26	1.00E-03	1.5	Implicit	-	Abaqus
28	2.00E-04	1.5	Implicit	Free-field	Abaqus
31	1.00E-04	1.5	Implicit	-	Abaqus
32	1.00E-02	1.5	NA	-	SOFiSTiK
34	2.50E-04	1	Implicit	Free-field	ADINA

Case C1 - Dam-Foundation-Reservoir for High Frequency Pulse



➢ Verification of the input load record



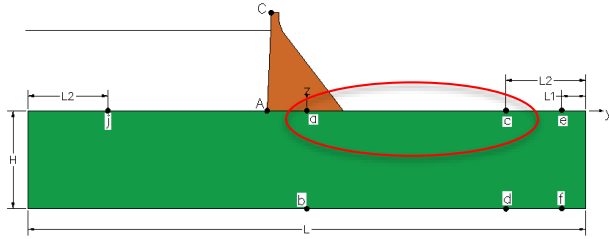
➢ Expectations

The same maximum velocity is expected at the base of the foundation

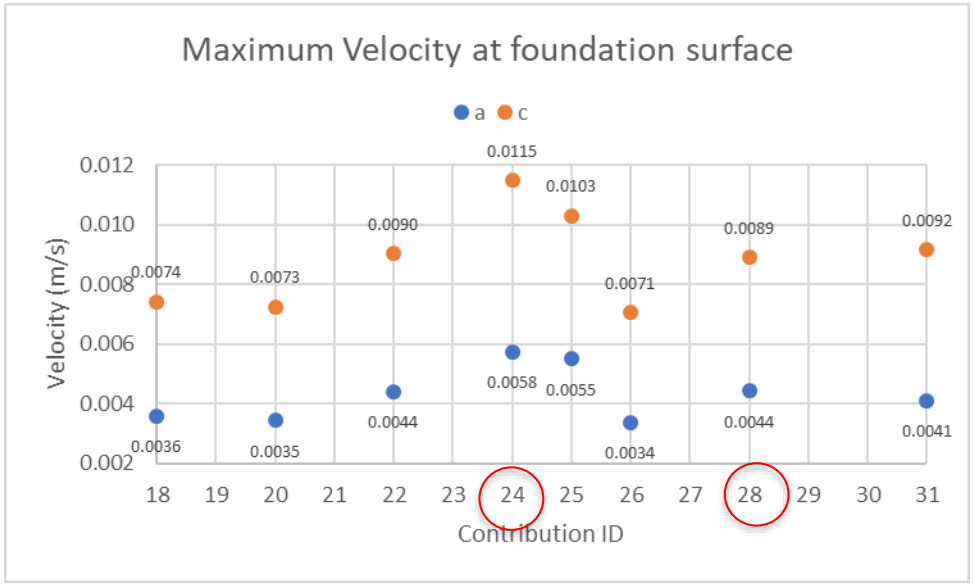
➢ Observations

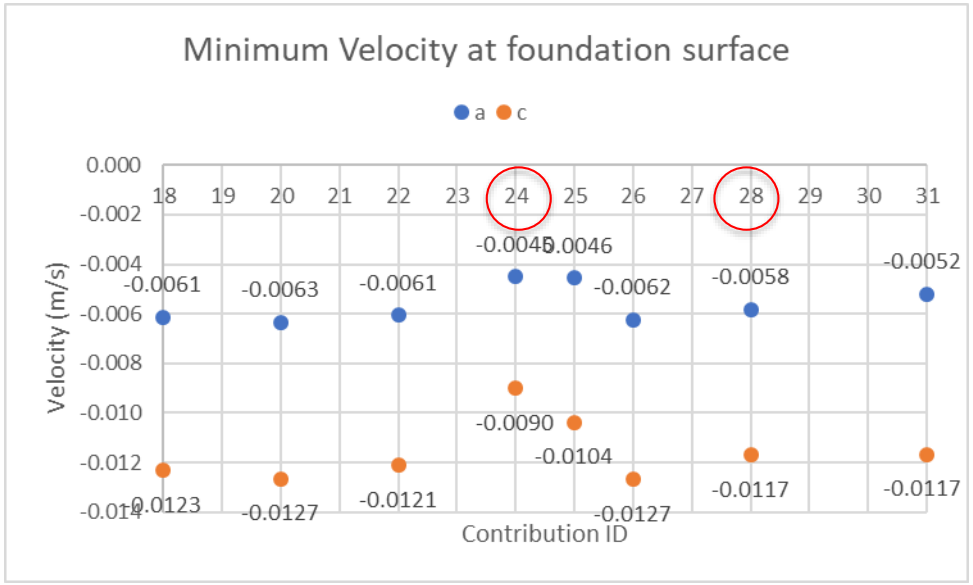
- ➢ Variation in the load input records
- ➢ For further comparisons only results within a narrow range of the maximum velocities at the foundation base are considered

Case C1 - Dam-Foundation-Reservoir for High Frequency Pulse



- **Maximum and minimum velocities at the foundation surface,** Points **a & c**
  (Contributions 24 and 28 using the far-field boundary conditions)





- **Observation**
  - Velocity amplitude at the base of the dam is lower when compared with the free surface velocities

Case C1 - Dam-Foundation-Reservoir for High Frequency Pulse

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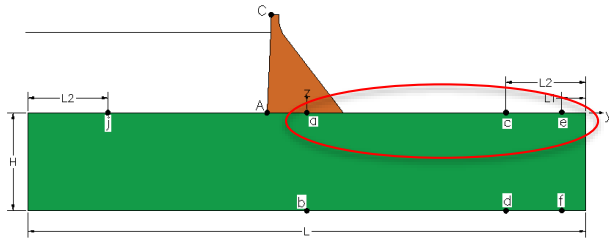
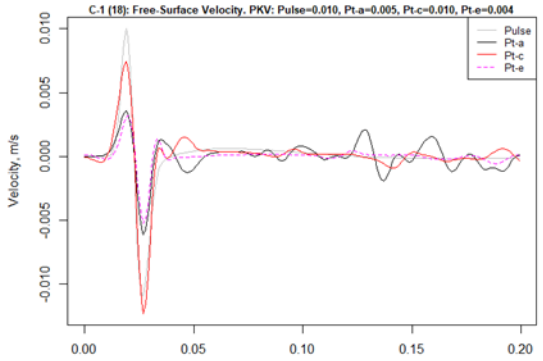
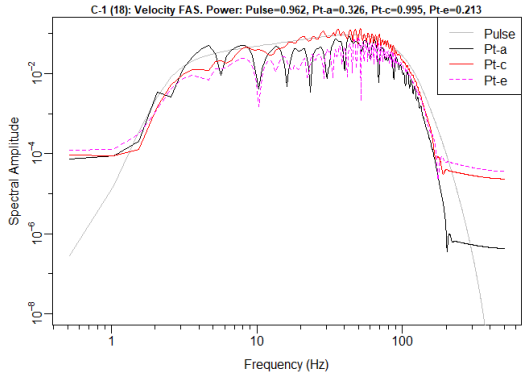
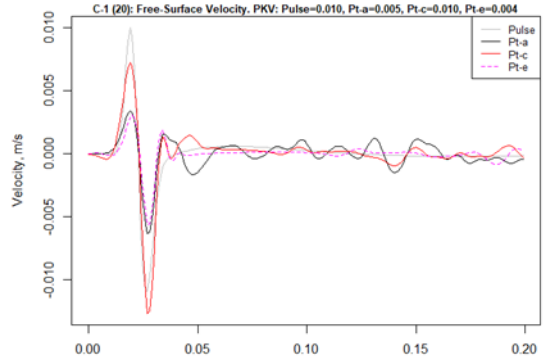
Numerical analysis of dams

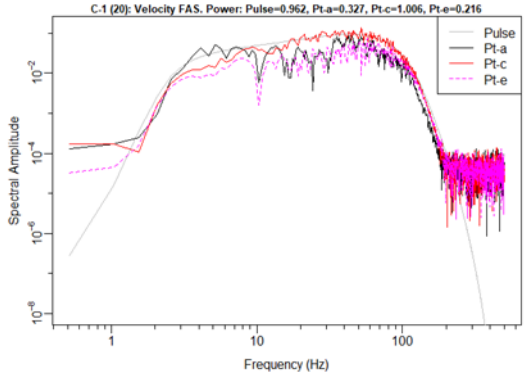
➢ Velocity time histories and corresponding Fourier amplitude spectra

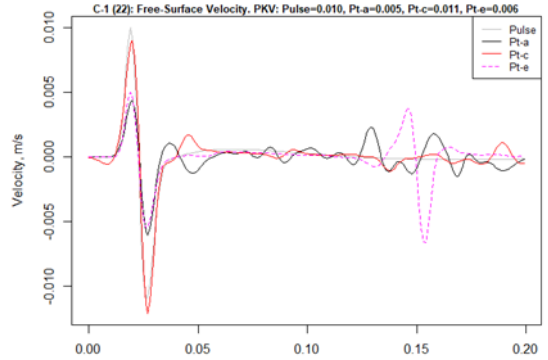


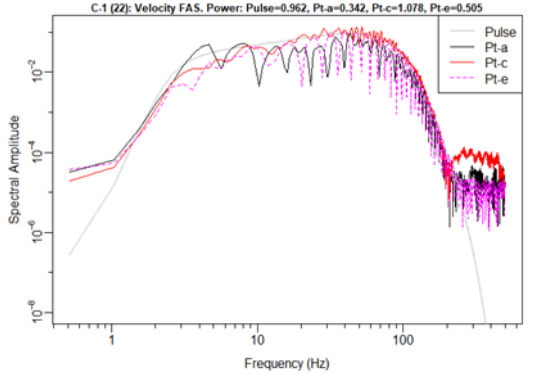


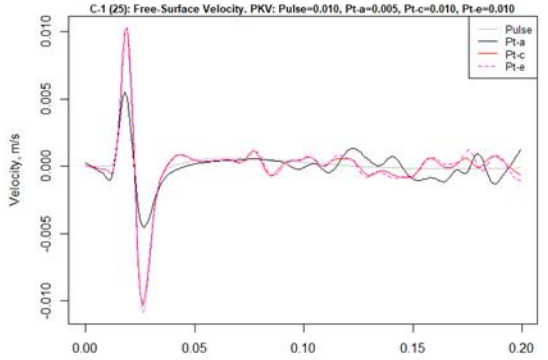


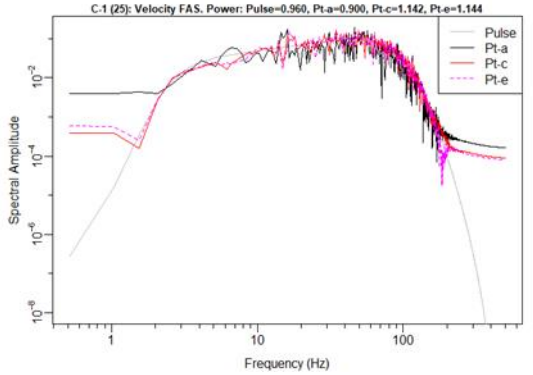




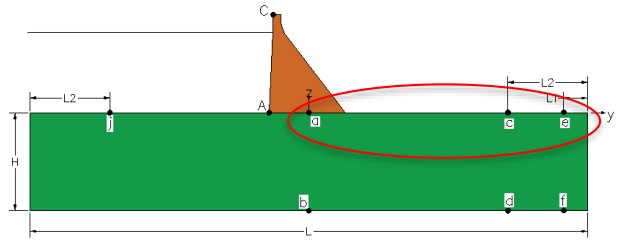






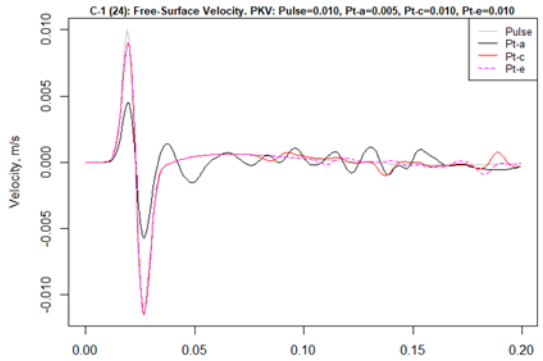


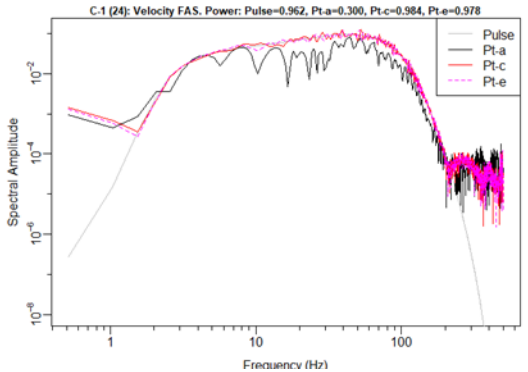
Case C1 - Dam-Foundation-Reservoir for High Frequency Pulse

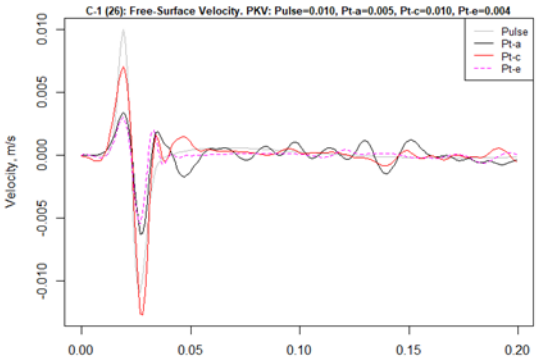


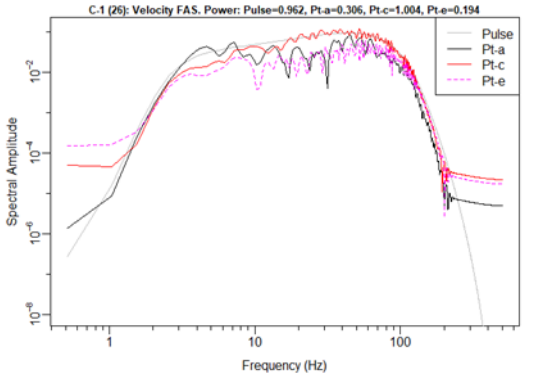
- **Velocity time histories and corresponding Fourier amplitude spectra**

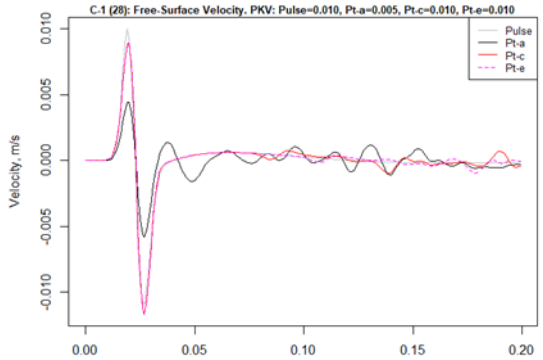
  Contribution 24 and 28 using free-field boundary conditions

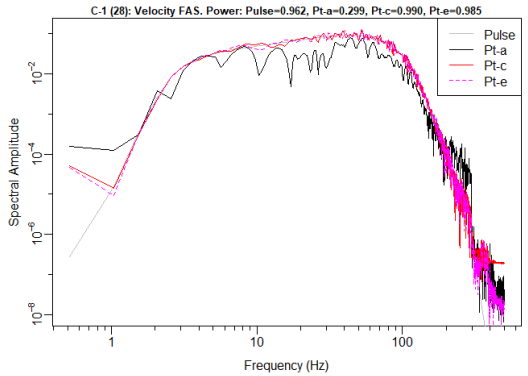


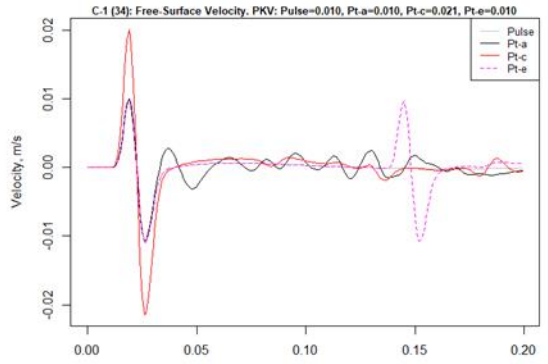


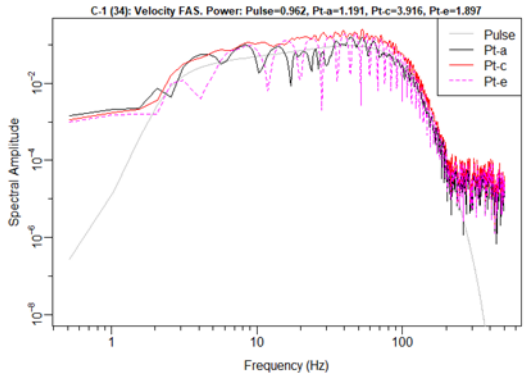






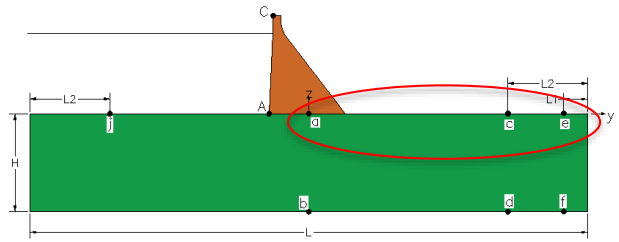






Case C1 - Dam-Foundation-Reservoir for High Frequency Pulse

➢ Summary results



At Point **a**

ID	Peak Velocity (m/s)	Spectral Power	Energy Integral	Duration (sec)
18	0.0049	0.33	3.37E-07	0.17
20	0.0049	0.33	3.38E-07	0.31
22	0.0052	0.34	3.53E-07	0.17
24	0.0051	0.30	3.10E-07	0.16
25	0.0050	0.90	9.31E-07	1.10
26	0.0049	0.31	3.16E-07	0.14
28	0.0051	0.30	3.08E-07	0.14
31	0.0047	2.87	2.87E-06	1.02

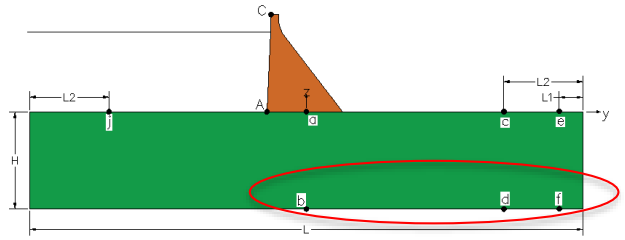
At Point **e**

ID	Peak Velocity (m/s)	Spectral Power	Energy Integral	Duration (sec)
18	0.0042	0.21	2.20E-07	0.34
20	0.0043	0.22	2.23E-07	0.39
22	0.0058	0.51	5.21E-07	0.14
24	0.0103	0.98	1.01E-06	0.02
25	0.0103	1.14	1.18E-06	0.59
26	0.0042	0.19	2.00E-07	0.30
28	0.0103	0.98	1.02E-06	0.02
31	0.0106	10.01	1.00E-05	0.13

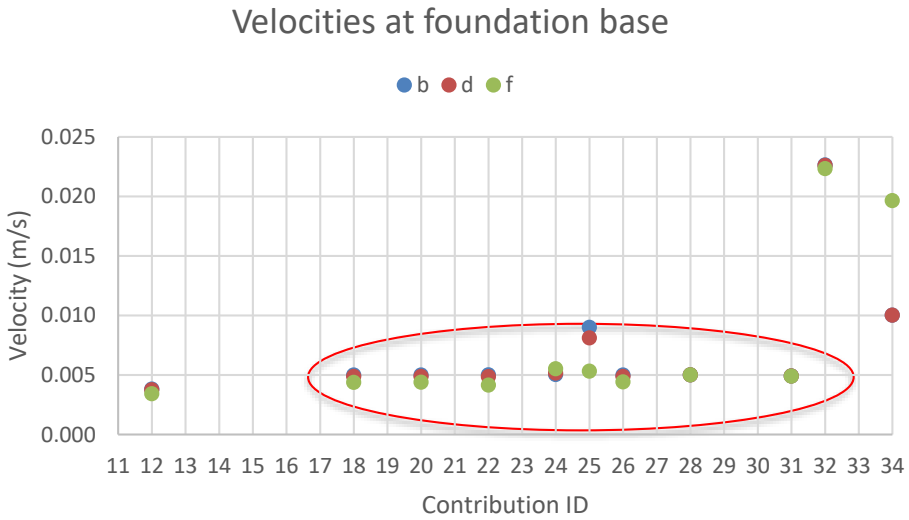
➢ Observation

Consistency in the results for the model with the free-field boundary condition (contributions 24 and 28)

Case C2 - Dam-Foundation-Reservoir for Low Frequency Pulse



➢ Verification of the input load record



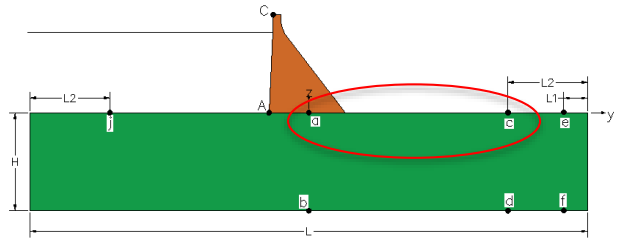
➢ Expectations

The same maximum velocity is expected at the base of the foundation

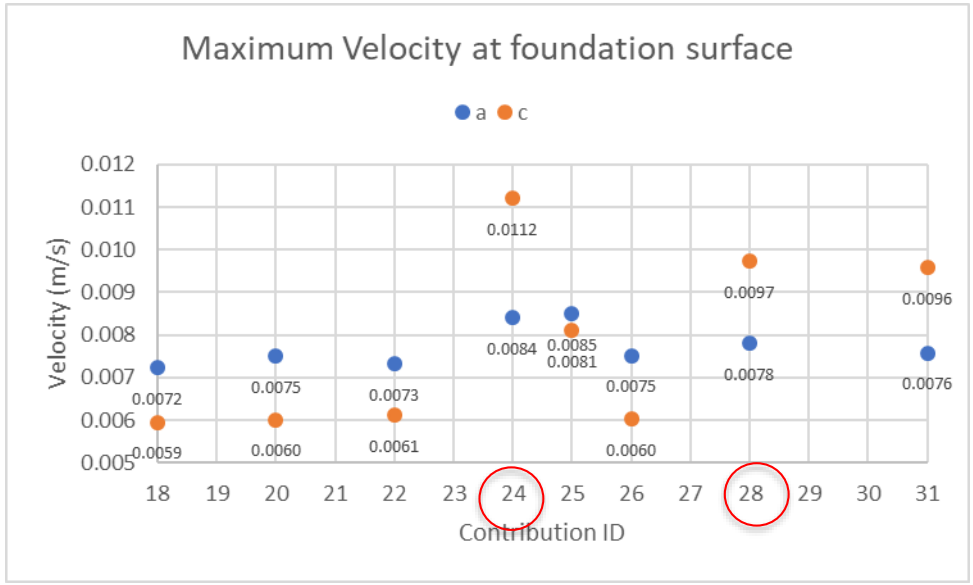
➢ Observations

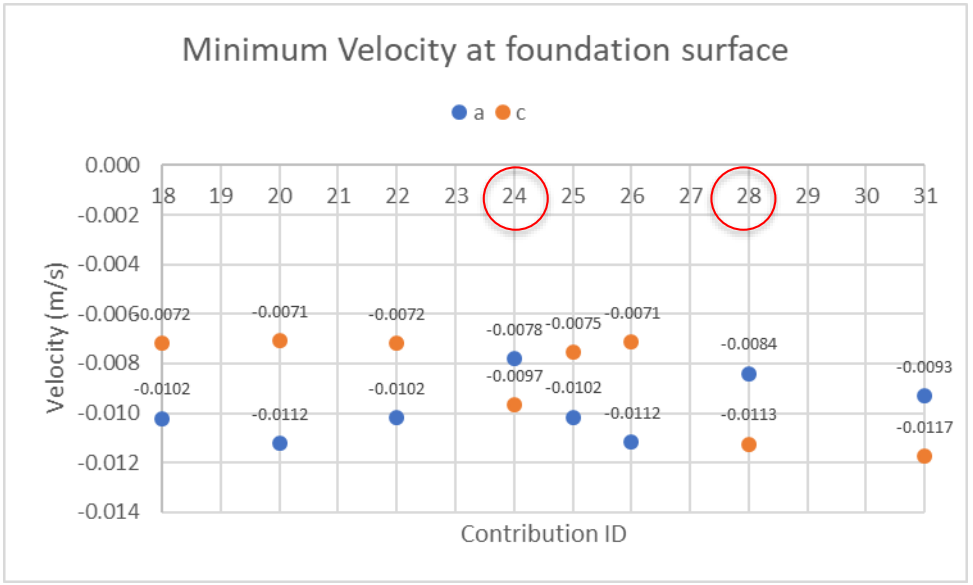
- ➢ Variation in the load input records
- ➢ For further comparisons only results within a narrow range of the maximum velocities at the foundation base are considered

Case C2 - Dam-Foundation-Reservoir for Low Frequency Pulse



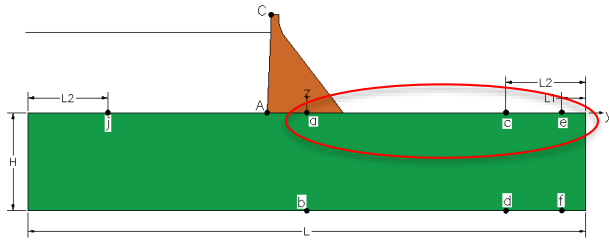
- **Maximum and minimum velocities at the foundation surface,** Points **a & c**
  (Contributions 24 and 28 using the far-filed boundary conditions)



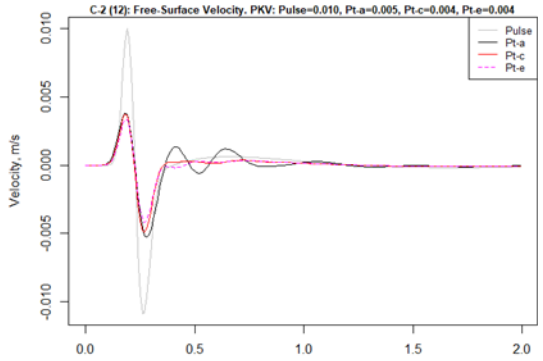


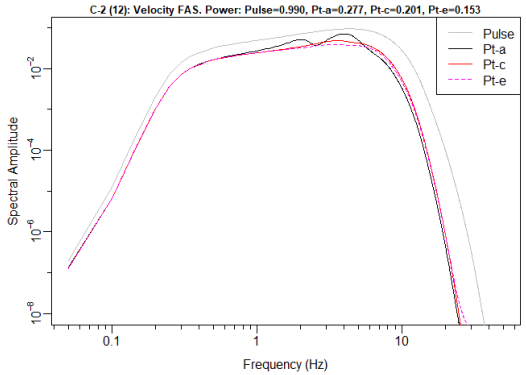
- **Observation**
  Velocity amplitude is reduced at the base of the dam when compared with the amplitude at the free surface

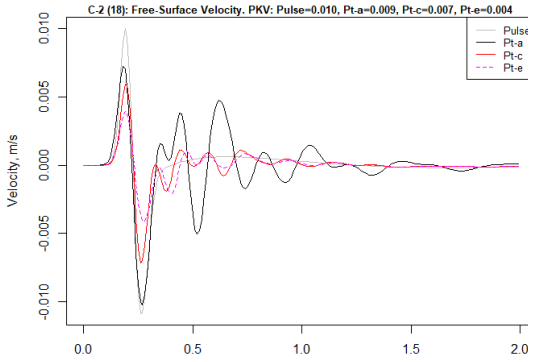
Case C2 - Dam-Foundation-Reservoir for Low Frequency Pulse

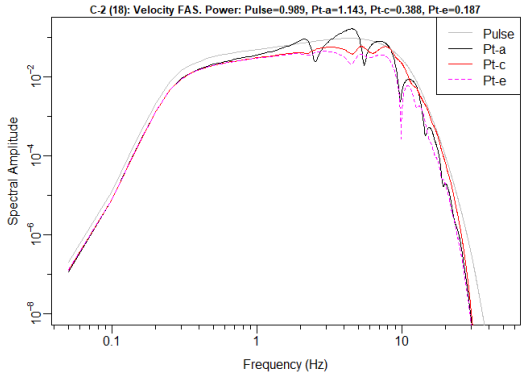


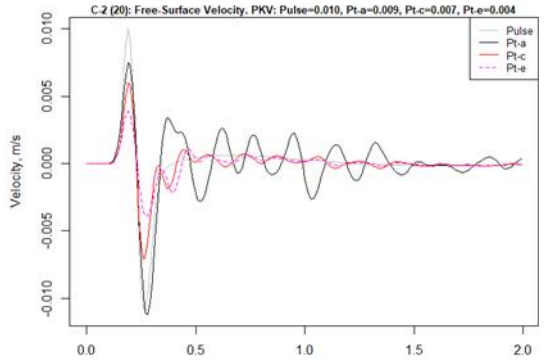
➢ Velocity time histories and corresponding Fourier amplitude spectra

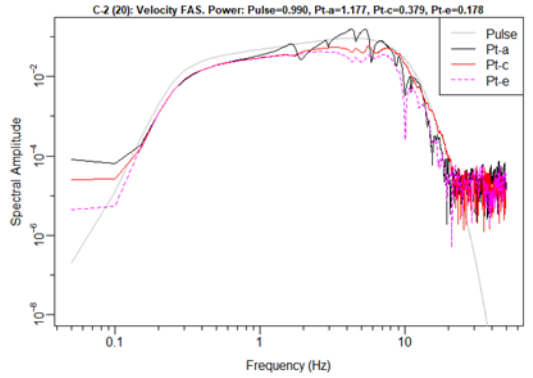


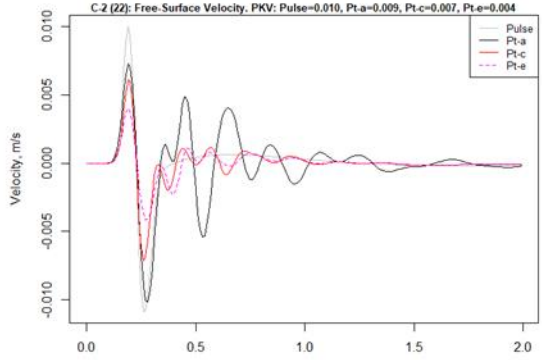


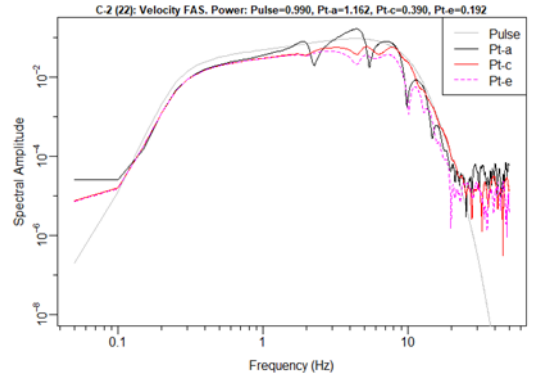








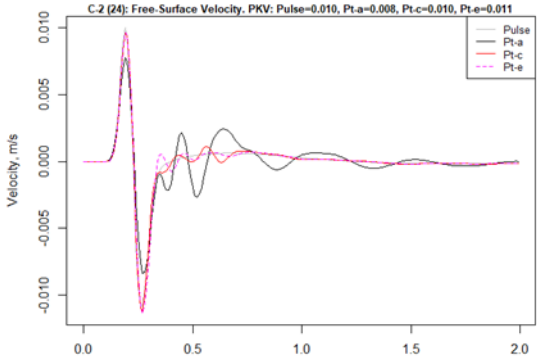


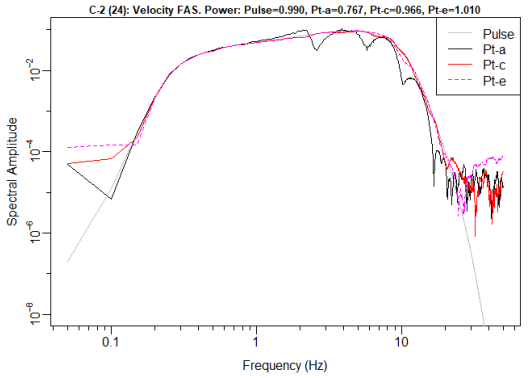


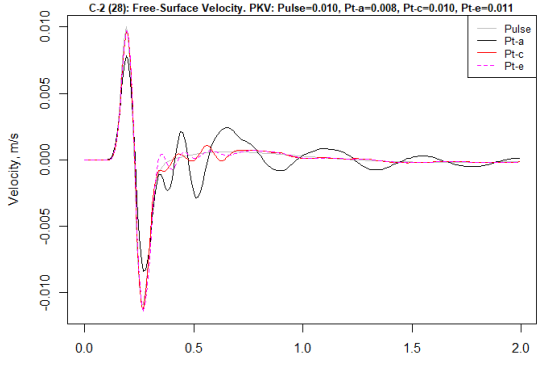
Case C2 - Dam-Foundation-Reservoir for Low Frequency Pulse

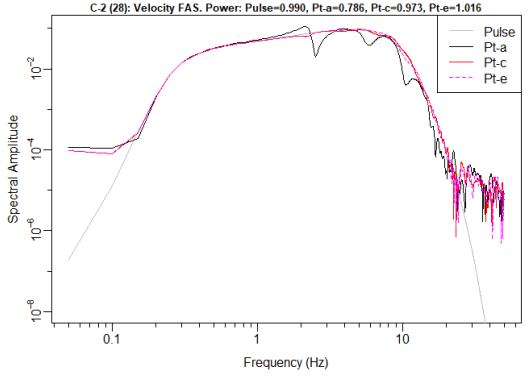
- **Velocity time histories and corresponding Fourier amplitude spectra**

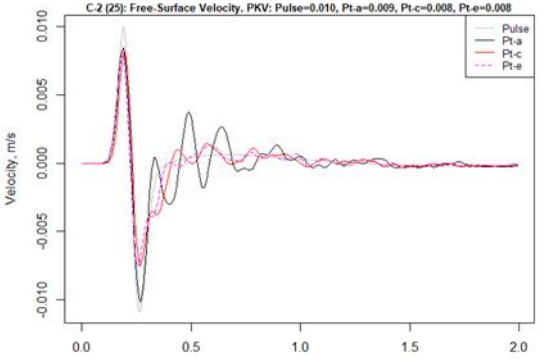
  Contribution 24 and 28 using free-field boundary conditions

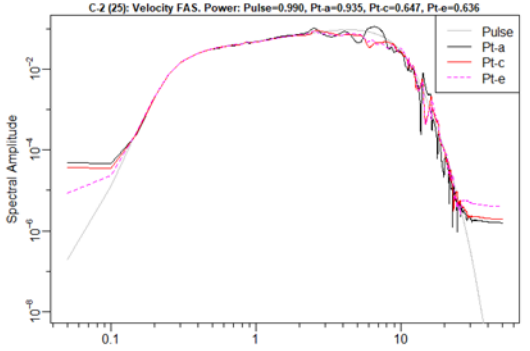


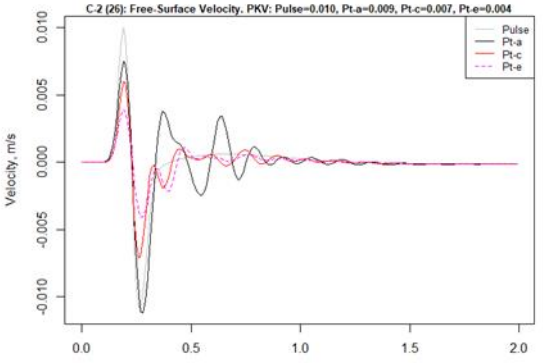


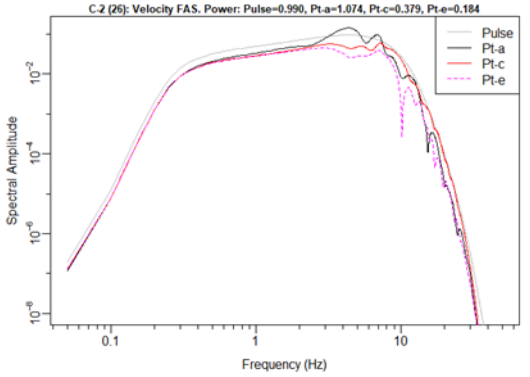


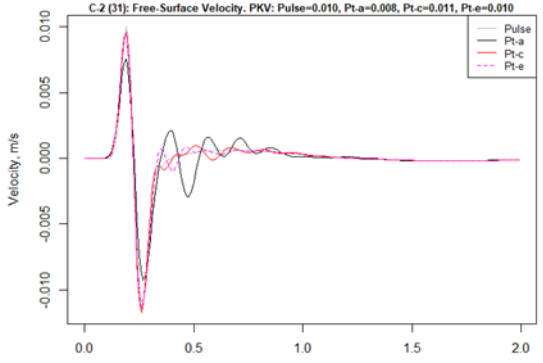


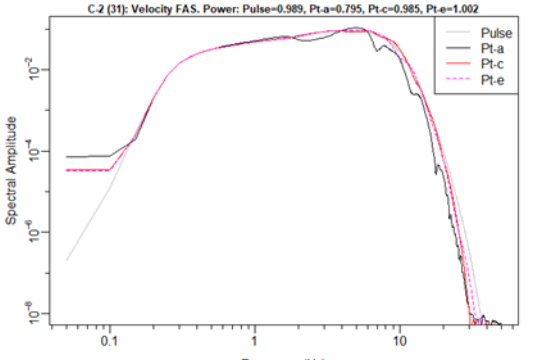






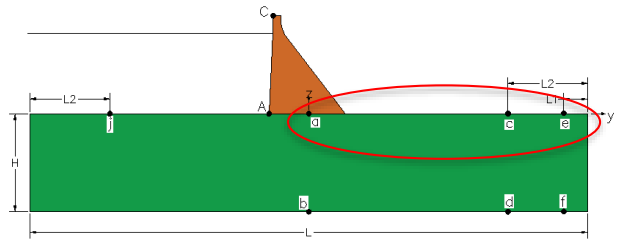






Case C2 - Dam-Foundation-Reservoir for Low Frequency Pulse

➢ Summary results



At Point **a**

ID	Peak Velocity (m/s)	Spectral Power	Energy Integral	Duration (sec)
18	0.0088	1.14	1.15E-05	0.50
20	0.0094	1.18	1.18E-05	0.86
22	0.0088	1.16	1.17E-05	0.49
24	0.0081	0.77	7.70E-06	0.49
25	0.0093	0.94	9.39E-06	0.46
26	0.0094	1.07	1.08E-05	0.45
28	0.0081	0.79	7.89E-06	0.54
31	0.0084	0.80	7.99E-06	0.33

At Point **e**

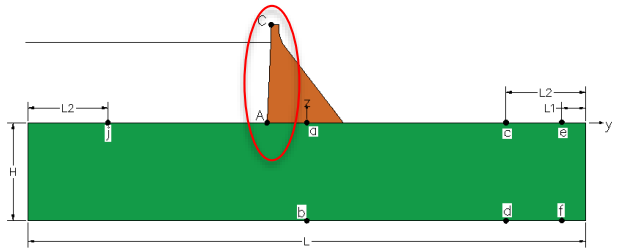
ID	Peak Velocity (m/s)	Spectral Power	Energy Integral	Duration (sec)
18	0.0040	0.19	1.87E-06	0.39
20	0.0039	0.18	1.79E-06	0.30
22	0.0041	0.19	1.93E-06	0.35
24	0.0105	1.01	1.01E-05	0.13
25	0.0079	0.64	6.38E-06	0.19
26	0.0040	0.18	1.84E-06	0.30
28	0.0106	1.02	1.02E-05	0.13
31	0.0104	1.00	1.01E-05	0.13

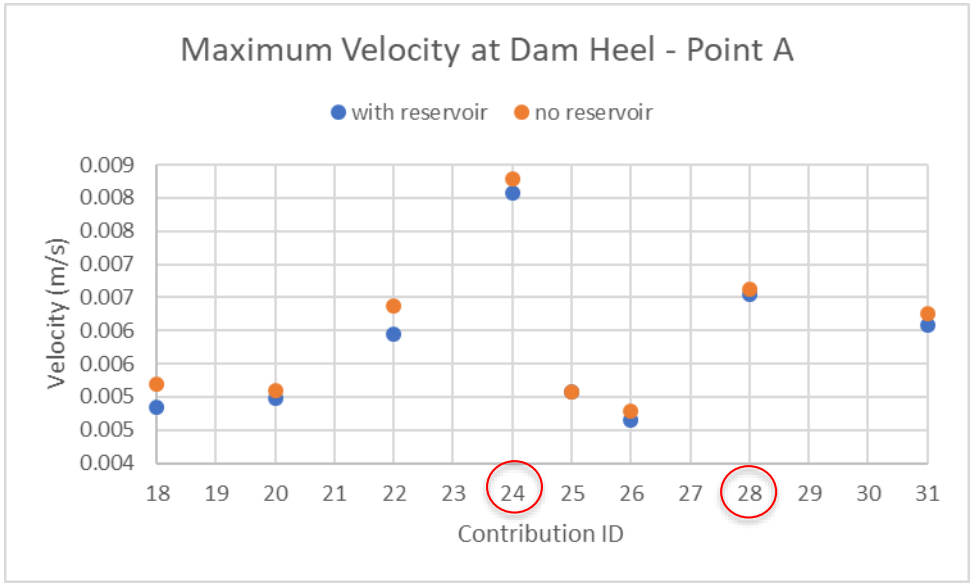
➢ Observation

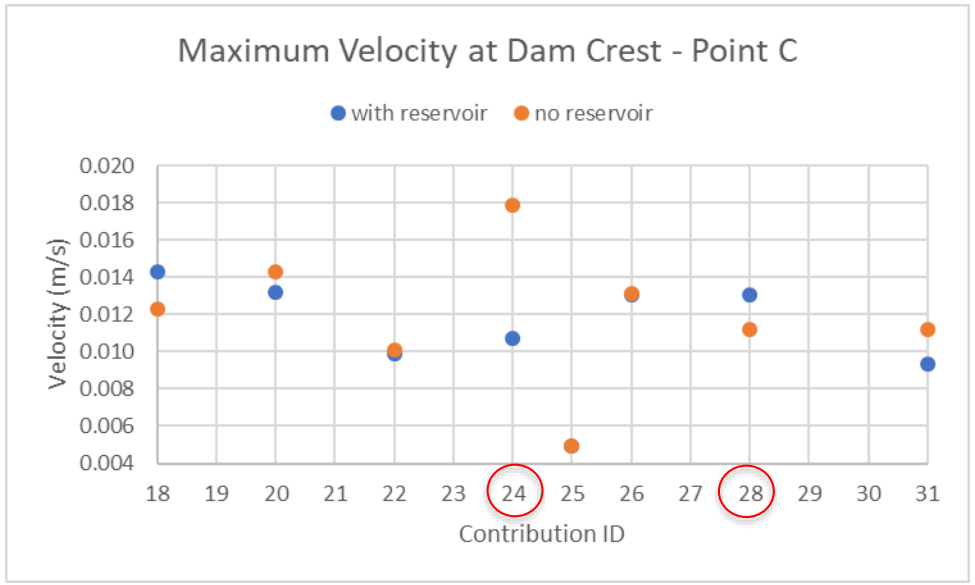
Consistency in the results for the model with the free-field boundary condition (contributions 24 and 28)

Case C1 and C3 - Comparison

- **Effect of reservoir presence** – comparison at dam heel and dam crest – (Case C1 with reservoir but Case C3 no reservoir)







- **Observation**
  - Presence of the reservoir has limited influence on the results at the dam heel
  - Notable difference in the maximum velocity is observed at the dam crest

Case B and C - Final Remarks

- **Effect of free-field boundary conditions** – Results obtained from models with free-field boundary conditions are in very good agreement with the theoretical solutions

- **Effect of the foundation block size** – Size of the foundation has very limited influence on the results, especially when the free-field boundary conditions are implemented

- **Effect of the dam presence** – Significant reduction of the velocity amplitude is observed at the dam base when compared with the corresponding velocity amplitude at the free-surface

- **Effect of the reservoir presence** – Studies showed that the reservoir presence in the model has a limited influence on the velocity amplitude at the dam heel but more significant difference is observed at the dam crest.

Thank you