ICOLD
INTERNATIONAL COMMISSION ON LARGE DAMS

ICOLD-BW 2019
9^{th}-11^{th} 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 Cases D and F

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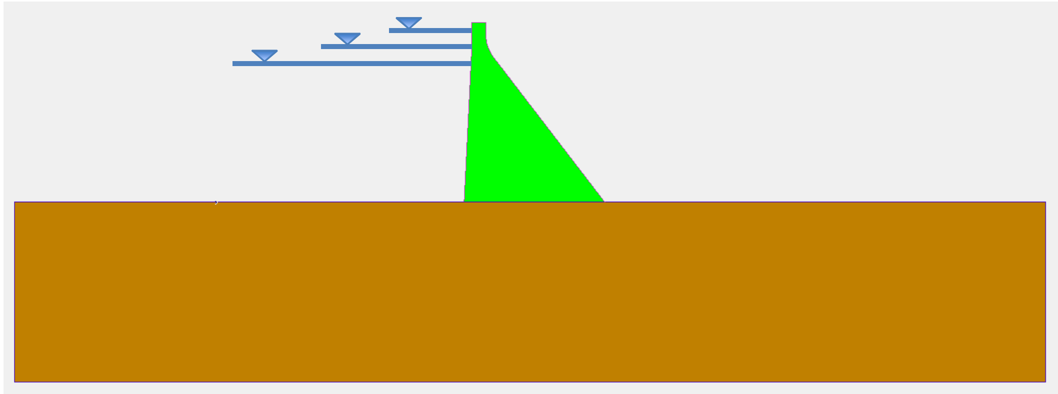
Case D and Case F: General info and requested results

Linear Dynamic Analysis for various reservoir levels

Case Studies

- **Case D**: foundation with mass & wave propagation approach
- **Case F**: massless approach



Required analyses

D-1	F-1	Winter Reservoir Water Level: WRWL	268.21 m a.s.l.
D-2	F-2	Summer Reservoir Water Level: SRWL	278.57 m a.s.l.
D-3	F-3	Normal Reservoir Water Level: NRWL	290.00 m a.s.l.

Input

- Geometry
- Material properties
- Static loads
- Seismic input (Taft)

Given in formulation

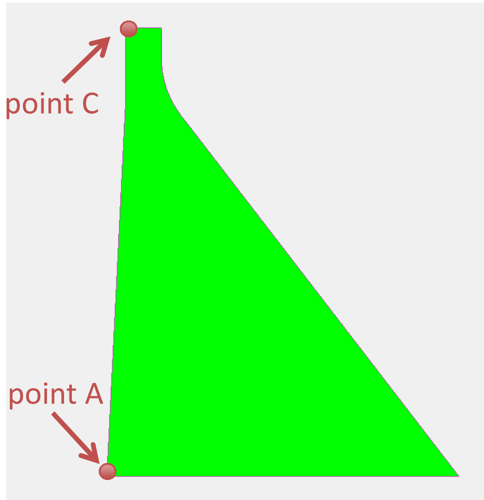
- FEM mesh
- FSI & SSI approach
- Boundary conditions

Chosen by contributors

Output

- Hydrodynamic pressure TH at dam heel (point A)
- Total displacement TH at dam heel (point A) & crest (point C)
- Acceleration TH at dam heel (point A) & crest (point C)

Only results for WRWL are here compared



Case D and Case F: Contributors choices

Contributor	FEM code	Integration scheme	Element size	Fluid-Structure Interaction	Fluid Type	Non-Reflecting BC	Free Field BC	Case D	Case F
11	Real ESSI	Implicit/ explicit(FSI)	2 m	Acoustic-structural coupling	compressible	Domain reduction method to input motions with absorbing damping layers	No*	Y	
12	Diana	implicit	2.5-5 m	Acoustic-structural coupling	incompressible	lateral sides: 50m thick PML bottom: Free field BC	Only on the bottom*	Y	
13	Code_aster	implicit	10 m	Acoustic-structural coupling	compressible	Viscous-spring artificial boundaries	Yes	Y	
14	ANSYS	implicit	6 m	Acoustic-structural coupling	compressible	Infinite radiation boundaries	No	Y	Y
15	SAP2000	explicit	1 m	Links-gap	incompressible	Simple supports bottom: H & V restrictions lateral sides: V restriction	No	Y	
16	ABAQUS	implicit	3-6 m	Acoustic-structural coupling	compressible	Viscous-spring artificial boundaries	Yes	Y	Y
17	Parmac2D	explicit	3-5 m	Interface elements with only normal stiffness	compressible	Viscous boundaries (Lysmer and Kuhlemeyer)	Yes	Y	

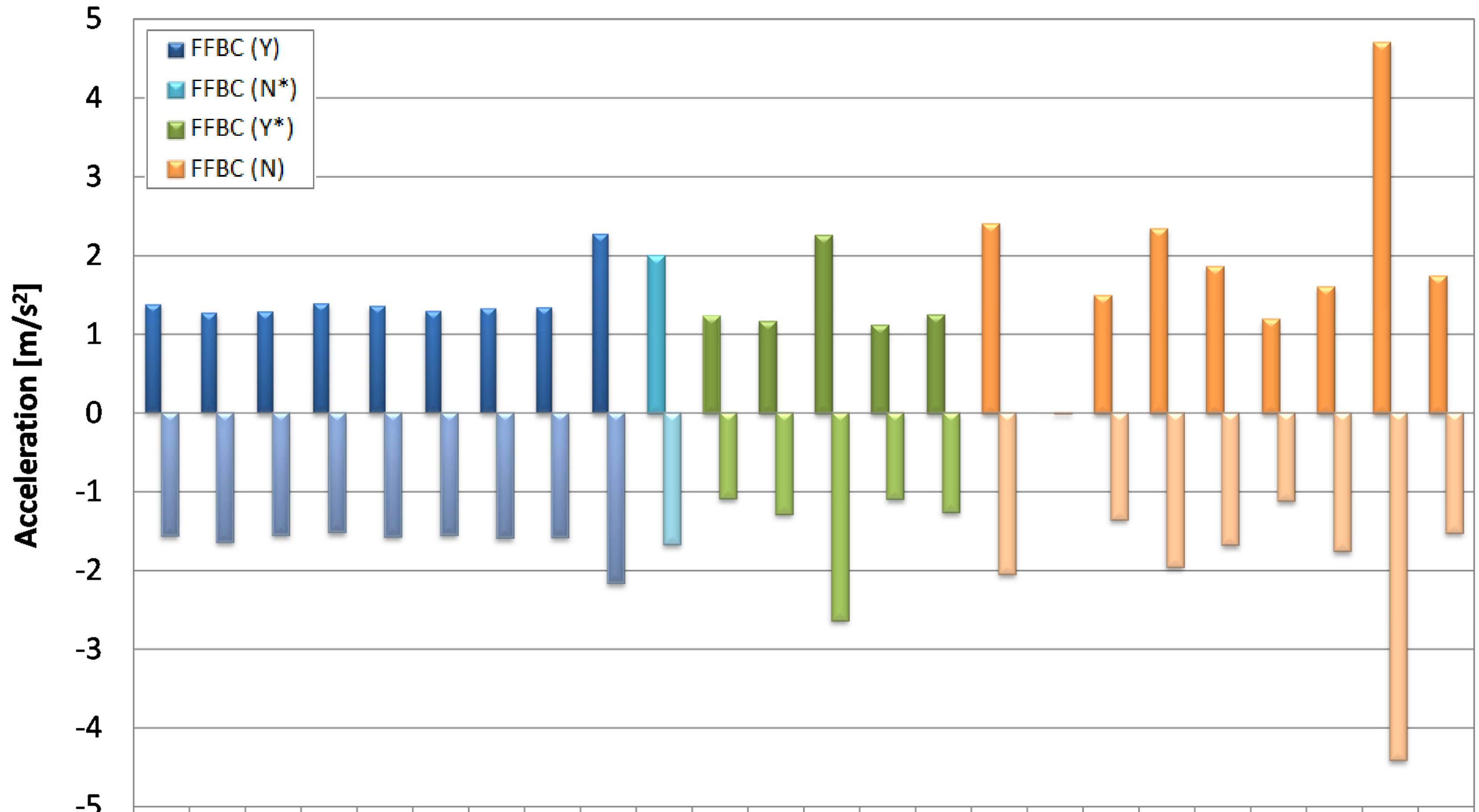
Case D and Case F: Contributors choices

Contributor	FEM code	Integration scheme	Element size	Fluid-Structure Interaction	Fluid Type	Non-Reflecting BC	Free Field BC	Case D	Case F
18	Diana	implicit	3-30 m	Acoustic-structural coupling	compressible	Interface element with low stiffness and damping coefficient	No	Y	Y
19	Code_aster	implicit	15 m	Acoustic-structural coupling	compressible	Paraxial anechoic elements	Yes	Y	Y
20	ABAQUS	implicit	1.48 m	Acoustic-structural coupling	compressible	Viscous boundaries	Yes*	Y	
21	Code_aster	implicit	1-37.5 m	Acoustic-structural coupling	compressible	Absorbing BC (for fluid elements only)	No	Y	Y
22	Diana	implicit	2 m	Acoustic-structural coupling	incompressible	Viscous boundaries (variation of Lysmer and Kuhlemeyer)	Yes*	Y	Y
23	ANSYS	implicit	0.5-4 m	Acoustic-structural coupling	compressible	Viscous-spring artificial boundaries	No	Y	Y
24	FLAC-3D	explicit	7.2 m	Mixed discretization scheme	compressible	Viscous boundaries (Lysmer and Kuhlemeyer)	Yes	Y	Y
25	Diana	implicit	2.5-4 m	Fluid like structural elements	incompressible	Interface element (Lysmer and Kuhlemeyer)	Yes*	Y	

Case D and Case F: Contributors choices

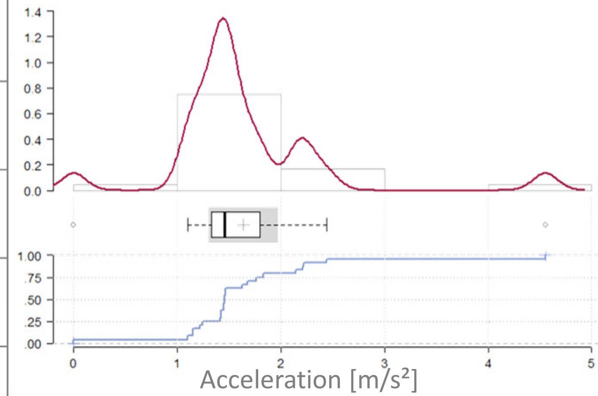
Contributor	FEM code	Integration scheme	Element size	Fluid-Structure Interaction	Fluid Type	Non-Reflecting BC	Free Field BC	Case D	Case F
26	ABAQUS	implicit	1 m	Acoustic-structural coupling	compressible	Infinite acoustic elements (Lysmer and Kuhlemeyer)	Yes*	Y	Y
27	Parmac2D	explicit	3-5 m	Interface elements with only normal stiffness	compressible	Viscous boundaries (Lysmer and Kuhlemeyer)	Yes	Y	
28	ABAQUS	implicit	1.5 m	Acoustic-structural coupling	compressible	Viscous boundaries (Lysmer and Kuhlemeyer)	Yes	Y	Y
29	ANSYS	implicit	2.5 m	Acoustic-structural coupling	compressible	Viscous-spring artificial boundaries	No	Y	Y
30	ABAQUS	implicit	3.5 m	Acoustic-structural coupling	compressible	Infinite elements	Yes	Y	
31	ABAQUS	implicit	1.5 m	Acoustic-structural coupling	compressible	Viscoelastic artificial boundary	No	Y	Y
32	SOFiSTiK	implicit	10 m	Fluid like structural elements	incompressible	Damper elements	No	Y	Y
33	ABAQUS	implicit	6 m	Acoustic-structural coupling	compressible	Infinite elements	No	Y	
34	ADINA	implicit	1 m	Fluid like structural elements	incompressible	Viscoelastic artificial boundary	Yes	Y	

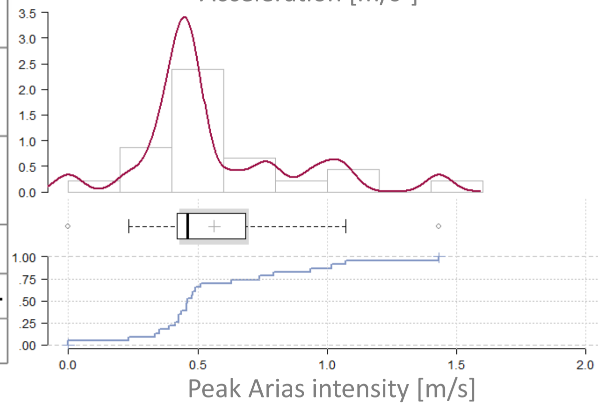
Case D-1: Acceleration at point A. Comparison among peak values



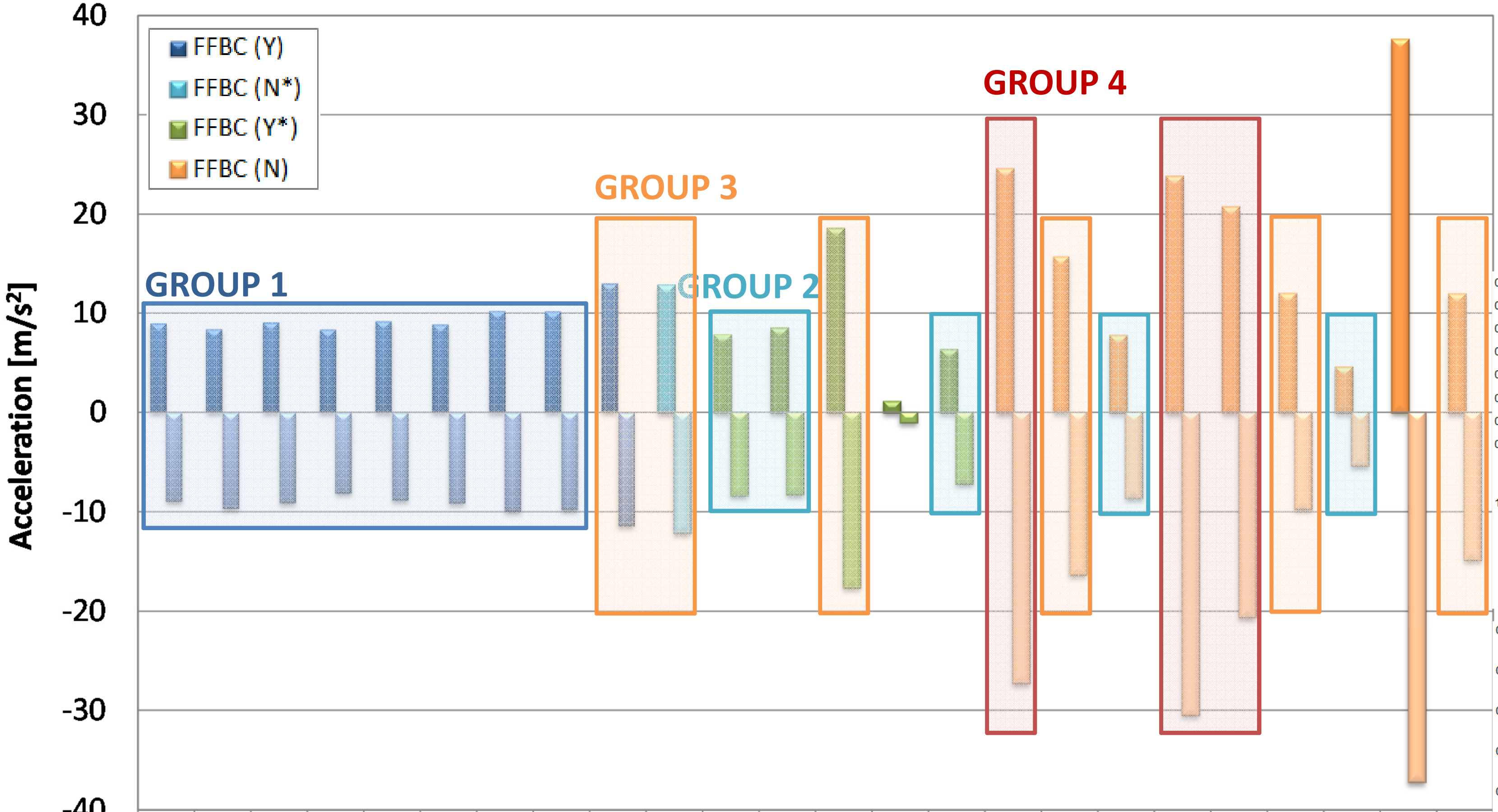
contributor	13	16	17	19	24	27	28	30	34	11	12	20	22	25	26	14	15	18	21	23	29	31	32	33
max	1.38	1.27	1.29	1.4	1.36	1.3	1.34	1.35	2.28	2	1.23	1.16	2.25	1.11	1.24	2.4	0	1.49	2.34	1.86	1.19	1.6	4.7	1.74
min	-1.6	-1.6	-1.5	-1.5	-1.6	-1.5	-1.6	-1.6	-2.2	-1.7	-1.1	-1.3	-2.6	-1.1	-1.3	-2	-0	-1.3	-1.9	-1.7	-1.1	-1.7	-4.4	-1.5

Point A		
Median Peak Acc. (av.)	[m/s²]	1.46
Mean Peak Acc. (av.)	[m/s²]	1.64
SD Peak Acc. (av.)	[m/s²]	0.79
Median Peak AI	[m/s]	0.46
Mean Peak AI	[m/s]	0.56
SD Peak AI	[m/s]	0.31



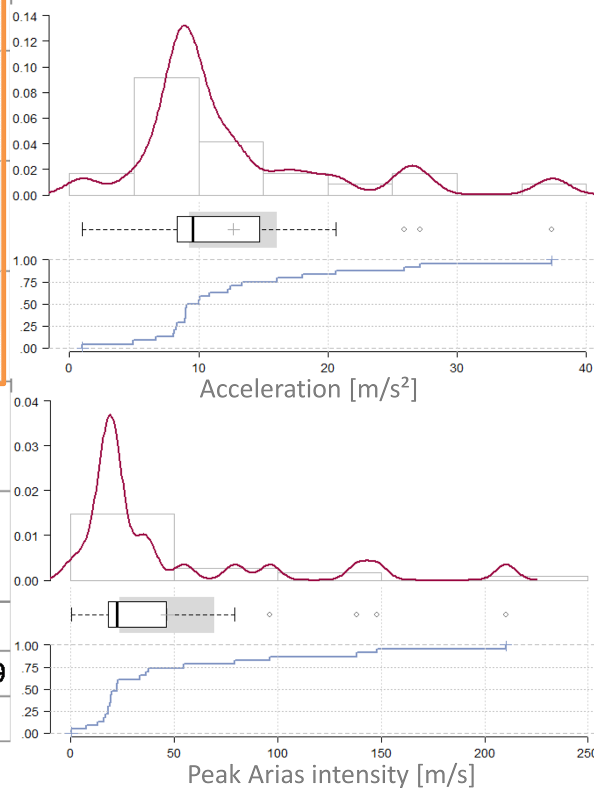


Case D-1: Acceleration at point C. Comparison among peak values

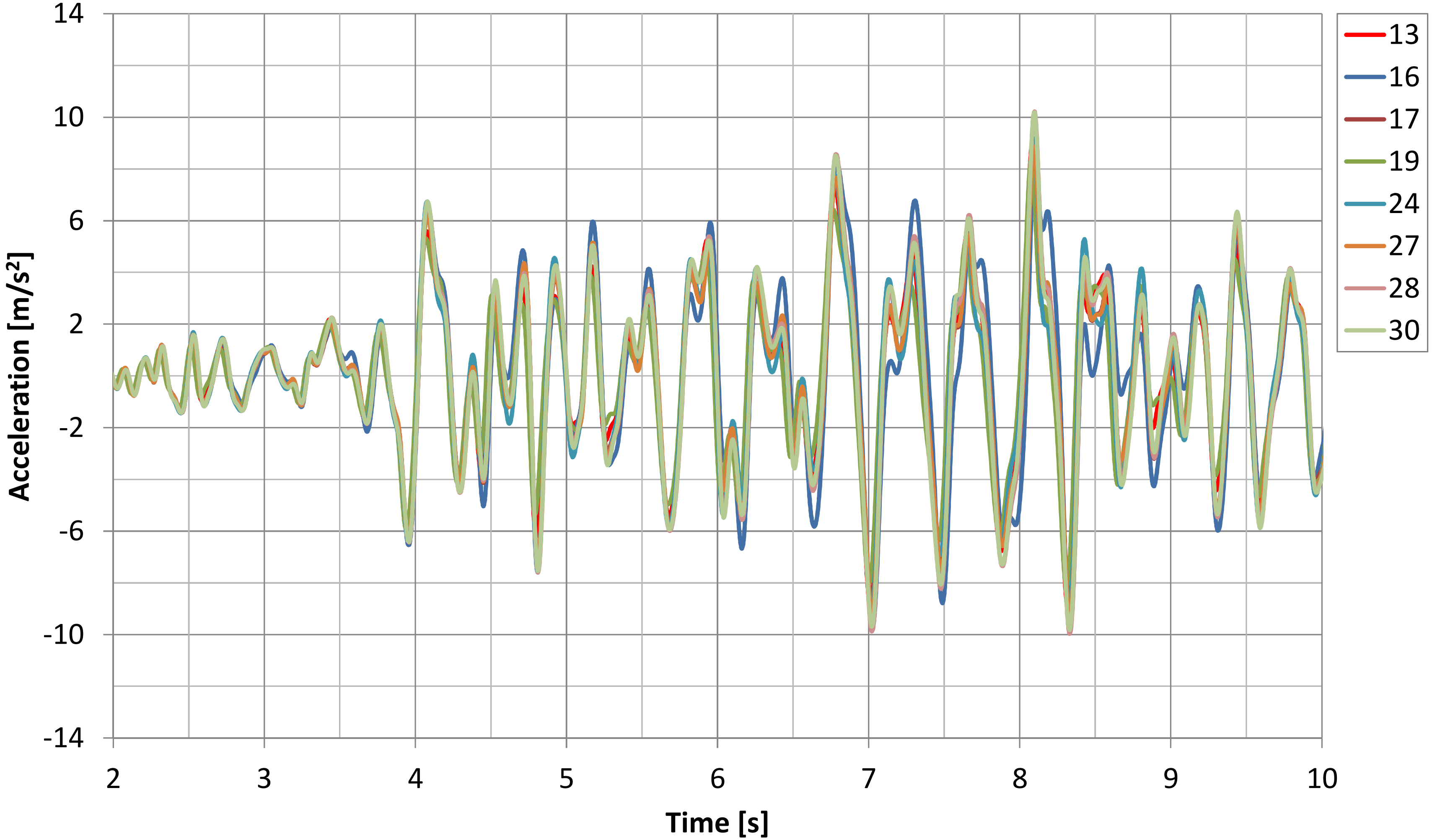


contributor	13	16	17	19	24	27	28	30	34	11	12	20	22	25	26	14	15	18	21	23	29	31	32	33
max	8.96	8.38	9.05	8.34	9.19	8.85	10.2	10.2	13	12.8	7.77	8.45	18.5	1.05	6.28	24.5	15.7	7.7	23.8	20.7	12	4.53	37.6	11.9
min	-9	-9.7	-9.1	-8.1	-8.9	-9.2	-10	-9.8	-11	-12	-8.4	-8.3	-18	-1	-7.2	-27	-16	-8.6	-30	-21	-9.7	-5.4	-37	-15

Point C		
Median Peak Acc. (av.)	[m/s²]	9.55
Mean Peak Acc. (av.)	[m/s²]	12.7
SD Peak Acc. (av.)	[m/s²]	8.06
Median Peak AI	[m/s]	22.2
Mean Peak AI	[m/s]	46.5
SD Peak AI	[m/s]	53.3



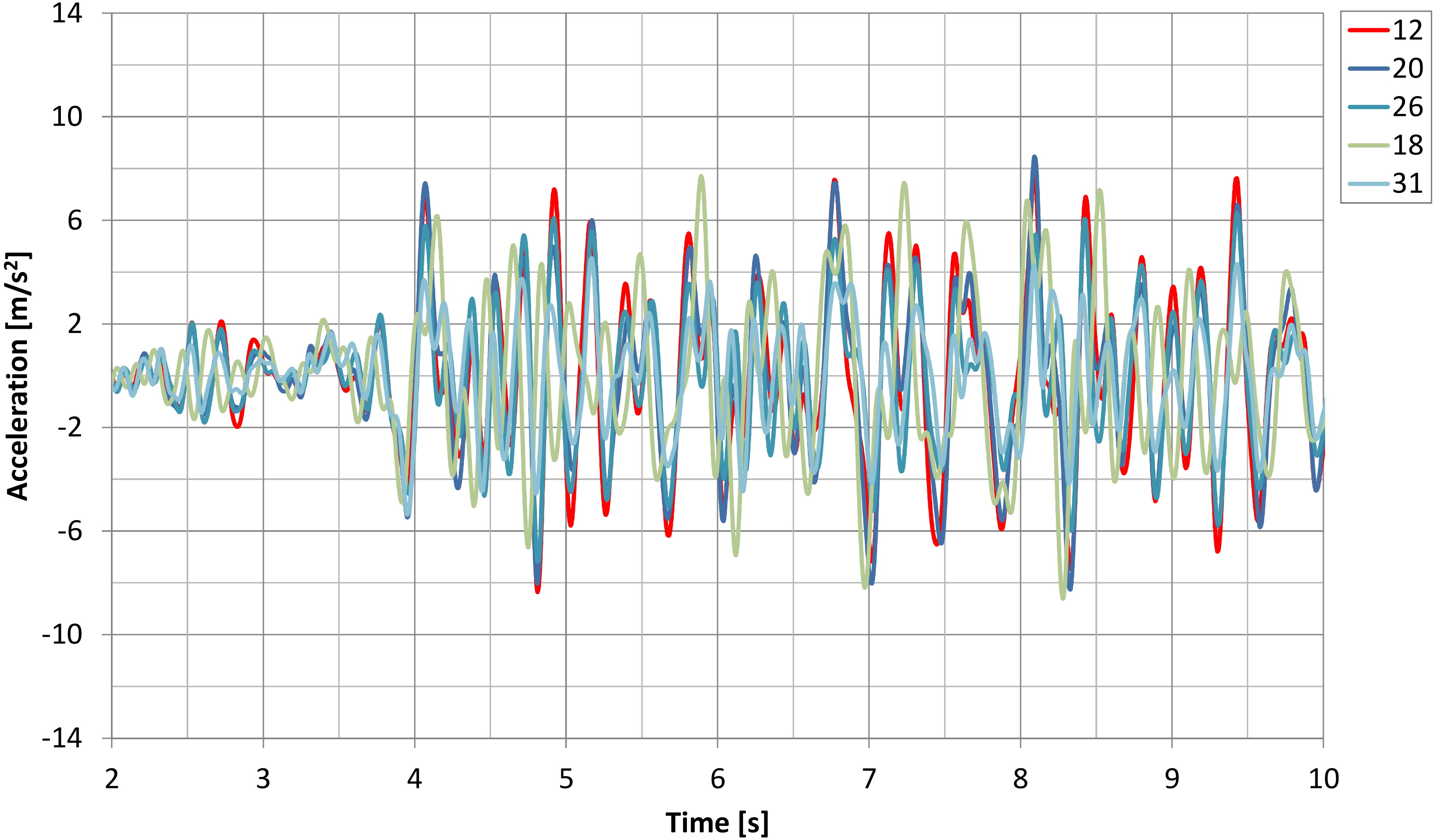
Case D-1: Time history of Acceleration at point C (group 1)



GROUP 1
Contributors with FFBC & similar peak values

- ✓ Very good agreement also in the trend of acceleration.

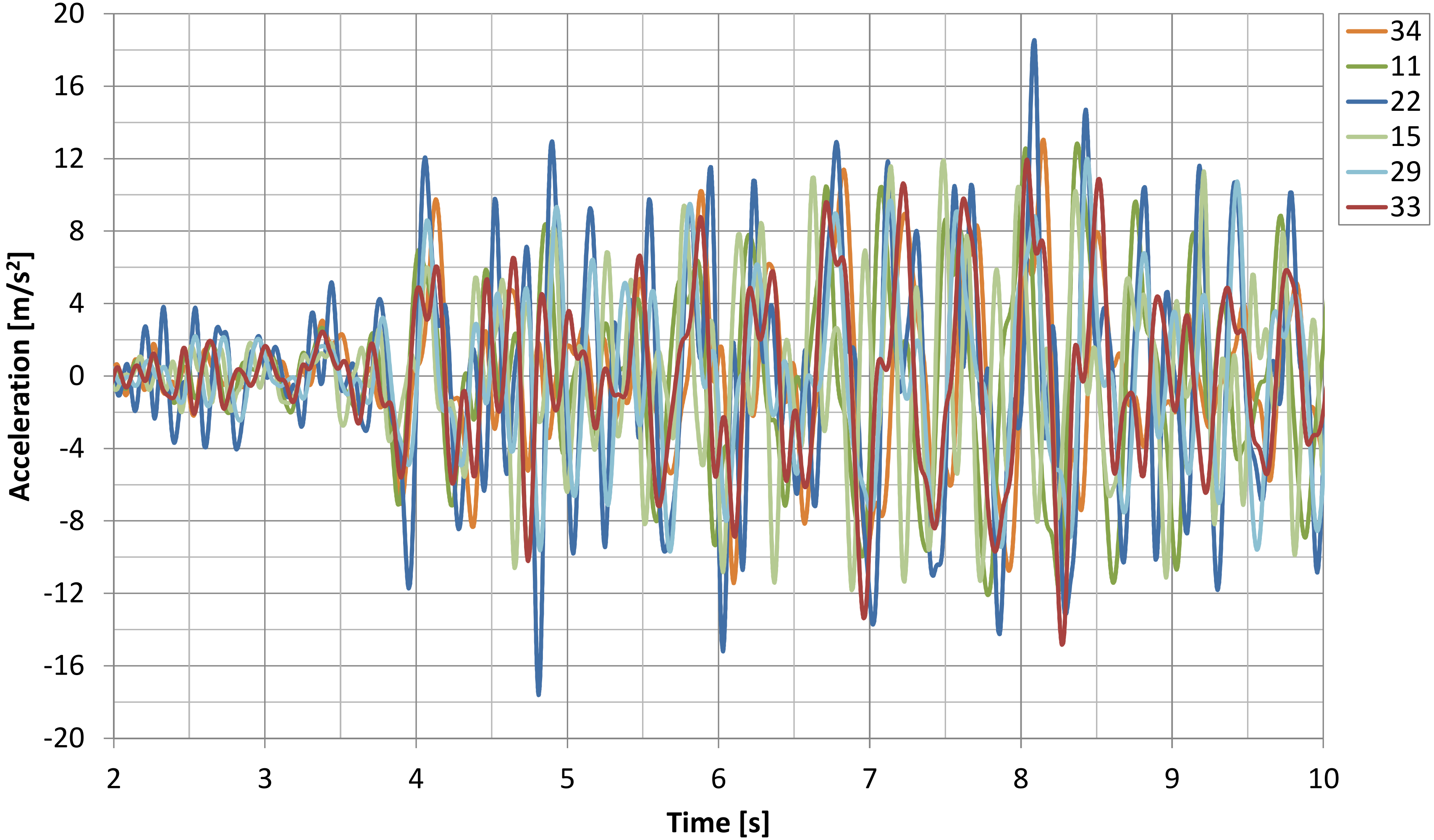
Case D-1: Time history of Acceleration at point C (group 2)



GROUP 2
Contributors without FFBC & with peak values lesser than 10 m/s²

- ✓ Fair agreement in the trend of acceleration: except for 18, peaks occur at the same time

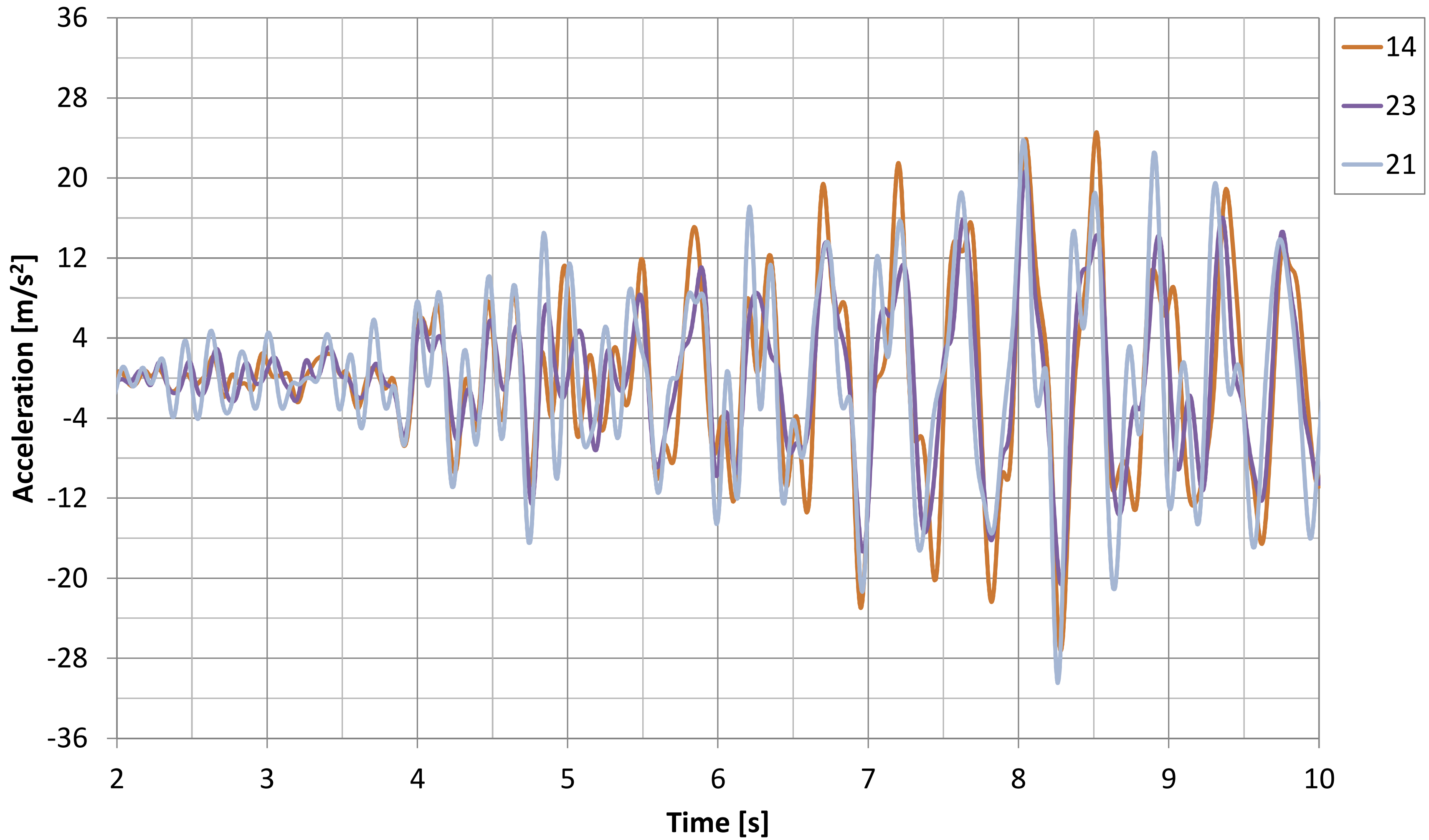
Case D-1: Time history of Acceleration at point C (group 3)



GROUP 3
Contributors with and without FFBC & with peak values greater than 10 m/s²

- ✓ Poor agreement in the trend of acceleration

Case D-1: Time history of Acceleration at point C (group 4)



GROUP 4
Contributors without FFBC & with very high peak values (greater than 20 m/s²)

- ✓ Poor agreement in the trend of acceleration

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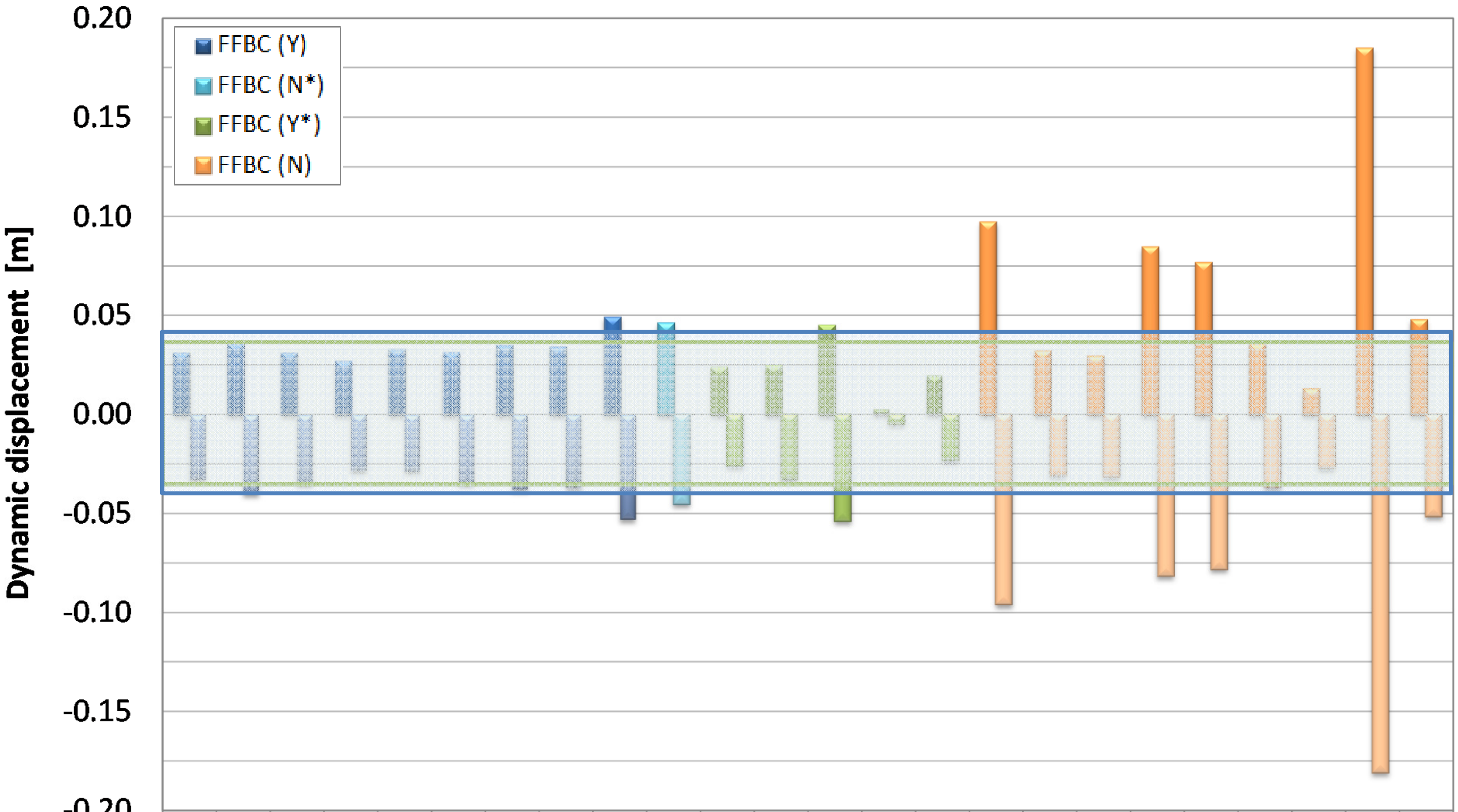
Case D-1: Relative dynamic displacement at point C. Comparison among peak values



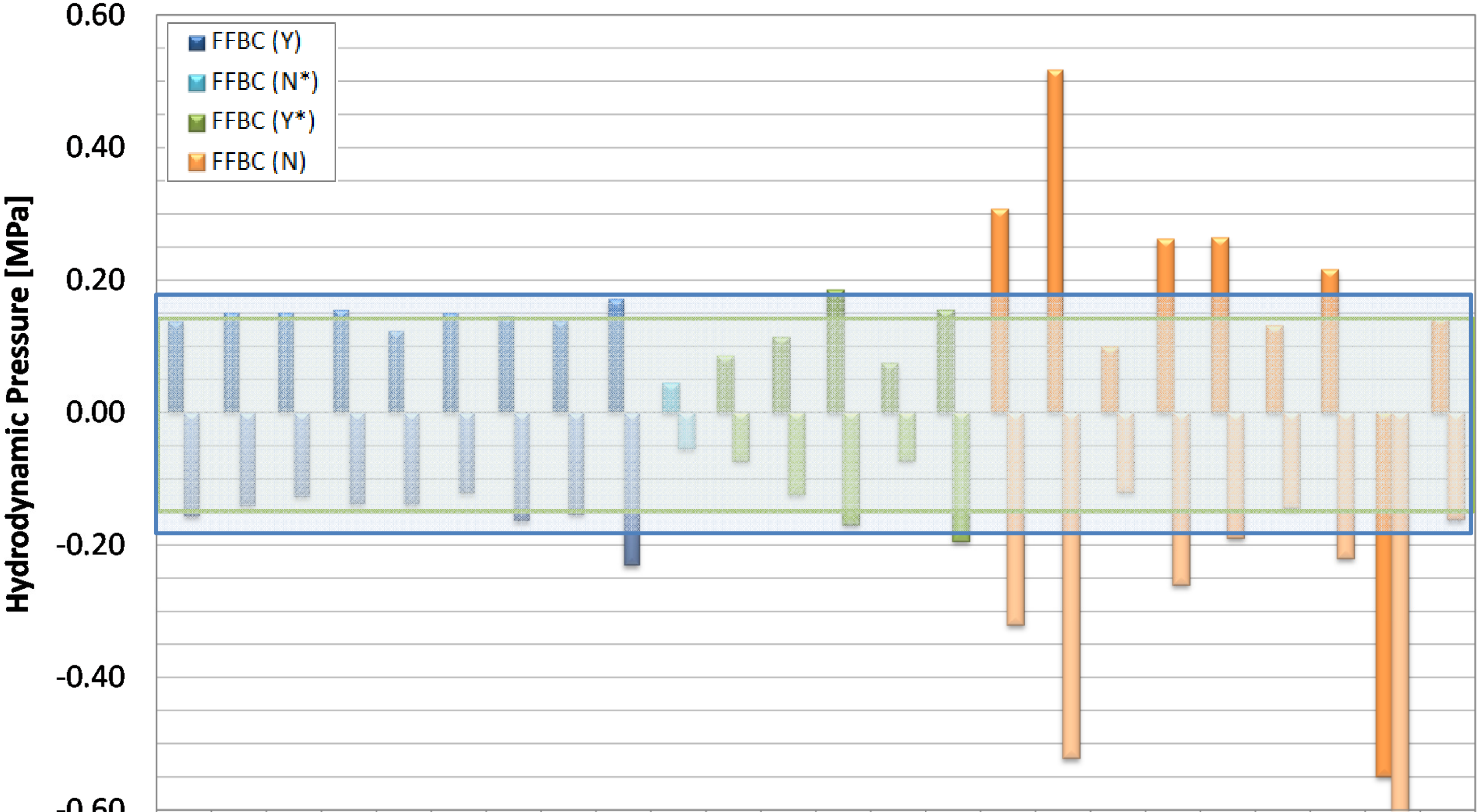
contributor	13	16	17	19	24	27	28	30	34	11	12	20	22	25	26	14	15	18	21	23	29	31	32	33
max	0.031	0.035	0.031	0.027	0.033	0.031	0.035	0.034	0.049	0.046	0.024	0.024	0.045	0.003	0.02	0.097	0.032	0.029	0.084	0.077	0.035	0.013	0.185	0.048
min	-0.03	-0.04	-0.03	-0.03	-0.03	-0.03	-0.04	-0.04	-0.05	-0.05	-0.03	-0.03	-0.05	-0	-0.02	-0.1	-0.03	-0.03	-0.08	-0.08	-0.04	-0.03	-0.18	-0.05

Point C		
Median Peak DD (av.)	[m]	3.29E-02
Mean Peak DD (av.)	[m]	3.93E-02
SD Peak DD (av.)	[m]	2.18E-02

Only Contributors with FFBC

Point C		
Median Peak DD (av.)	[m]	3.41E-02
Mean Peak DD (av.)	[m]	3.61E-02
SD Peak DD (av.)	[m]	7.13E-03

Case D-1: Hydrodynamic pressure at point A. Comparison among peak values



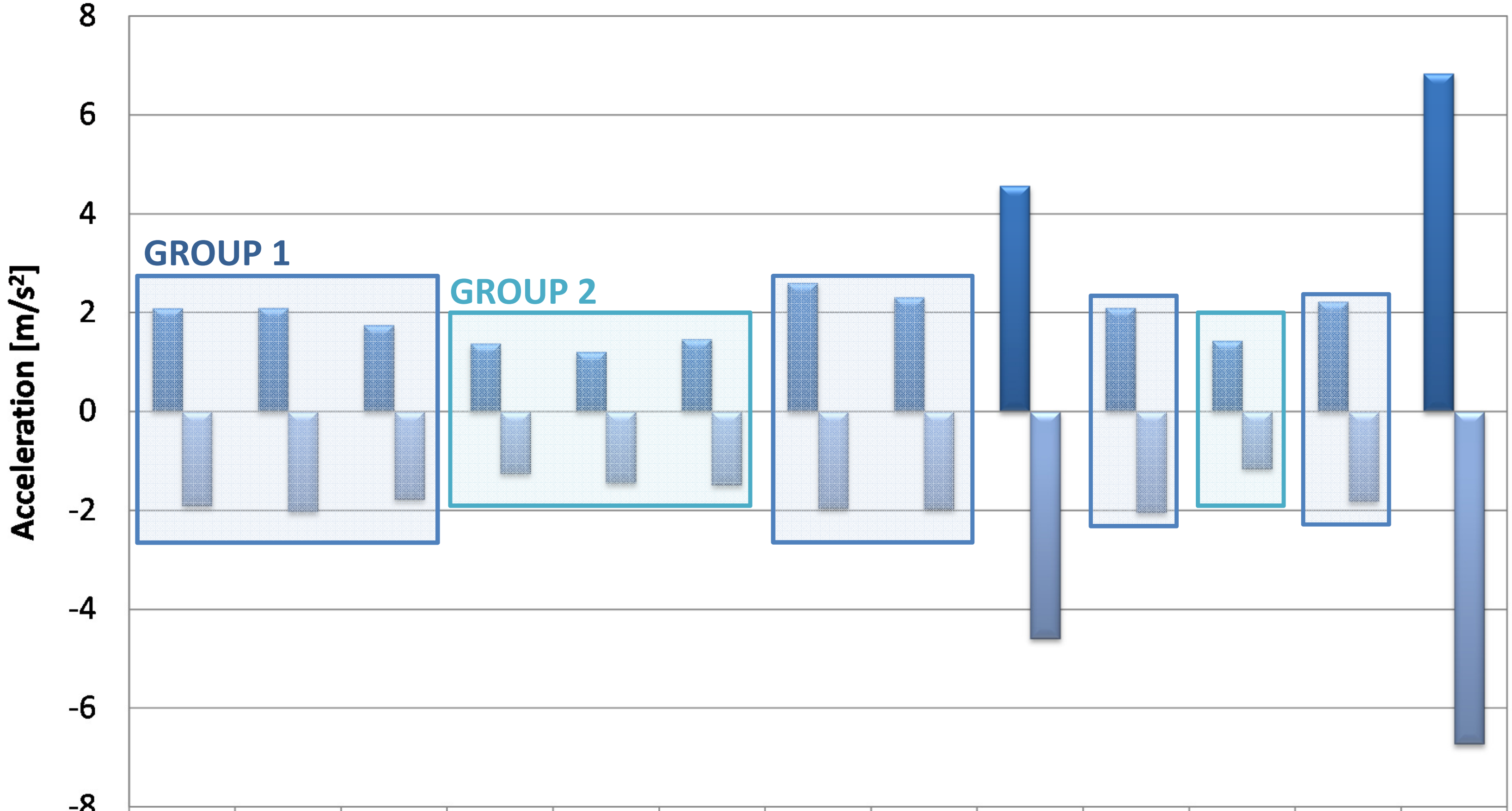
contributor		13	16	17	19	24	27	28	30	34	11	12	20	22	25	26	14	15	18	21	23	29	31	32	33
x E-1	max	1.38	1.51	1.51	1.55	1.23	1.50	1.45	1.39	1.72	4.39	8.46	1.13	1.85	7.41	1.54	3.07	5.18	9.84	2.62	2.63	1.30	2.16	-5.4	1.42
x E-1	min	-1.5	-1.4	-1.2	-1.3	-1.3	-1.2	-1.6	-1.5	-2.3	-5.3	-7.2	-1.2	-1.6	-7.1	-1.9	-3.2	-5.2	-1.2	-2.5	-1.8	-1.4	-2.1	-11	-1.6

Point C		
Median Peak HP (av.)	[MPa]	0.147
Mean Peak HP (av.)	[MPa]	0.177
SD Peak HP (av.)	[MPa]	0.097

Only Contributors with FFBC

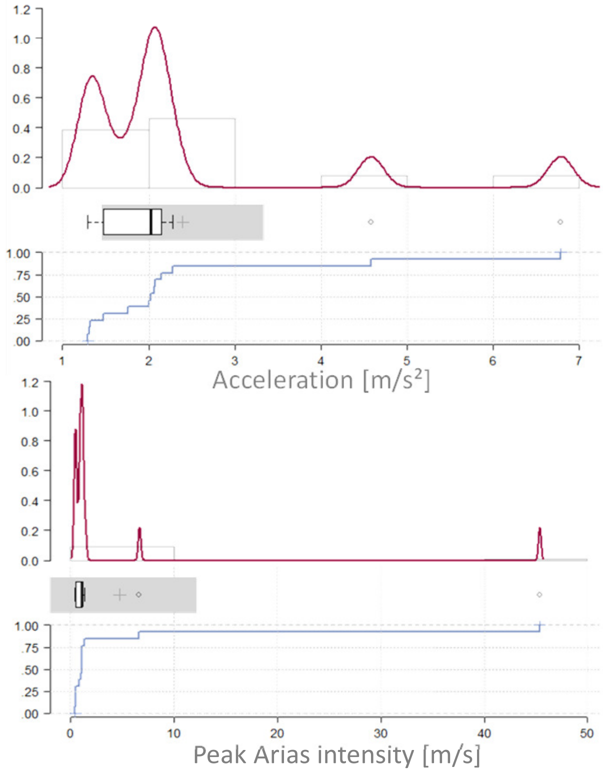
Point C		
Median Peak DD (av.)	[MPa]	0.146
Mean Peak DD (av.)	[MPa]	0.140
SD Peak DD (av.)	[MPa]	0.037

Case F-1: Acceleration at point A. Comparison among peak values

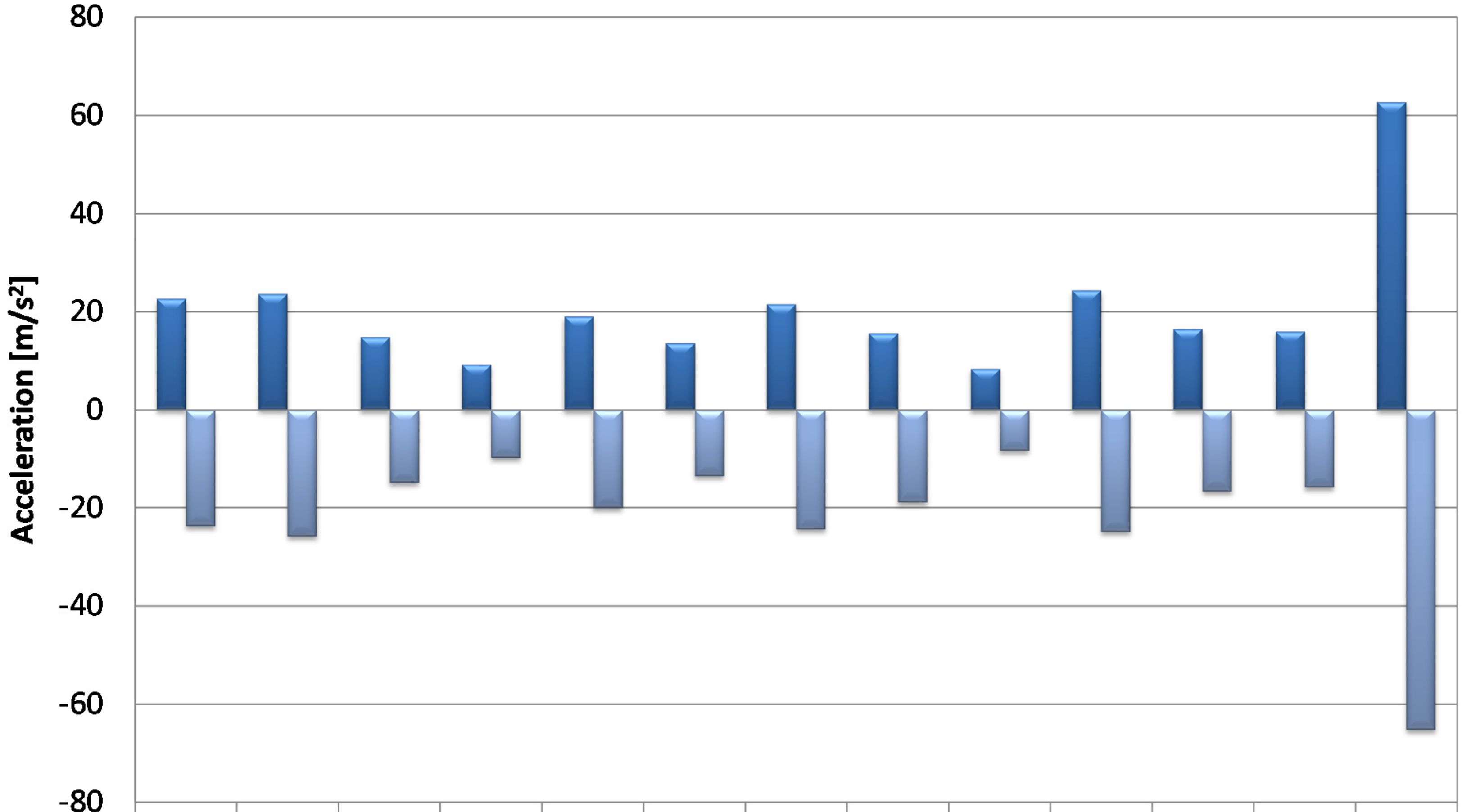


contributor	14	16	18	19	21	22	23	24	26	28	29	31	32
max	2.10	2.11	1.75	1.38	1.21	1.46	2.61	2.32	4.57	2.10	1.43	2.23	6.84
min	-1.91	-2.03	-1.78	-1.25	-1.45	-1.49	-1.96	-1.97	-4.59	-2.05	-1.16	-1.82	-6.73

Point A		
Median Peak Acc. (av.)	[m/s²]	2.03
Mean Peak Acc. (av.)	[m/s²]	2.40
SD Peak Acc. (av.)	[m/s²]	1.56
Median Peak AI	[m/s]	1.05
Mean Peak AI	[m/s]	4.71
SD Peak AI	[m/s]	12.3

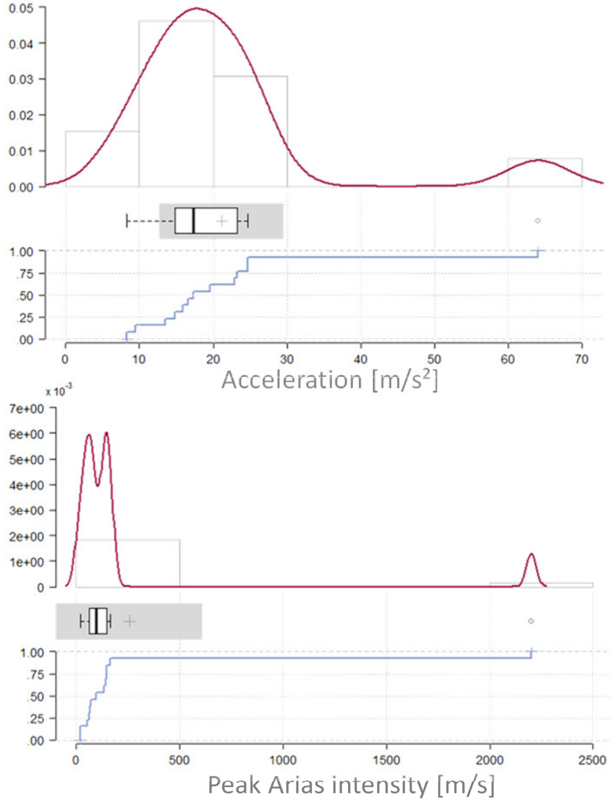


Case F-1: Acceleration at point C. Comparison among peak values



contributor	14	16	18	19	21	22	23	24	26	28	29	31	32
max	22.65	23.61	14.82	9.20	19.04	13.60	21.50	15.61	8.36	24.33	16.49	15.98	62.77
min	-23.74	-25.85	-14.87	-9.77	-20.03	-13.46	-24.40	-18.91	-8.29	-24.91	-16.66	-15.87	-65.24

Point C		
Median Peak Acc.	[m/s²]	17.3
Mean Peak Acc. (av.)	[m/s²]	21.2
SD Peak Acc. (av.)	[m/s²]	13.9
Median Peak AI	[m/s]	97.3
Mean Peak AI	[m/s]	256
SD Peak AI	[m/s]	587



Case F-1: Time history of Acceleration at point C

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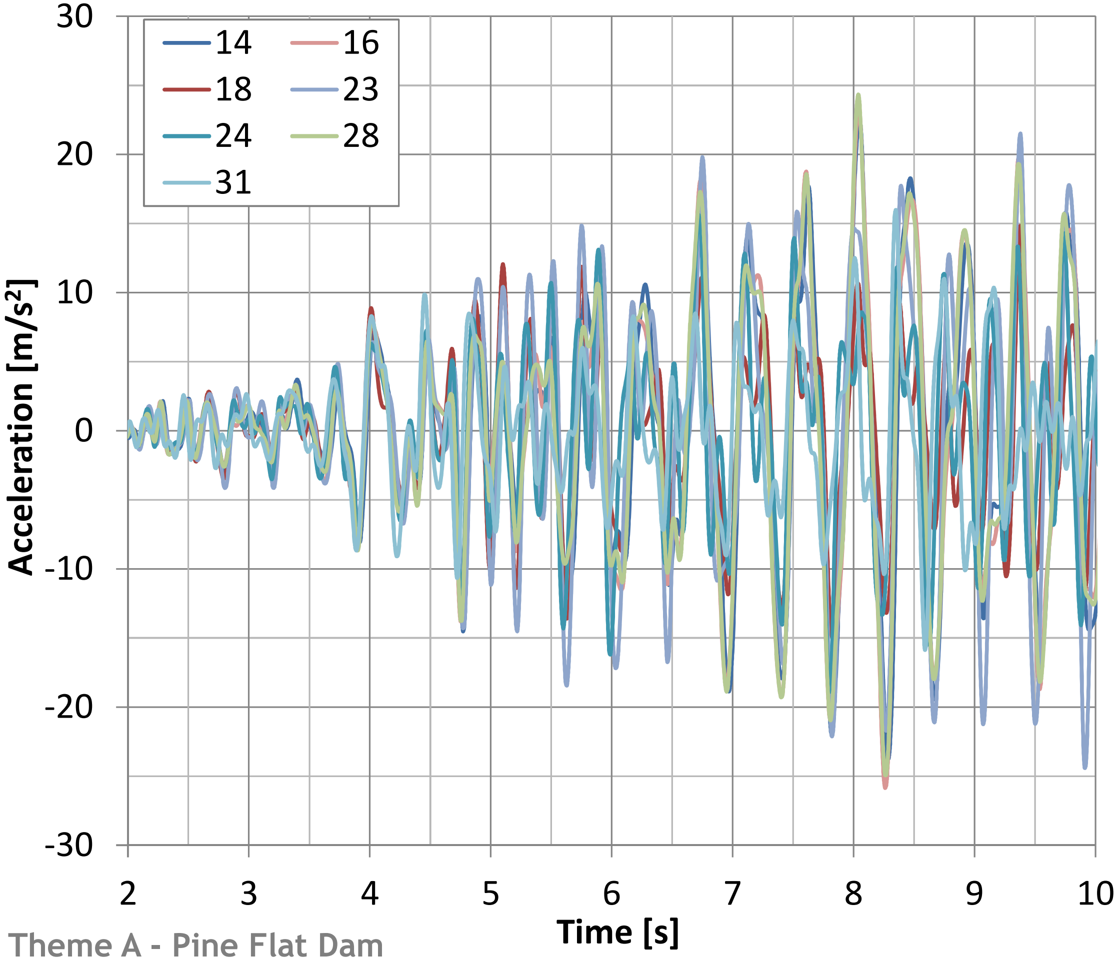
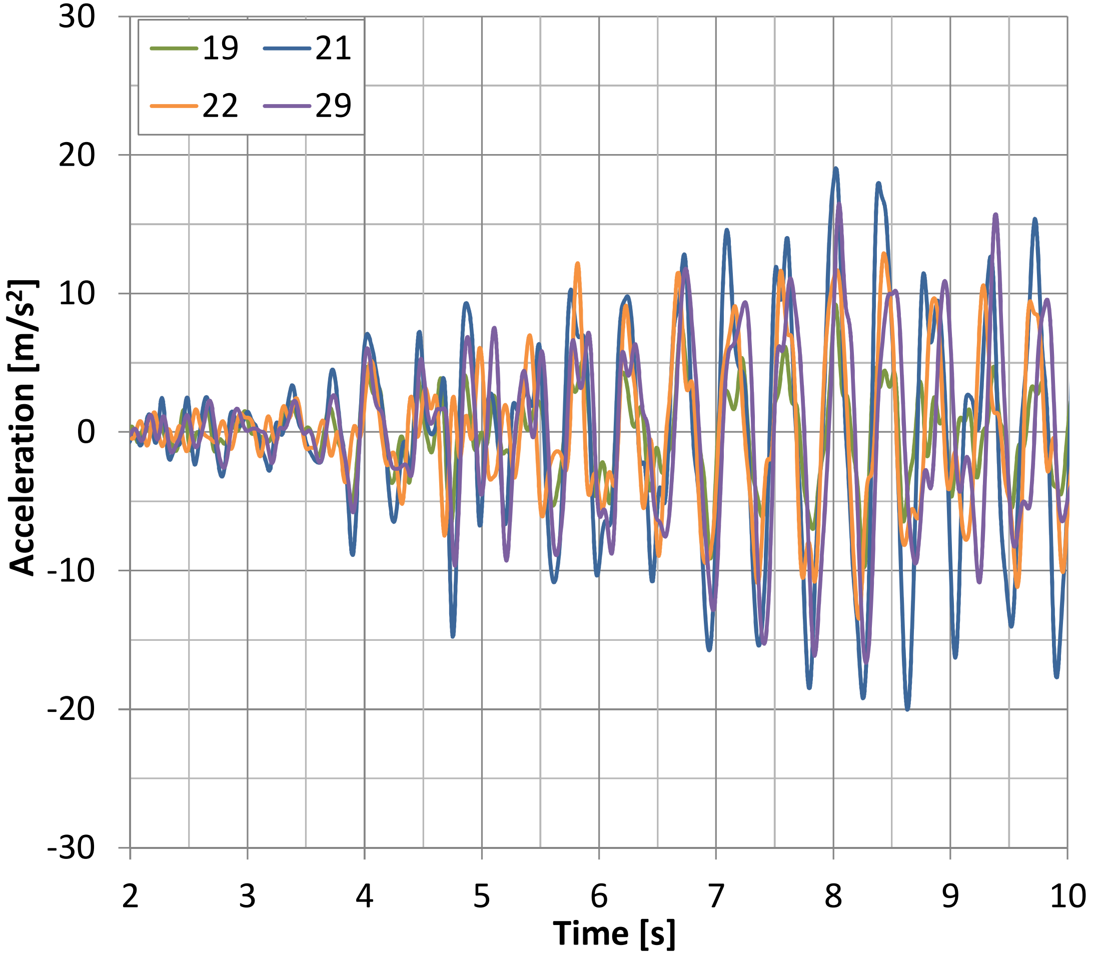
GROUP 1
Peak Acceleration at Point A greater than 1.77 m/s² (Taft PGA)



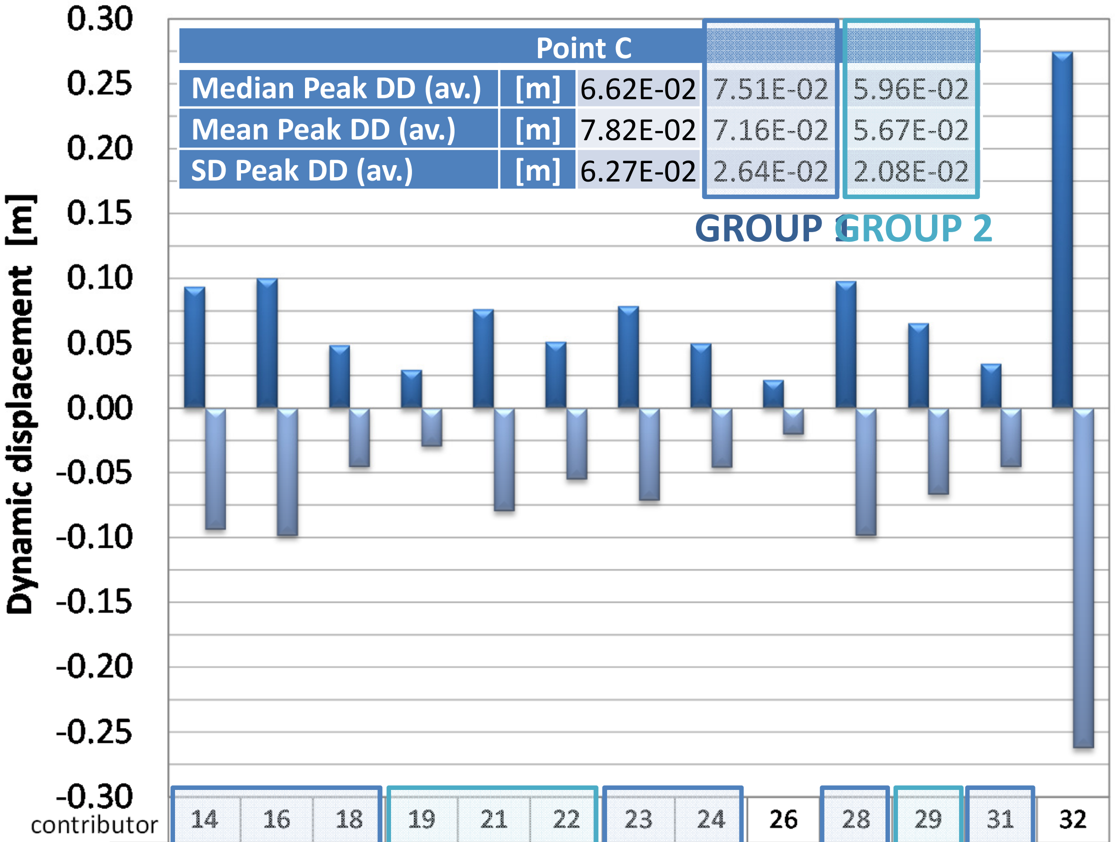
GROUP 2
Peak Acceleration at Point A lesser than 1.77 m/s² (Taft PGA)



Case F-1: Relative dynamic displacements and Hydrodynamic Pressure. Comparison among peak values

Relative dynamic displacements at Point C

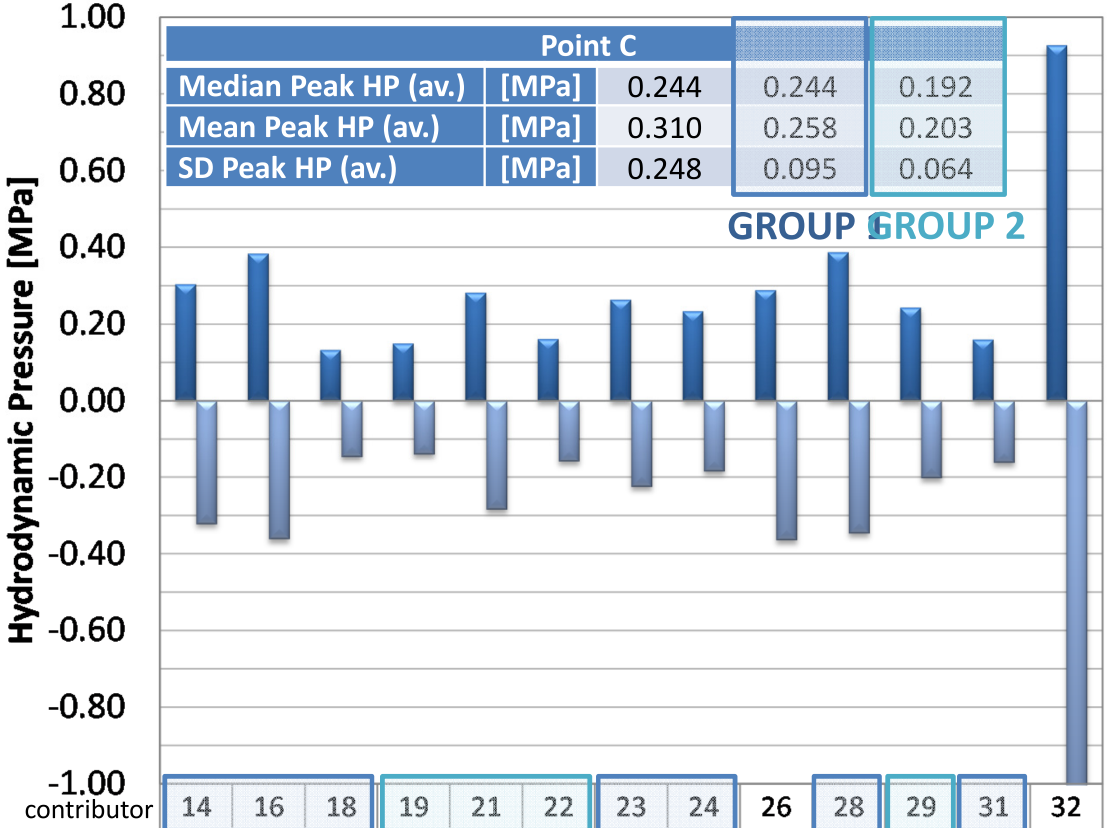
Point C			GROUP 1	GROUP 2
Median Peak DD (av.)	[m]	6.62E-02	7.51E-02	5.96E-02
Mean Peak DD (av.)	[m]	7.82E-02	7.16E-02	5.67E-02
SD Peak DD (av.)	[m]	6.27E-02	2.64E-02	2.08E-02



contributor	14	16	18	19	21	22	23	24	26	28	29	31	32
max	0.09	0.10	0.05	0.03	0.08	0.05	0.08	0.05	0.02	0.10	0.07	0.03	0.27
min	-0.09	-0.10	-0.05	-0.03	-0.08	-0.06	-0.07	-0.05	-0.02	-0.10	-0.07	-0.05	-0.26

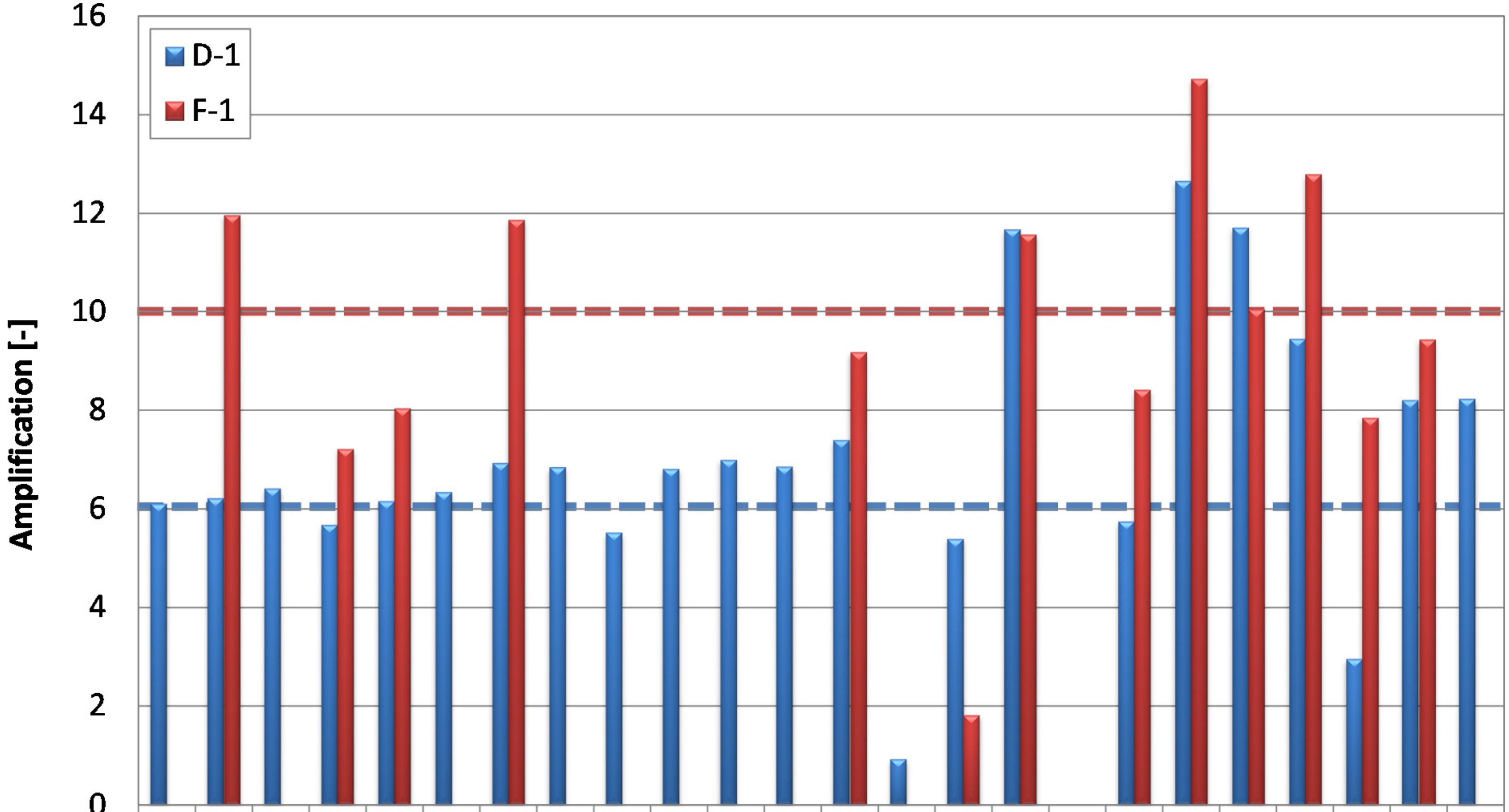
Hydrodynamic Pressure at Point A

Point C			GROUP 1	GROUP 2
Median Peak HP (av.)	[MPa]	0.244	0.244	0.192
Mean Peak HP (av.)	[MPa]	0.310	0.258	0.203
SD Peak HP (av.)	[MPa]	0.248	0.095	0.064



	contributor	14	16	18	19	21	22	23	24	26	28	29	31	32
x E-1	max	3.04	3.83	1.33	1.49	2.82	1.61	2.64	2.33	2.89	3.88	2.43	1.60	9.27
x E-1	min	-3.2	-3.6	-1.4	-1.4	-2.8	-1.5	-2.2	-1.8	-3.6	-3.4	-2.0	-1.6	-12

Cases D-1 & F-1: Amplification of acceleration at point C



contributor	13	16	17	19	24	27	28	30	34	11	12	20	22	25	26	14	15	18	21	23	29	31	32	33
D-1	6.1	6.2	6.4	5.7	6.2	6.3	6.9	6.8	5.5	6.8	7	6.9	7.4	0.9	5.4	12		5.7	13	12	9.4	3	8.2	8.2
F-1		12		7	8		12						9		2	12		8	15	10	13	8	9	

- Mean amplification in case D-1 (about 6) obtained considering only contributors with FFBC
- Mean amplification in case F-1 (about 10) obtained considering only contributors with Peak Acceleration at Point A greater than 1.77 m/s² (Taft PGA)

The models with the seismic wave propagation approach provide a less demanding seismic response of the system with respect to that achieved with the massless approach

Case D and Case F: final remarks

- **Models with seismic wave propagation approach**
  A very good agreement is observed among contributors using the free-field boundary conditions. Results provided by contributors not using the free-field boundary conditions generally show higher variability to be further investigated.

- **Models with massless approach**
  Results obtained from models with massless approach, although unexpectedly quite variable, confirm the general belief regarding the conservativeness of the method.