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

Presentation of the Benchmark Analysis Results

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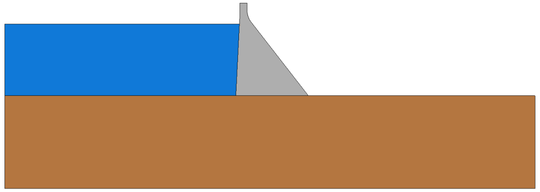
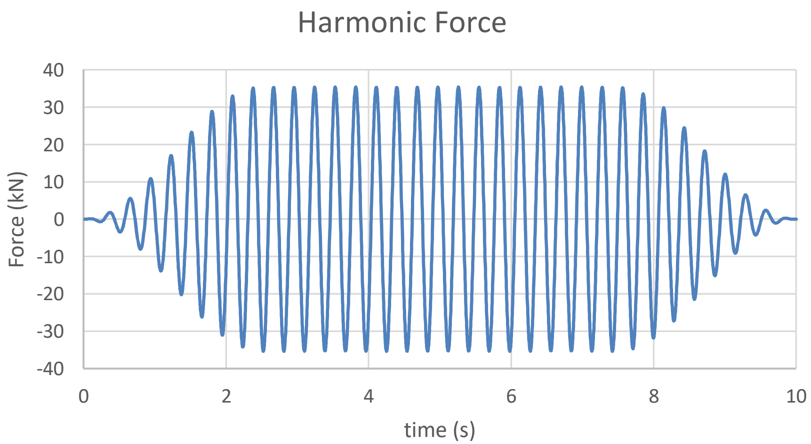


Case A

- Determine the natural frequencies and the mode shapes of the dam
  - Requested output;
    - Natural frequencies (6 first modes)
    - Mode shapes (6 first modes)
- Perform a simplified eccentric mass vibration generator (EMVG) test similar to the tests performed by Rea, Liaw & Chopra (1972).
  - Requested output;
    - Acceleration and displacement at the crest and the upstream heal.
- Two cases;
  - winter conditions (+268.21 m.a.s.l.)
  - summer conditions (+278.57 m.a.s.l.)



Case A and Case E: participants choices

Contributor	FEM code	Integration scheme	Element size	Fluid-Structure Interaction	Non-linear materialmodel	Type of model	Case A	Case E
11	Real ESSI	Implicit/ explicit(FSI)	2 m	Acoustic-structural coupling	-	-		
12	Diana	implicit	2.5-5 m	Acoustic-structural coupling	Total strain based crack model	Fracture mechanics with fixed crack orientation	Y	Y
13	Code_aster	implicit	10 m	Acoustic-structural coupling	ENDO_PORO_BETON	orthotropic damage model	Y	Y
14	ANSYS	implicit	6 m	Acoustic-structural coupling	Drucker-Prager concrete model	Plasticity?	Y	Y
15	SAP2000	explicit	1 m	Links-gap	Concrete, non-linear properties	?	Y	Y
16	ABAQUS	implicit	3-6 m	Acoustic-structural coupling	Concrete damaged plasticity	Combined plasticity and isotropic damage	Y	Y
17	Parmac2D	explicit	3-5 m	Interface elements with only normal stiffness	Damage model	Discrete crack approach	Y	Y

Case D and Case F: participants choices

Contributor	FEM code	Integration scheme	Element size	Fluid-Structure Interaction	Non-linear materialmodel	Type of model	Case A	Case E
18	Diana	implicit	3-30 m	Acoustic-structural coupling	unknown	-	Y	Y
19	Code_aster	implicit	15 m	Acoustic-structural coupling	Linear strain based reduction of E-modulus	-	Y	Y
20	ABAQUS	implicit	1.48 m	Acoustic-structural coupling	Concrete damaged plasticity	Combined plasticity and isotropic damage	Y	Y
21	Code_aster	implicit	1-37.5 m	Acoustic-structural coupling	ENDO_ISO_BETON	isotropic damage model	Y	Y
22	Diana	implicit	2 m	Acoustic-structural coupling	-	-	Y	
23	ANSYS	implicit	0.5-4 m	Acoustic-structural coupling	Micro-plane model	Coupled damage-plasticity model	Y	Y
24	FLAC-3D	explicit	1.4 m	Mixed discretization scheme	Brittle fracture mechanics	Fixed crack approach	Y	Y
25	Diana	implicit	2.5-4 m	Fluid like structural elements	-	-	Y	

Case D and Case F: participants choices

Contributor	FEM code	Integration scheme	Element size	Fluid-Structure Interaction	Non-linear materialmodel	Type of model	Case A	Case E
26	ABAQUS	implicit	1 m	Acoustic-structural coupling	Concrete damaged plasticity	Combined plasticity and isotropic damage	Y	Y
27	Parmac2D	explicit	3-5 m	Interface elements with only normal stiffness	Damage model	Discrete crack approach	Y	Y
28	ABAQUS	implicit	1.5 m	Acoustic-structural coupling	Concrete damaged plasticity	Combined plasticity and isotropic damage	Y	Y
29	ANSYS	implicit	2.5 m	Acoustic-structural coupling	Concrete plasticity	Menetrey-Willam	Y	Y
30	ABAQUS	implicit	3.5 m	Acoustic-structural coupling	Concrete damaged plasticity	Combined plasticity and isotropic damage	Y	Y
31	ABAQUS	implicit	1.5 m	Acoustic-structural coupling	Concrete damaged plasticity	Combined plasticity and isotropic damage	Y	Y
32	SOFiSTiK	implicit	10 m	Fluid like structural elements	Simplied uniaxial?	?	Y	Y
33	ABAQUS	implicit	6 m	Acoustic-structural coupling	Concrete damaged plasticity	Combined plasticity and isotropic damage	Y	Y
34	ADINA	implicit	1 m	Fluid like structural elements	-	-	Y	

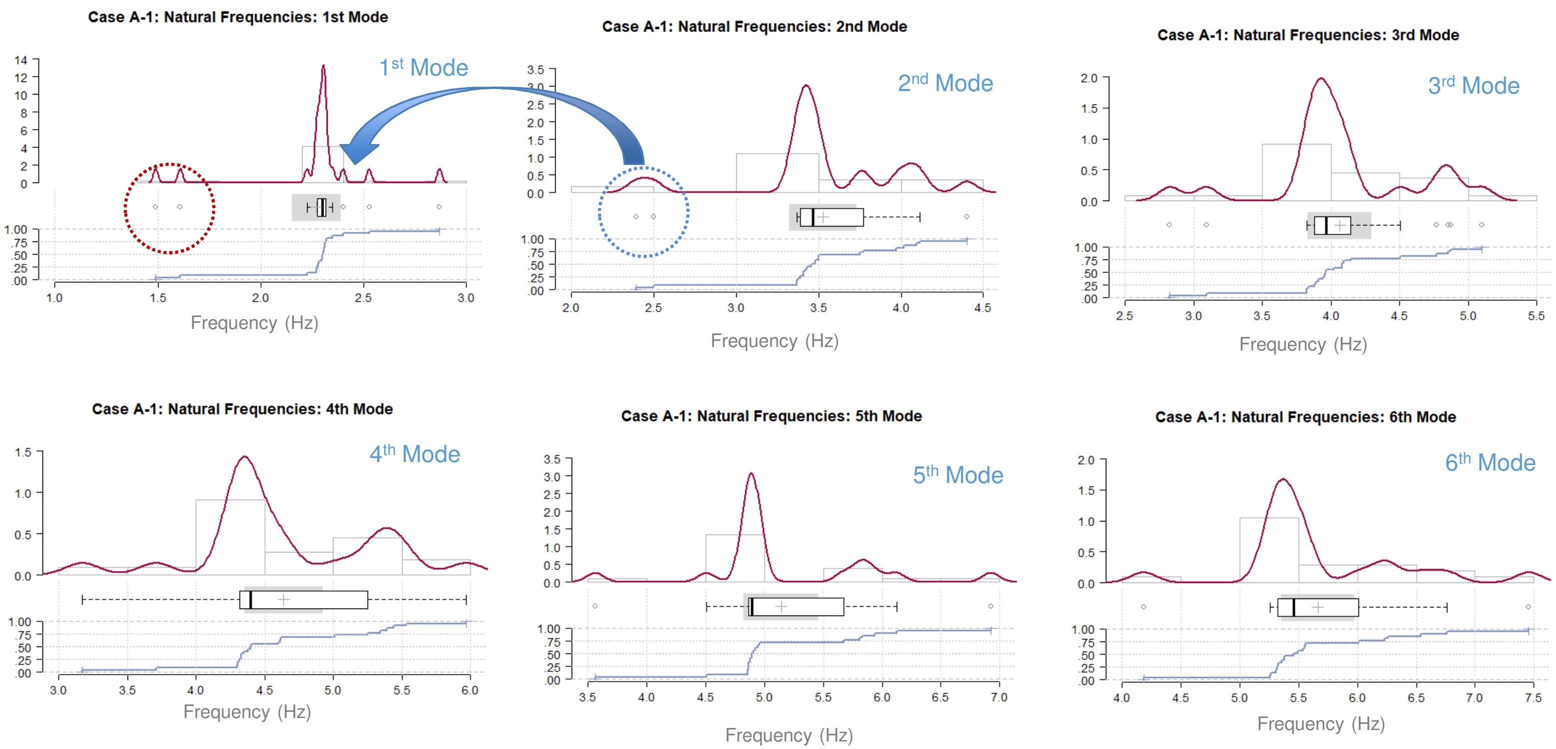
Case A1

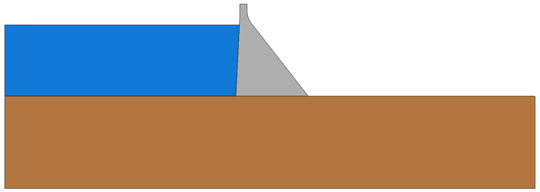
- Natural frequencies

	1st Mode	2nd Mode	3rd Mode	4th Mode	5th Mode	6th Mode
Median (Hz)	2.30	3.47	3.96	4.40	4.89	5.46
Mean (Hz)	2.27	3.53	4.06	4.64	5.14	5.66
SD (Hz)	0.27	0.46	0.53	0.64	0.70	0.68

Difficult to assess which modes are real – some contributors have found additional modes, which means that their results have shifted.

When this shift is adjusted, the SD is about half for the 1st Mode.



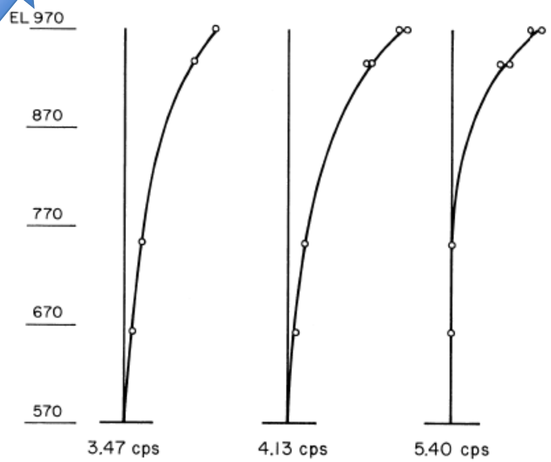


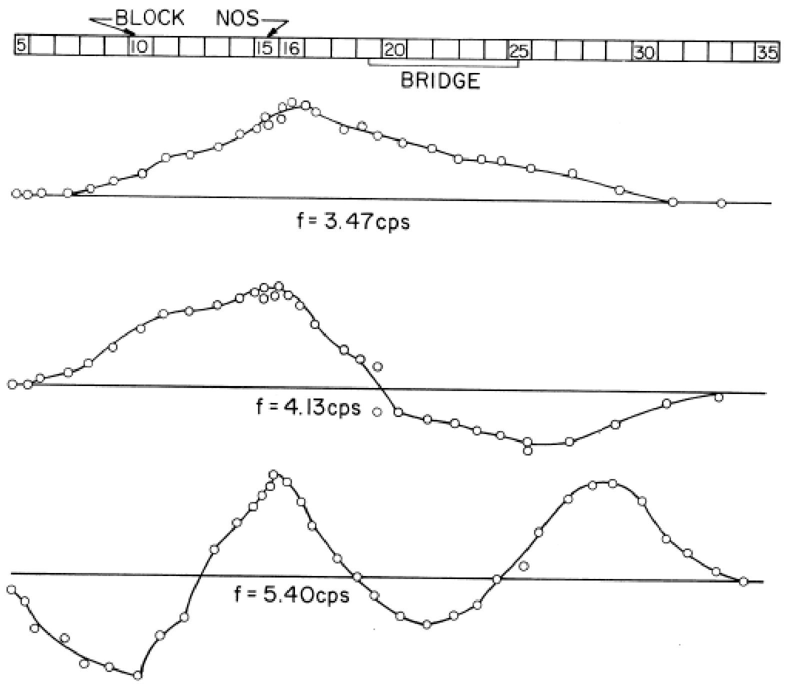
Case A1

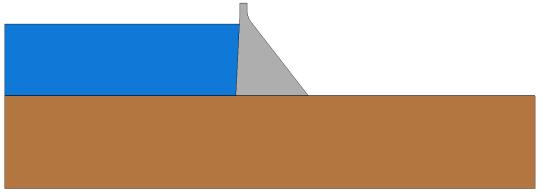
- Comparison of measured natural frequencies (Rea, Liaw & Chopra, 1972).
  - Global modes, of the whole dam. Difficult to assess these global modes based on obtained mode shapes from a 2D model

Analysis	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Median (Hz)	2.30	3.47	3.96	4.40	4.89	5.46
Exp.[1]	-	3.47	4.13	-	-	5.40

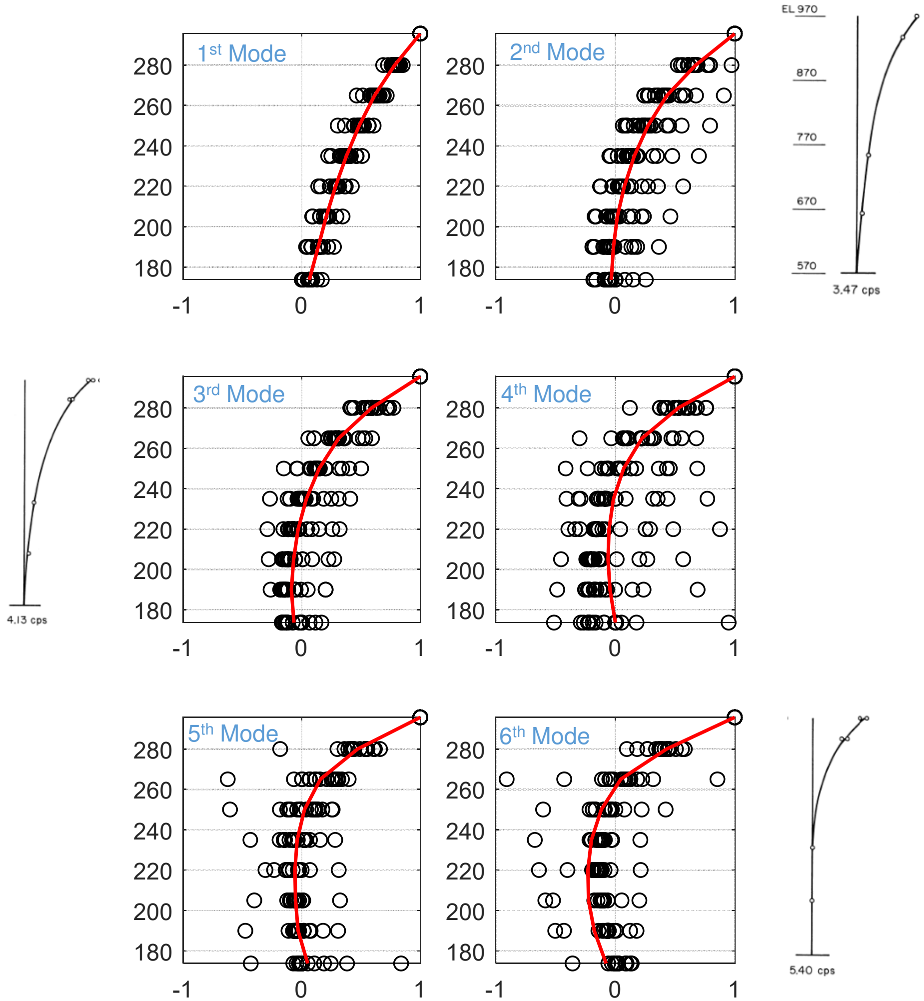
The median obtained natural frequency is identical to the fundamental mode from the EMVG test



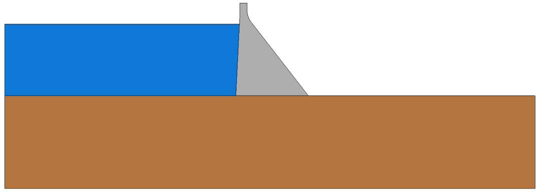




Case A1



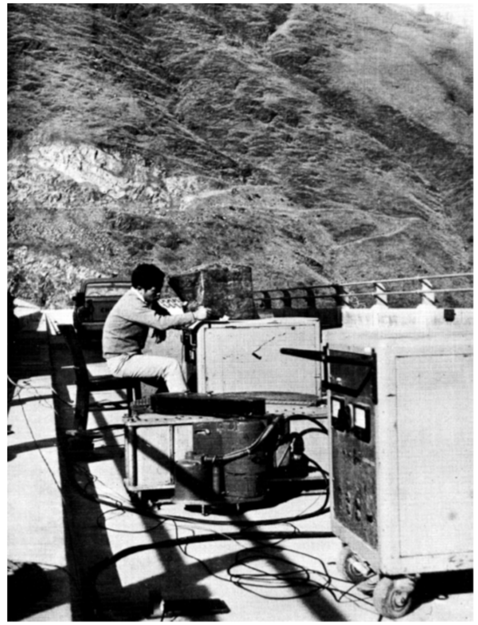
- Mode shapes
  - All normalized to have a displacement of one at the crest
  - Most of the results are rather consistent.
  - Significant scatter in the latter mode shapes from a few contributors (primarily a result that different modes have been found)

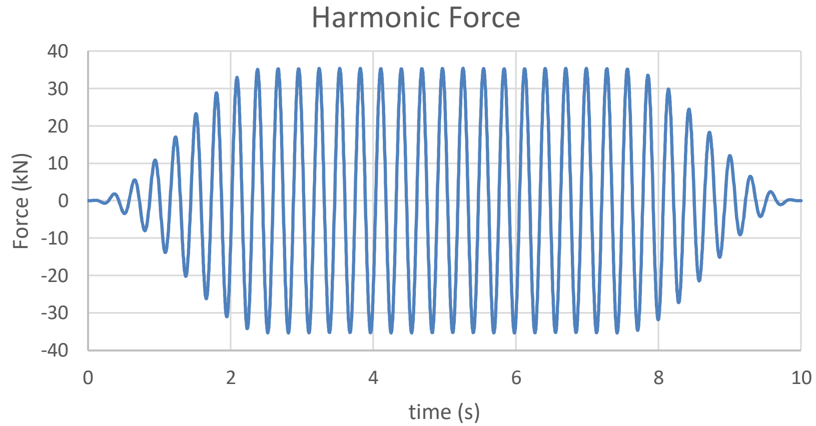


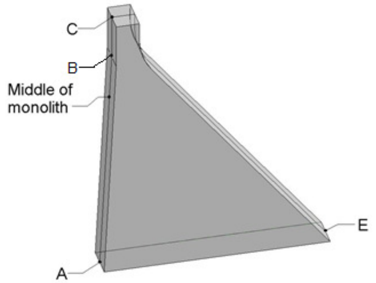
Case A3

- Excentric mass vibration generator (EMVG) test (Rea, Liaw & Chopra, 1972).

- Harmonic load with an amplitude of 35.4 kN and a frequency of 3.47 Hz, performed to simulate the EMVG test at the first mode in the experiments (i.e. second mode in the analyses).

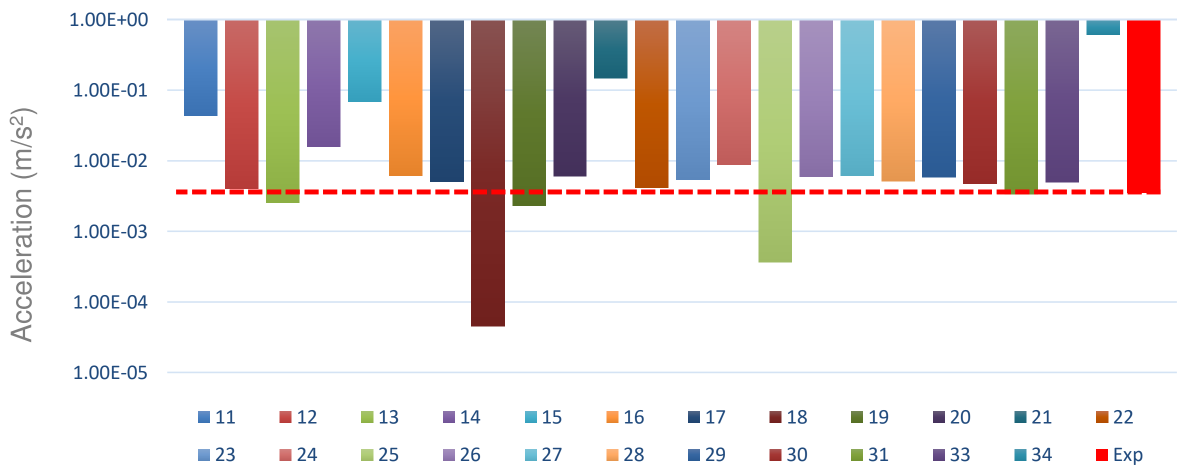


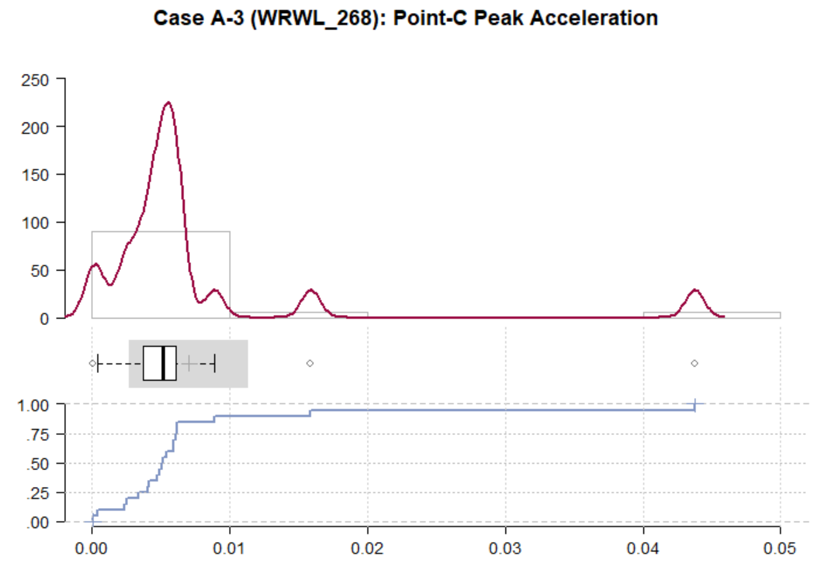




Case A3

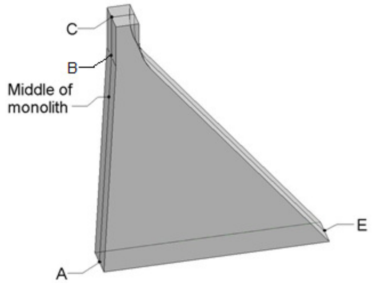
- Peak acceleration at the crest (point C)





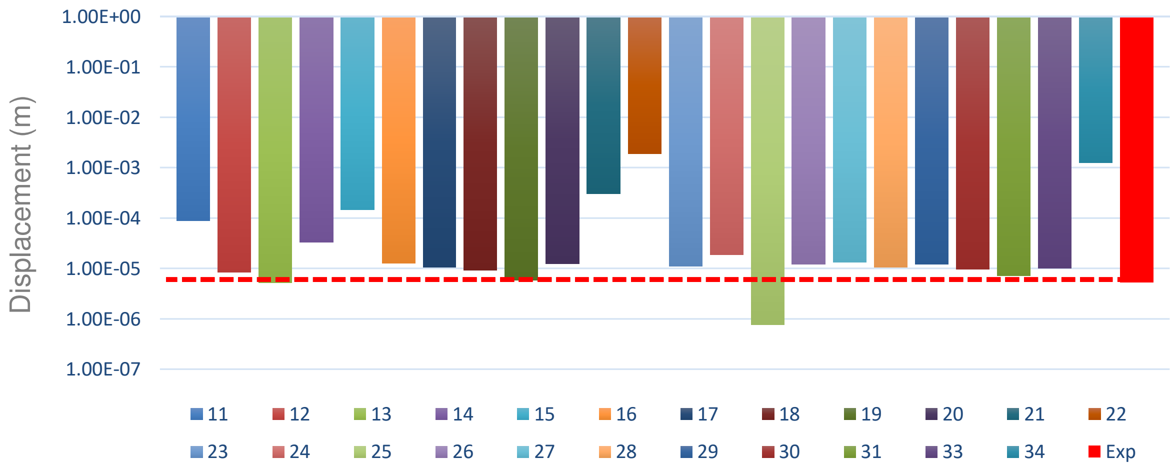
	Point C
Median Peak Acc. (m/s^2)	5.12×10^{-3}
Mean Peak Acc. (m/s^2)	7.05×10^{-3}
SD Peak Acc. (m/s^2)	9.24×10^{-3}

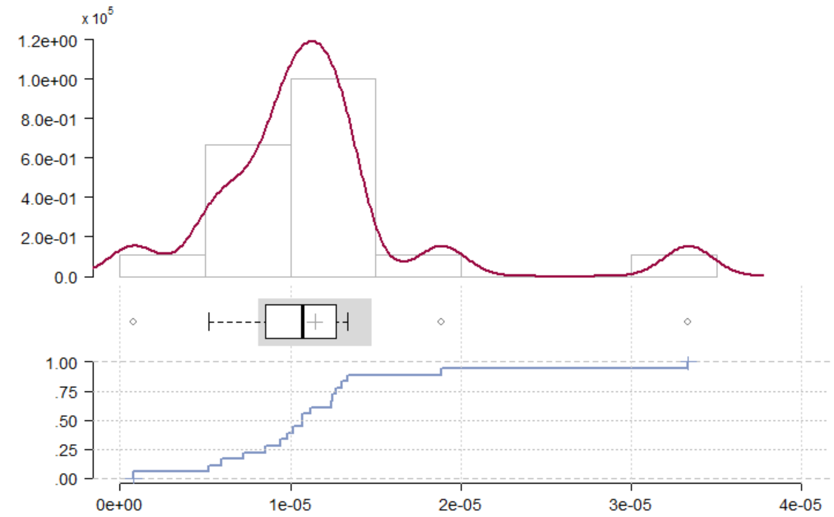
The peak acceleration during the EMVG test was about 3.5×10^{-3} m/s^2



Case A3

- Peak displacement at the crest (point C)



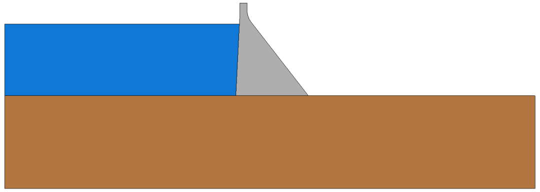


	Point C
Median Peak Disp. (m)	1.07×10^{-5}
Mean Peak Disp. (m)	1.14×10^{-5}
SD Peak Disp. (m)	6.70×10^{-6}

The peak displacement during the EMVG test was about 5.2 $\times 10^{-6}$ m

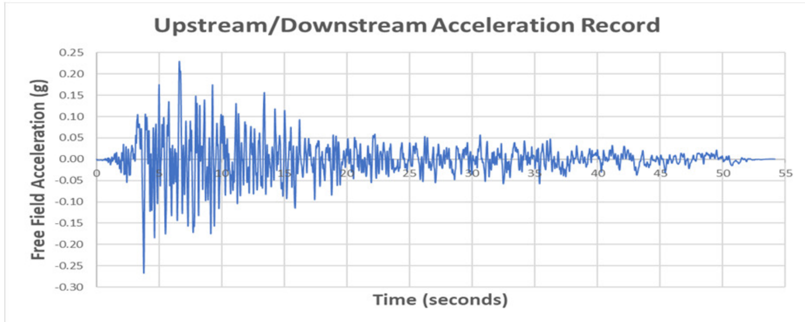
Summary Case A

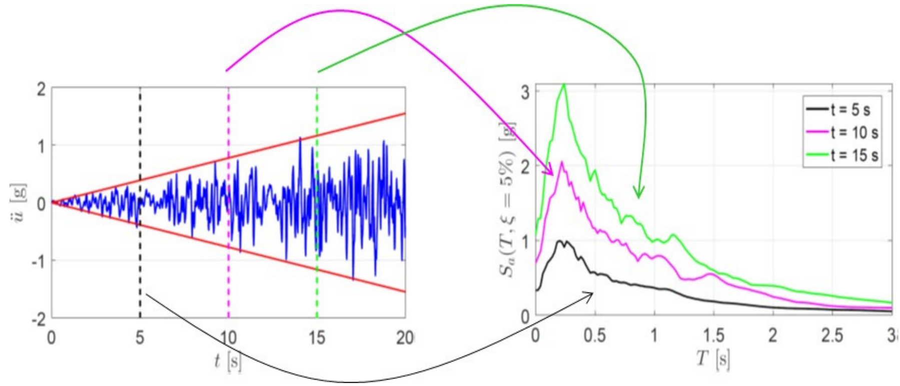
- Case A
  - Overall good agreement with obtained natural frequencies and mode shapes.
  - Most disregarded from non-reflecting boundaries during natural frequency extraction (to prevent artificial modes of the rock)
  - Some differences in the numbering of the modes
    - Difficult to assess which are the real structural modes
    - Difficult to interpret the real 3D modes based on 2D analyses
    - Massless frequency analyses can be an aid to identify structural modes
  - Fairly good agreement regarding peak acceleration during harmonic excitation, but not as good regarding peak displacement.



Case E

- Nonlinear dynamic analyses
  - Simulate the damage evolution (cracking) in the dam caused by
    - Real ground motion (Taft)*
    - Endurance Time Acceleration Function (ETAF)
  - Requested output;
    - Relative crest (C) displacement wrt heel (A)
    - Net Hydrodynamic pressure at heel (A)
    - Amplification of crest (C) acceleration wrt heel (A)
    - Damage extent (E-1: scalar; E-2: vector)
    - Damage index (DI): area and base length
    - Failure time in ETAF.

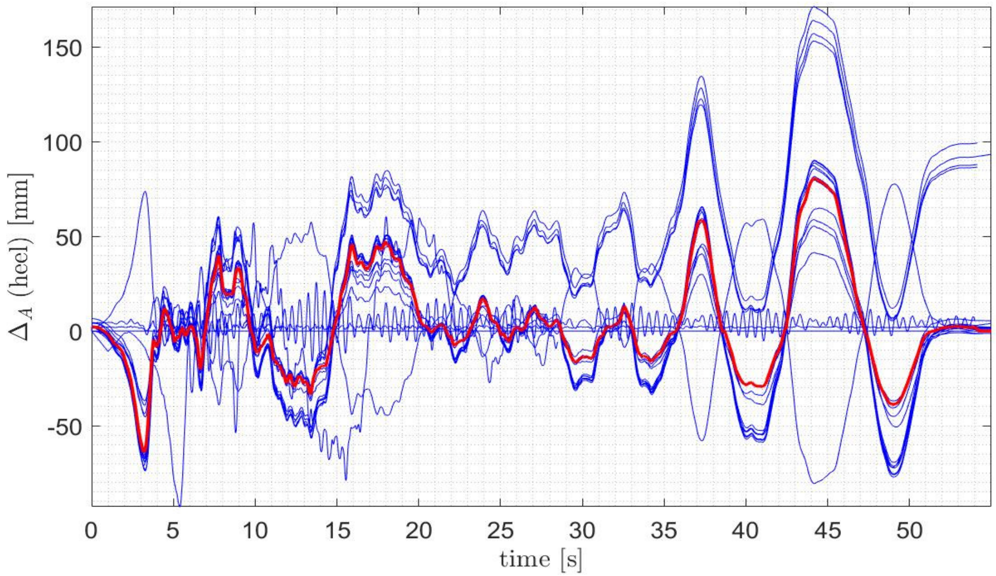


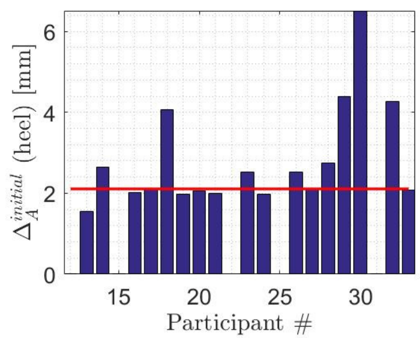


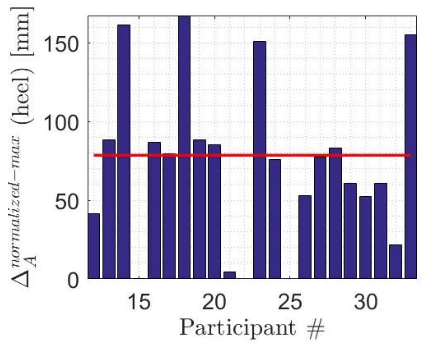
The TAFT earthquake was chosen since it is just at the border of introducing damage.

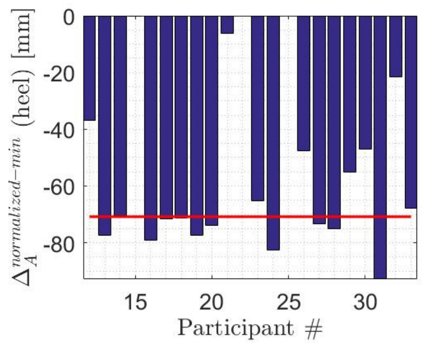
Case E1

- Variation of absolute displacement at the heel (A).
  - Red line is the median.
  - Many predicted well the peak values, but not time history.



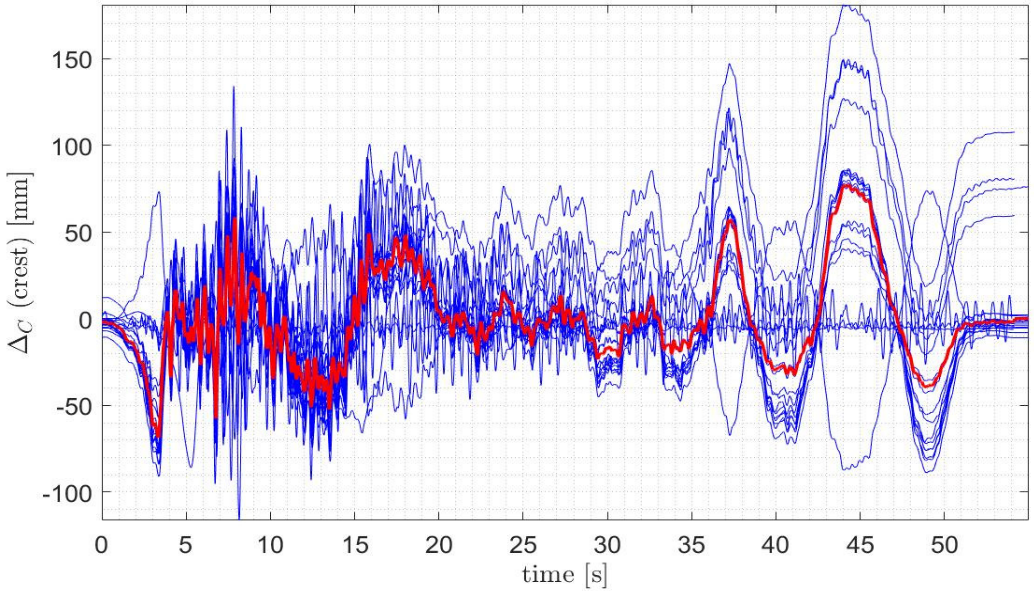


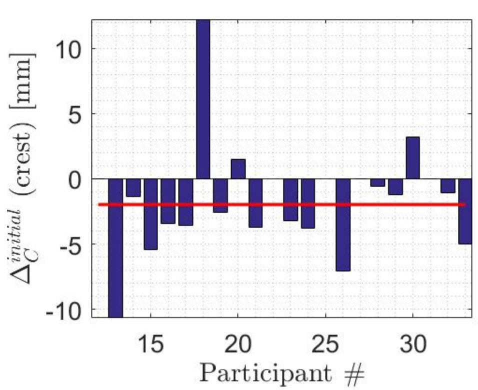


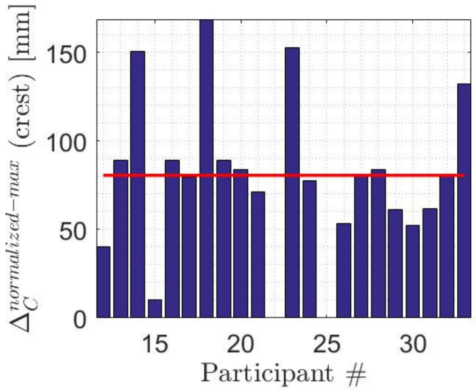


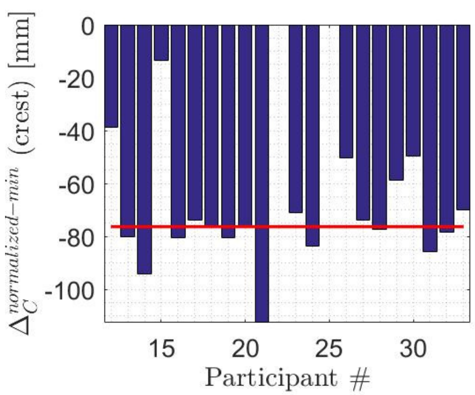
Case E1

- Variation of absolute displacement at the crest (C).
  - Red line is the median.
  - Initial displacement (non-seismic) also varies!



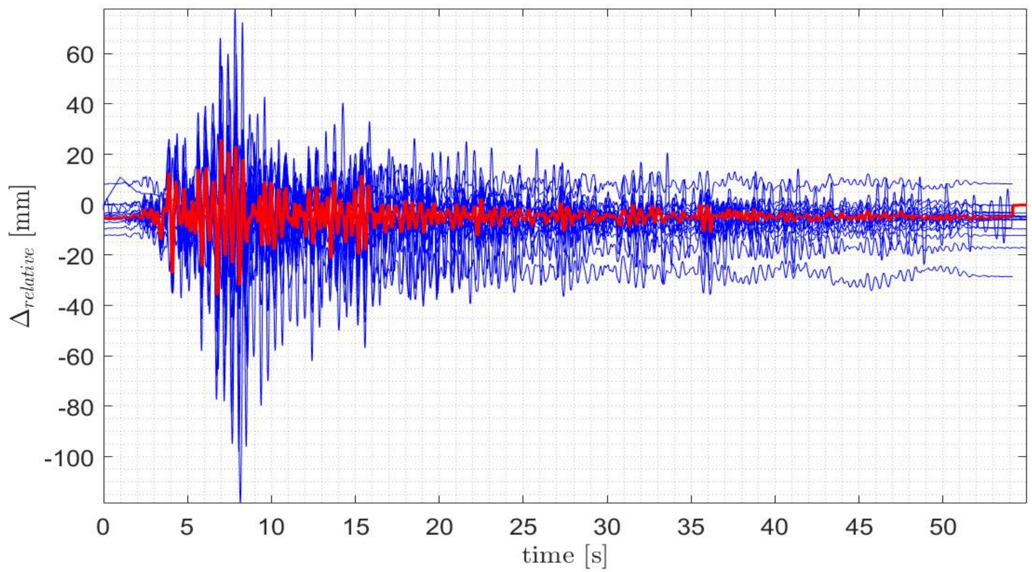


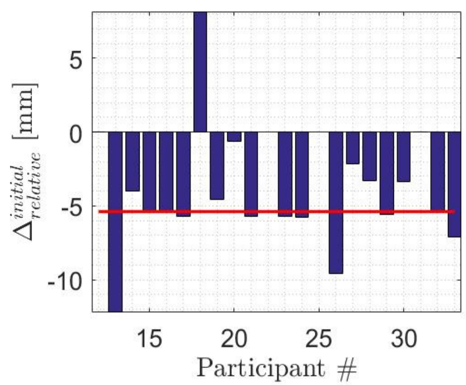


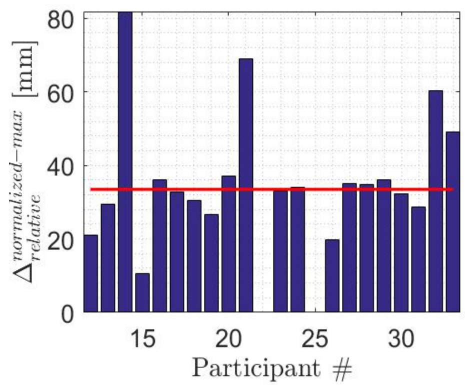


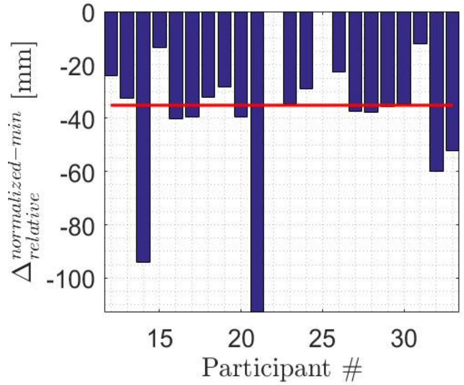
Case E1

- Variation of relative displacement at the crest (C wrt A).
  - Red line is the median.
  - In general, a good prediction.



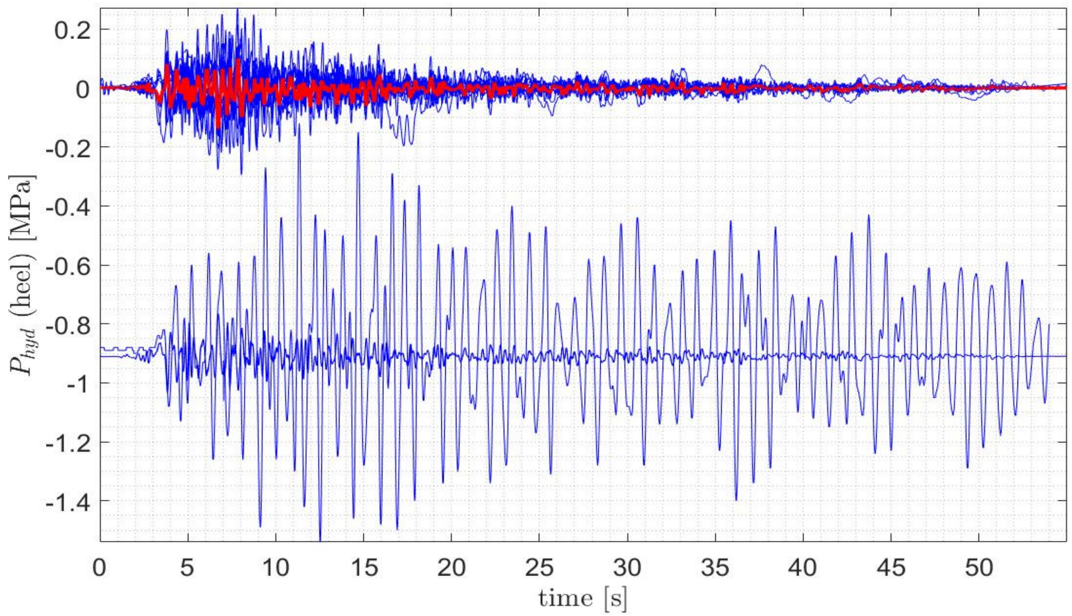


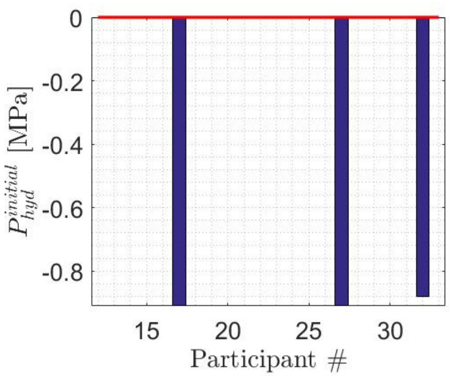


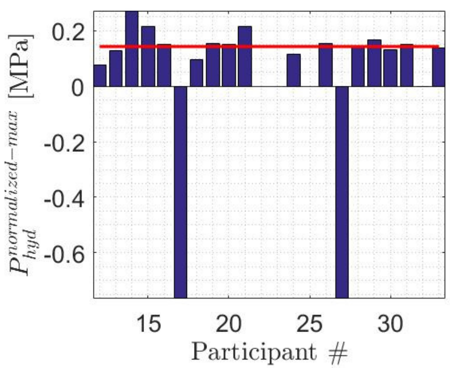


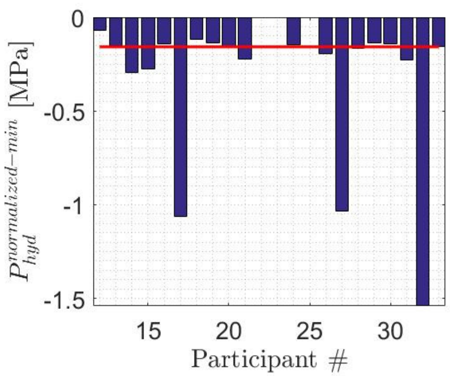
Case E1

- Variation of hydrodynamic pressure at the heel (A)
  - There are 3 outliers
  - Initial pressure is zero as it should be
  - Overall good prediction





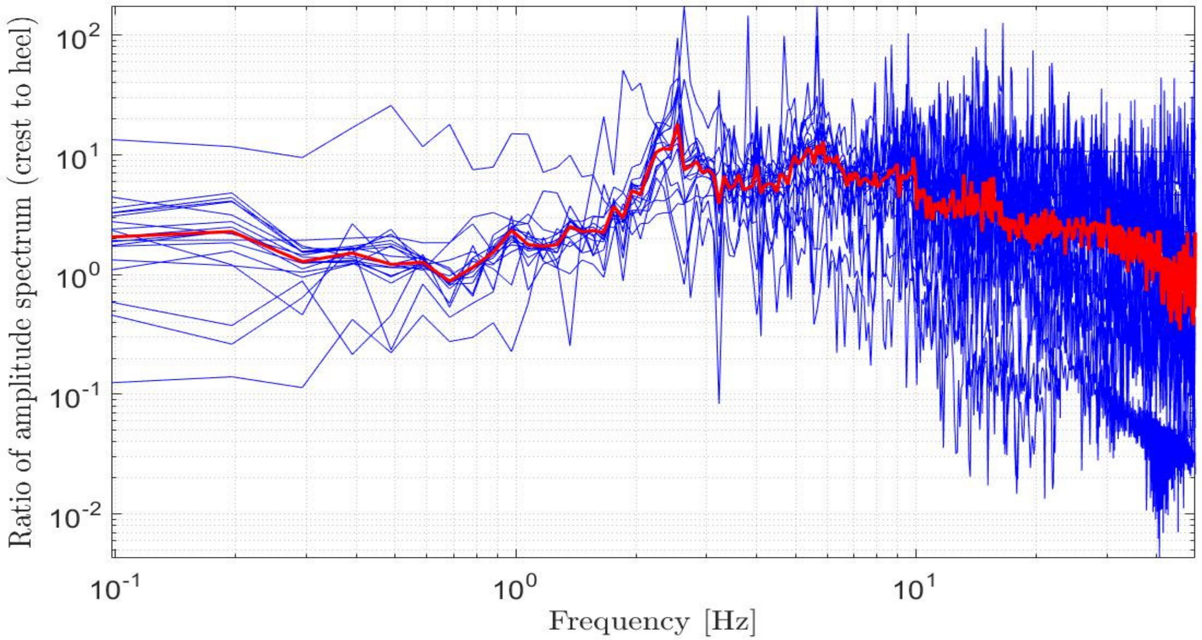




Case E1

- Variation of the acceleration response is presented as a ratio of amplitude spectrum of crest point wrt heel.

- Around the fundamental period of dam, the ratio is 10-20 times.

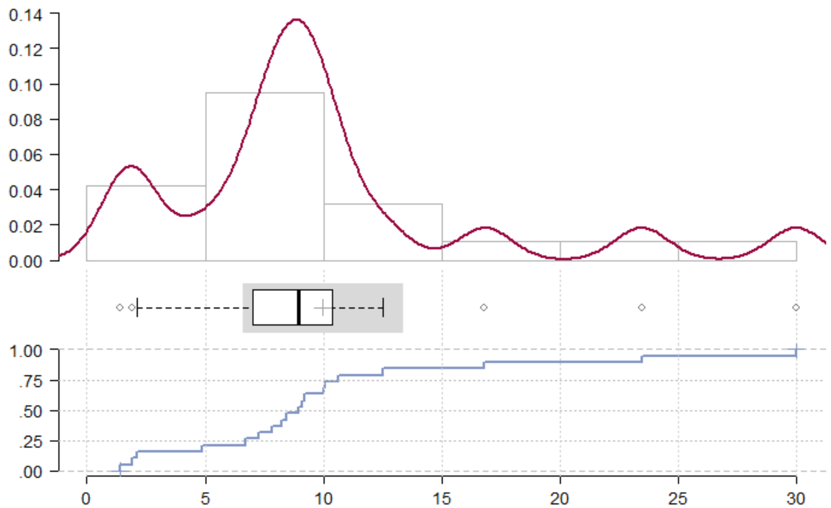


Case E1

- Peak acceleration at the crest (point C)

CASE E1 (non-linear)

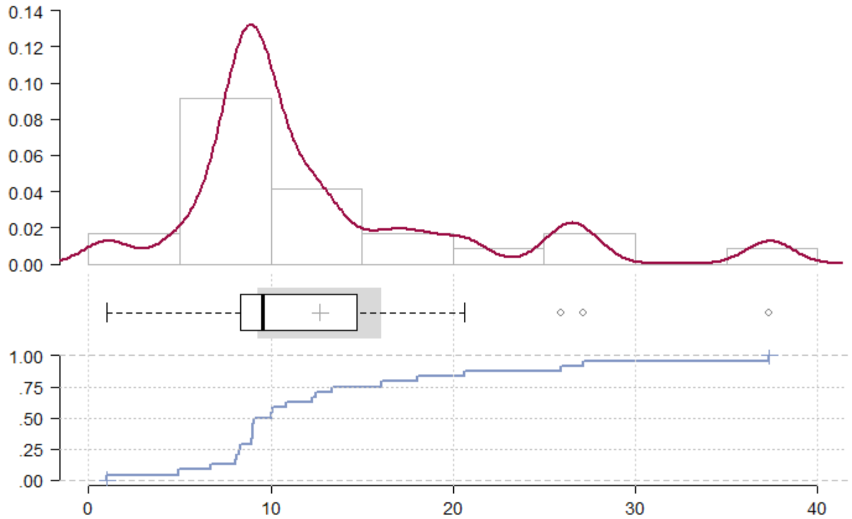
Case A-3 (Taft): Point-C Peak Acceleration



	Point A	Point C
Median Peak Acc. (m/s²)	1.65	8.93
Mean Peak Acc. (m/s²)	2.95	9.98
SD Peak Acc. (m/s²)	2.71	7.04

CASE D1 (linear)

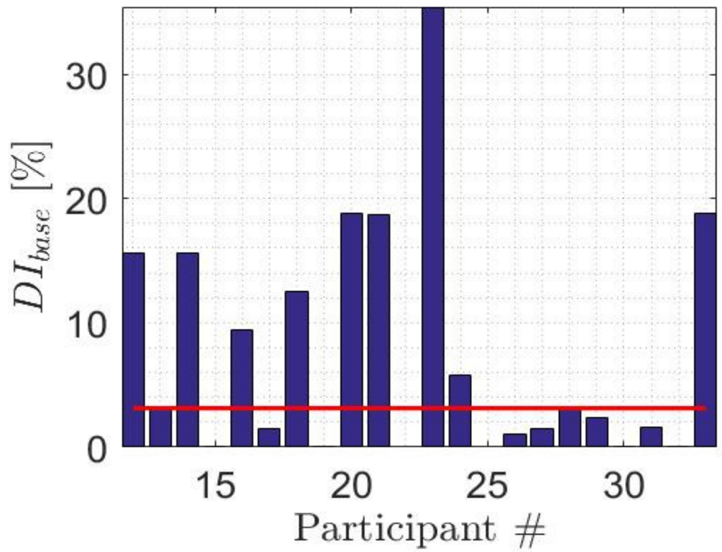
Case A-3 (wrwl_268): Point-C Peak Acceleration



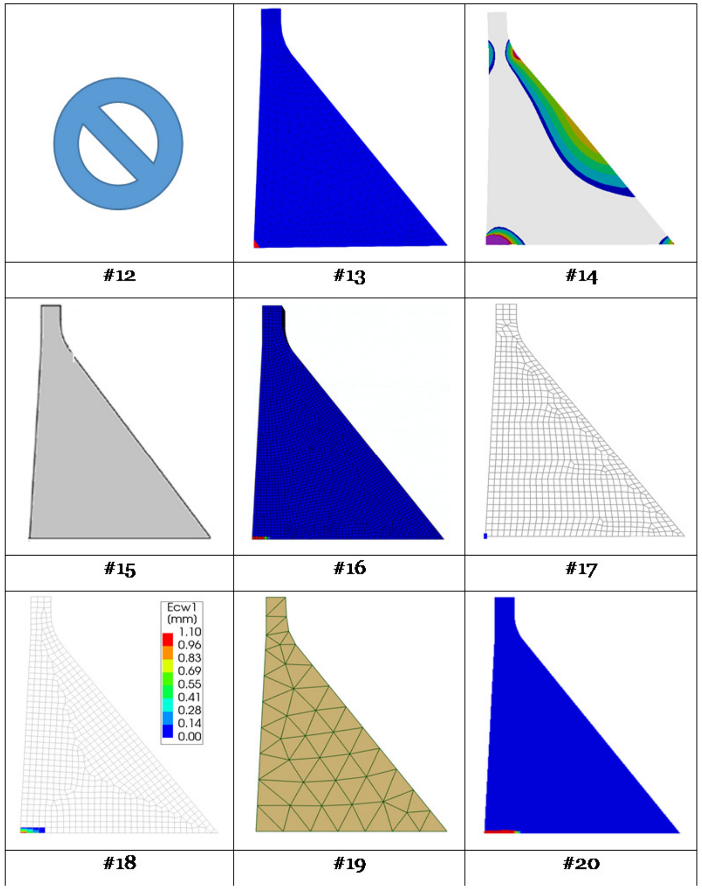
	Point A	Point C
Median Peak Acc. (m/s²)	1.46	9.55
Mean Peak Acc. (m/s²)	1.64	12.7
SD Peak Acc. (m/s²)	0.79	8.06

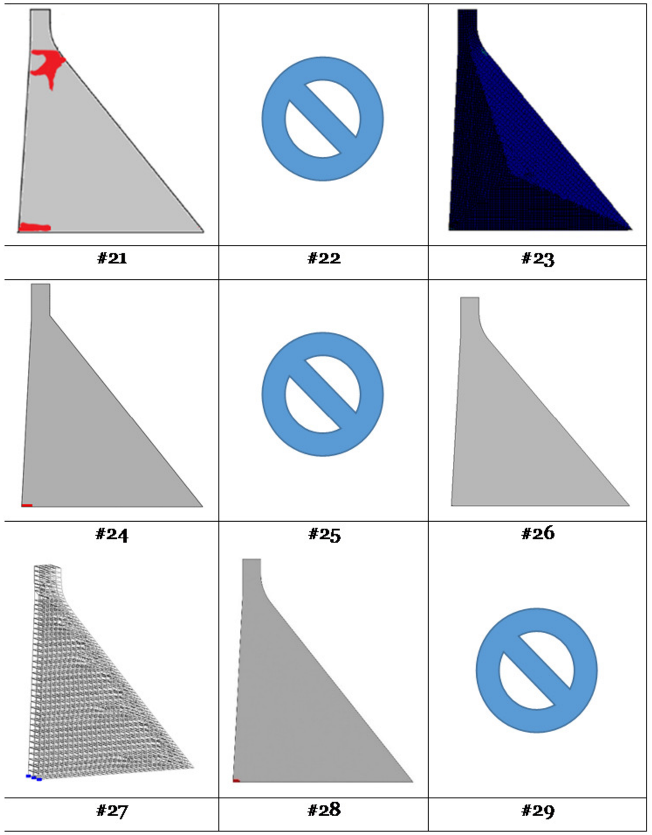
Case E1

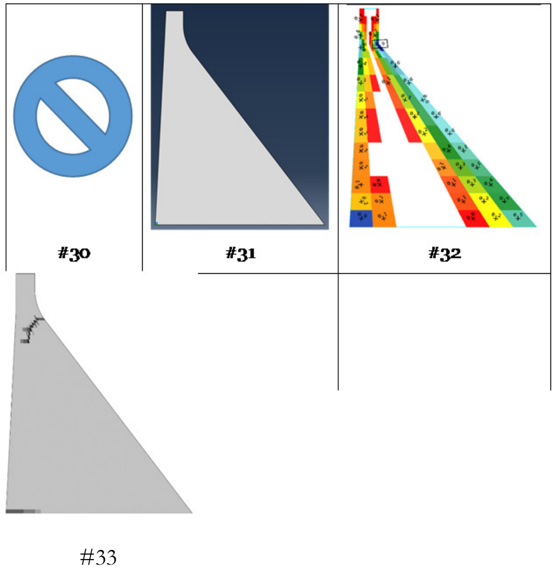
- Different nonlinear models have been used for concrete.
- Base damage varies from 0 (undamaged) to 35% of base length.
- Median damage index (DI) is 4%.
- DI based on base crack seems more reliable than ”area-based” criteria.
- DI is highly depends on cracking model, and mesh density.



Case E1







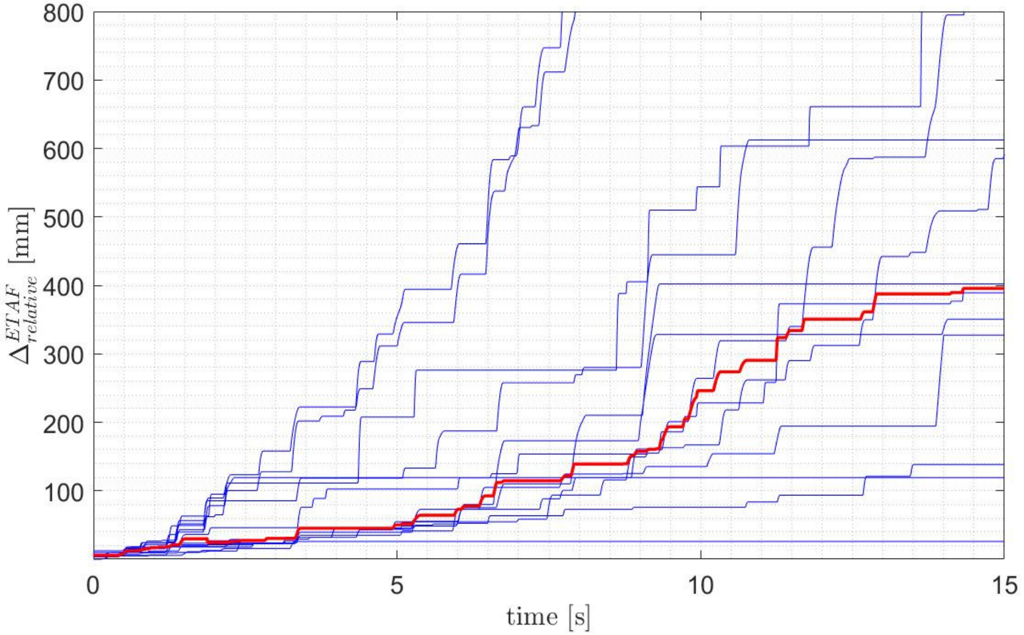
The predicted extent of damage depends on mesh size and material model used

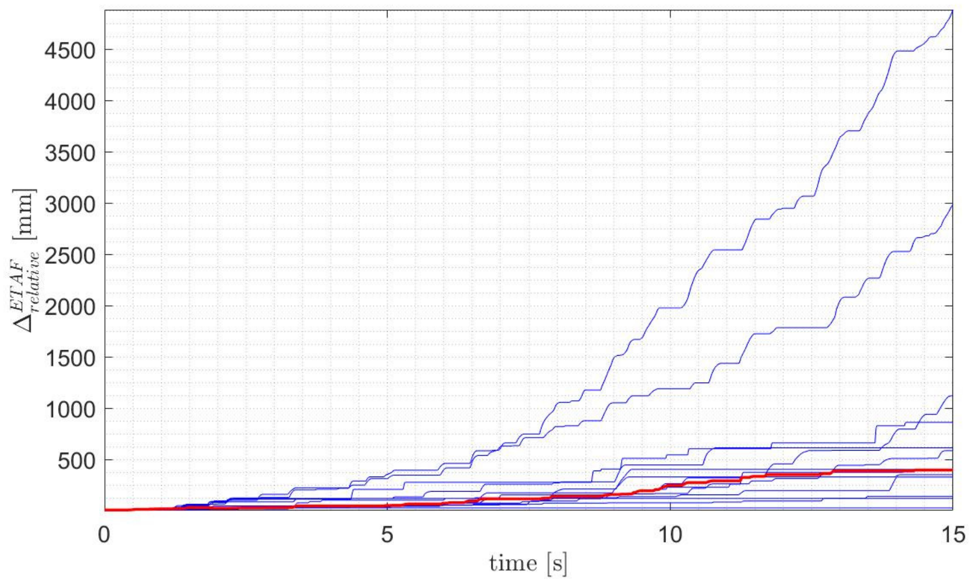
- Some meshes might be to coarse to capture the release of energy during cracking

4 predicted no damage
11 predicted minor damage at upstream heal
4 predicted damage also in upper part of the dam

Case E2

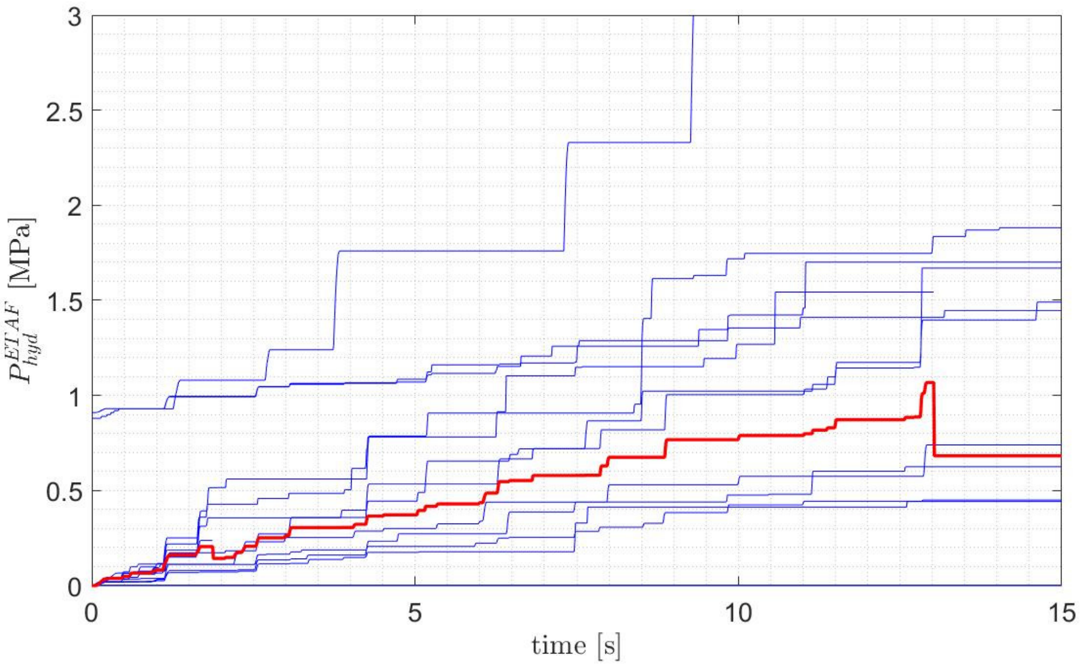
- Variation of increasing relative displacement.





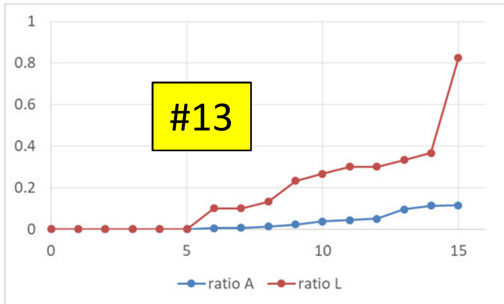
Case E2

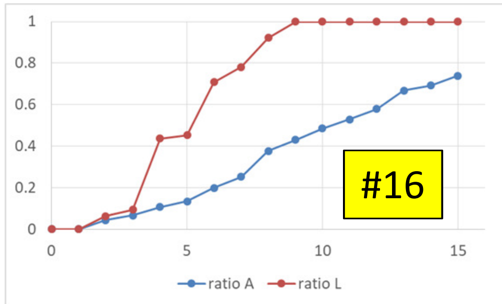
- Variation of hydrodynamic pressure.
  - Some outliers can be recognized.
  - There is a large dispersion among the participants.

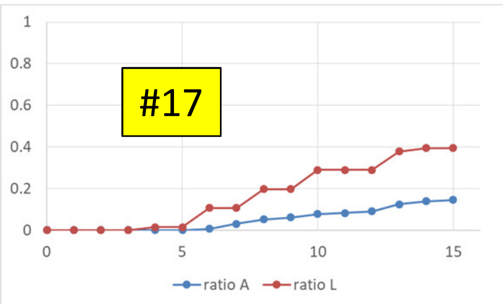


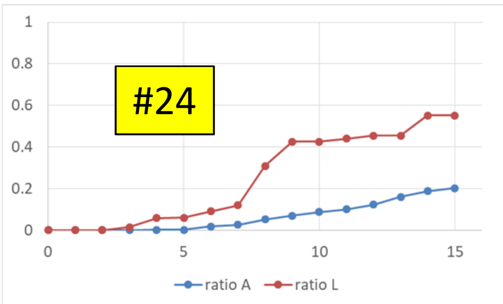
Case E2

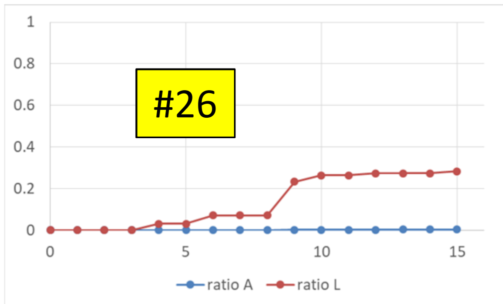
- There is a large uncertainty among the participants in the predicted DI.
  - Only few are shown here.
  - In all cases, the length-based criteria is higher than the area-based one.

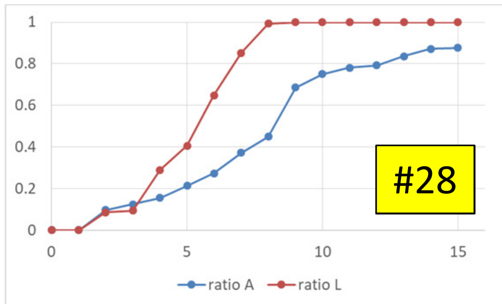








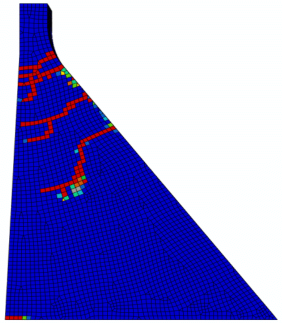




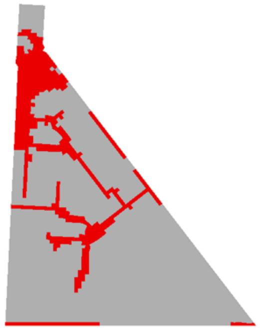
E2

- Example of damage pattern (at failure or end of ETAF)

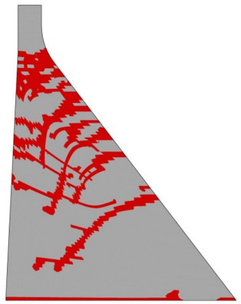
Failure prior to the full duration of ETAF:



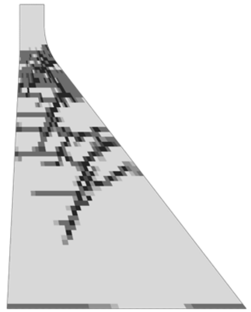
#16 (t = 3 s)



#24 (t = 14 s)

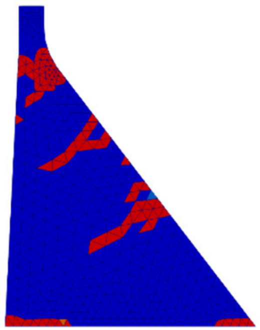


#28 (t = 8,5 s)

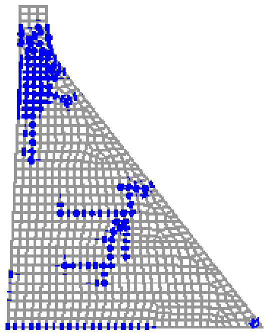


#33 (t = 6,5 s)

Damage after the full duration of ETAF:



#13 (t = 15 s)



#17 (t = 15 s)

#26 (t = 15 s)

Similar type of cracking, but significant difference in failure time

Summary Case E

- Case E1
  - Most of the participants showed no or minor cracking, and hence obtained results close to D1
  - Some differences already in static displacement
  - Overall, good predictions regarding relative displacement between crest and heal as well as the hydro-dynamic pressure.
    - Better estimation of the peak values than the time histories
- Case E2
  - Significant differences in estimation of the damage index (along the concrete/rock interface) and especially the damage index based on damaged areas.
  - Difficult to assess the ultimate capacity from the results
    - Variation in the duration of applied the ETAF analyses (failure time); may have ended due to convergence issues, at which point is the failure defined in the model?

Summary Case E

1. The choice of nonlinear model and solution technique highly affects the nonlinear analysis results,
2. Uncertainty in nonlinear analysis is more than linear cases,
3. For ETAF in which increases the nonlinear response of the system gradually, the uncertainty is time (or intensity) dependent, and increases with the duration,
4. Global response (like displacement) is less uncertainty than local one (like damage index). One may predict a (relatively) good nonlinear displacement while a poor damage prediction,
5. Finite element mesh size is highly affects the damage index, and
6. Still there is no clear definition of "damage" or "failure" concept in dam engineering.