Passive Monitoring of Buildings
USES2 Meeting
ISAMGEO

Apr. 08, 2024

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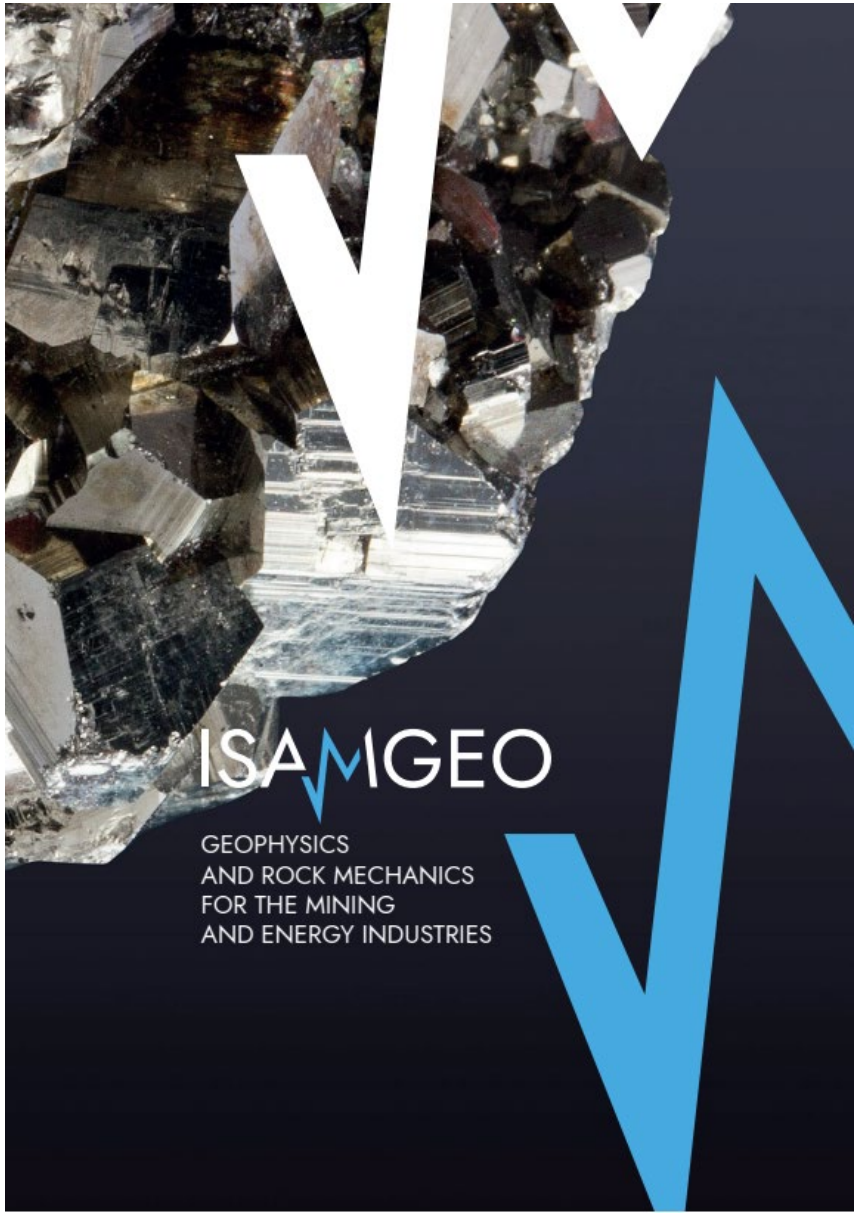
Agenda

- Passive Monitoring of Building
  - Structural Health Monitoring
  - Operational Modal Analysis
- Project I – Pressurized Vessel
  - Example of Method Application
- Project II – Critical, High-Risk Buildings Analysis
  - Example of Structural Health Assessment for major earthquake



About us

Team of 15 people

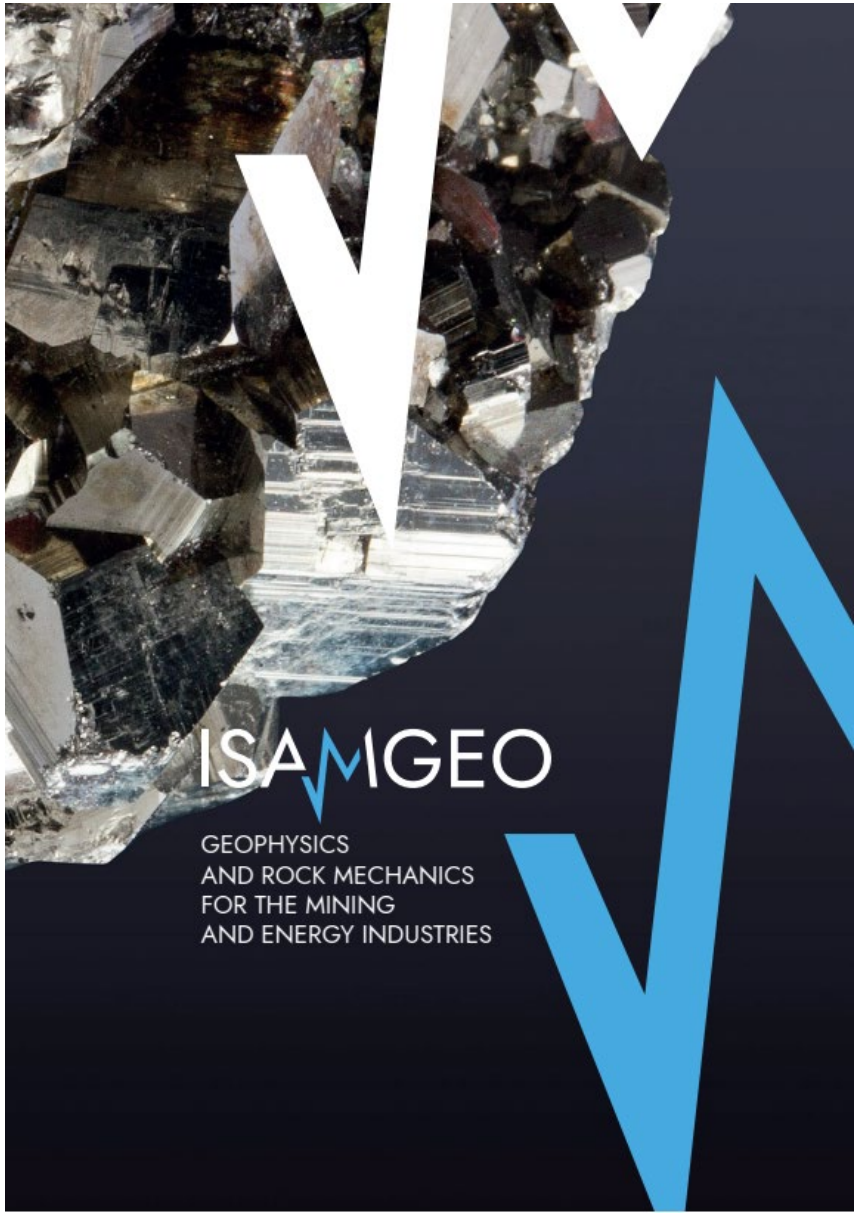
Founded in 1995 in Germany, based in Italy since 2010 with activities across Italy, France, Swiss, Norway, Turkey, …

Industries:

- Oil & Gas Reservoir Monitoring & Surveillance,
- Carbone Capture & Utilisation Storage
- Geothermal
- Mining

Services:

- Geomodelling, Rock Mechanics
- Geodynamic Monitoring
- Software Development for Geoscience Applications



Clients & Partnerships

TotalEnergies

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AkerBP

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GEOOL Géothermie de l'Ouest lausannois

agepp alpine geothermal power production

FONROCHE énergies renouvelables

Lithium de France GEOTHERMAL

Università degli Studi di Padova

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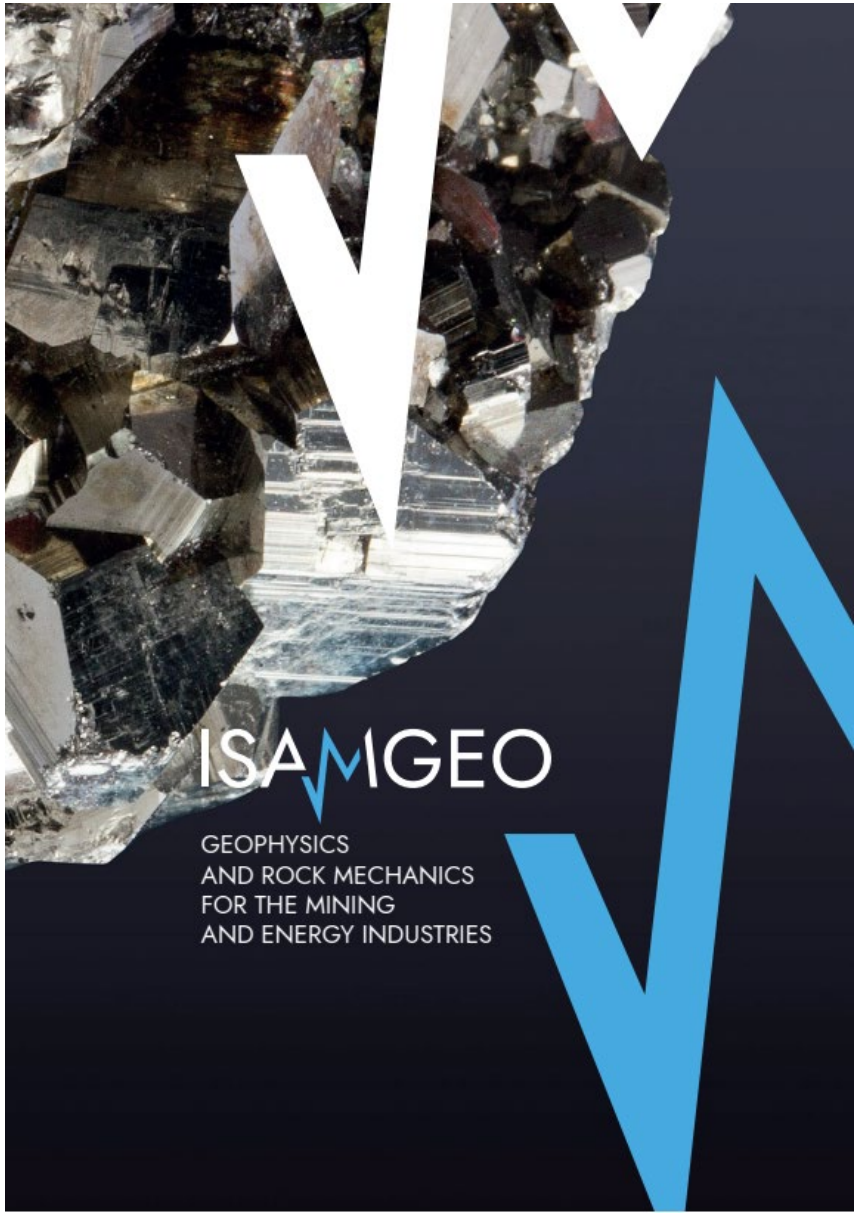


Structural Health Monitoring

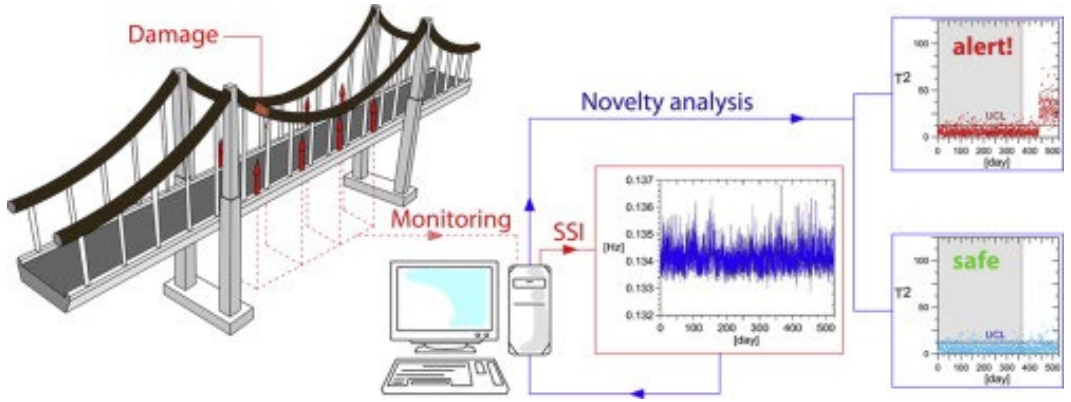
What: Observation and analysis of a structure over time using measurements to monitor changes to the material and geometric properties

Motivation:

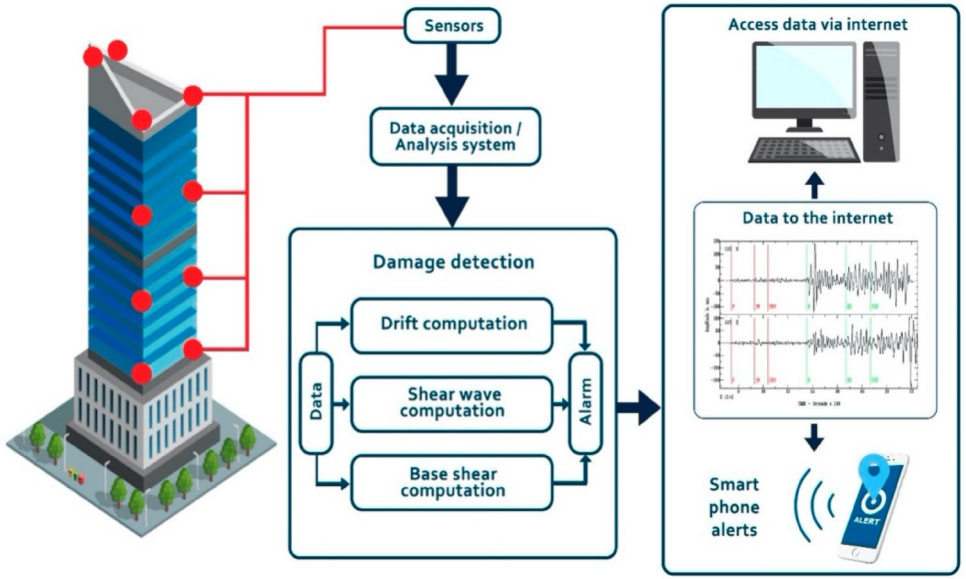
- In operational environments, structures degrade with age and use
- Structural integrity can be compromised by natural hazards such as earthquakes, storms, …

Objective:

- Long term monitoring to track structural integrity
- Early warning to detect possibly damaging events
- Assessment of damage after major event (earthquake, storm, blast, …)
- Understand weakness points to prevent major damage



Comanducci et al., 2015



Sivasuriyan et al., 2021

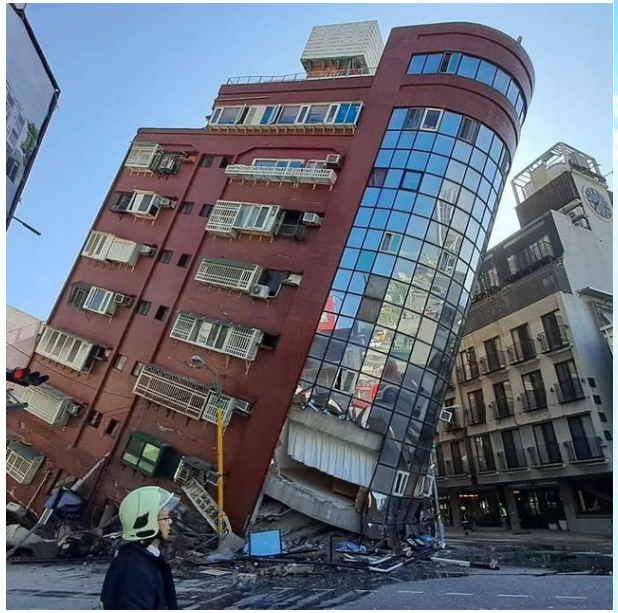
@ Taiwan 03-Apr-2024 | 7.4 Magnitude Earthquake

Various Structure Health:

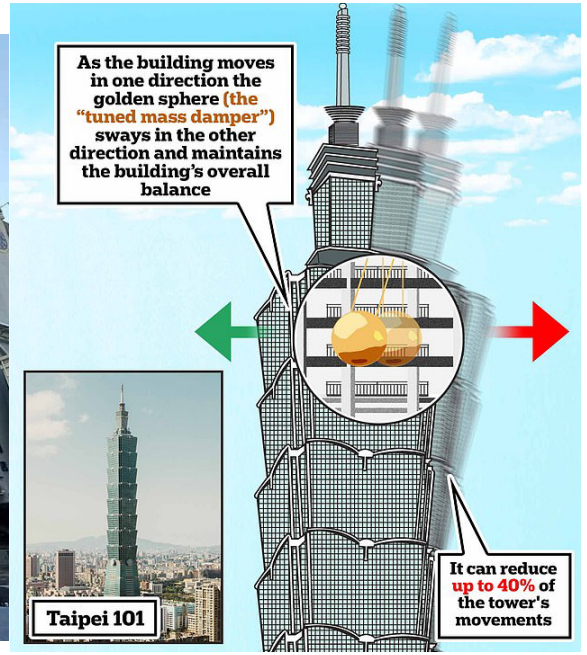
- Collapsed buildings
- Tilted buildings
- Taipei 101 with pendulum on 87° floor - Damper Baby

Consequences:

- Human - Lives & Injuries
- Economical - "… single vibration can destroy entire batches of precision-made semiconductors…" - Bloomberg



Reference Photo



Reference Photo

@ Turkey | Threats During Earthquakes

Threats:

- Soil-structure interactions
- Soil liquefaction
- Structural failure of the frame
- Fluid sloshing

Failure mechanism:

- Shear waves excite the structure
- Braces break
- Buckling and failure of the supporting columns

Pressurized vessels – potential threat during earthquake

Operational Modal Analysis

1. Measure acceleration/velocity of ground and structure

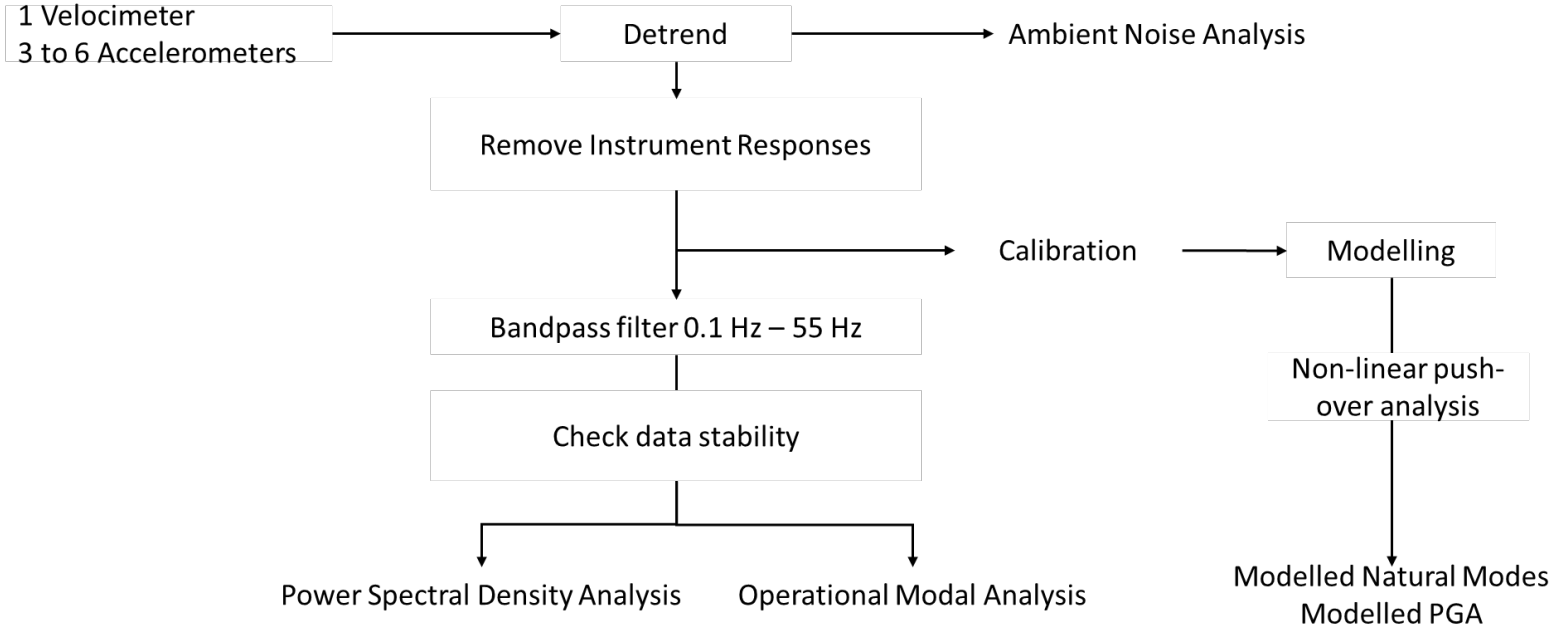
2. Compute response integrating acceleration/velocity measurements

3. Compute Frequency Response Function

4. Estimate modal parameters from data

5. Compare with model estimates

6. Update/calibrate model



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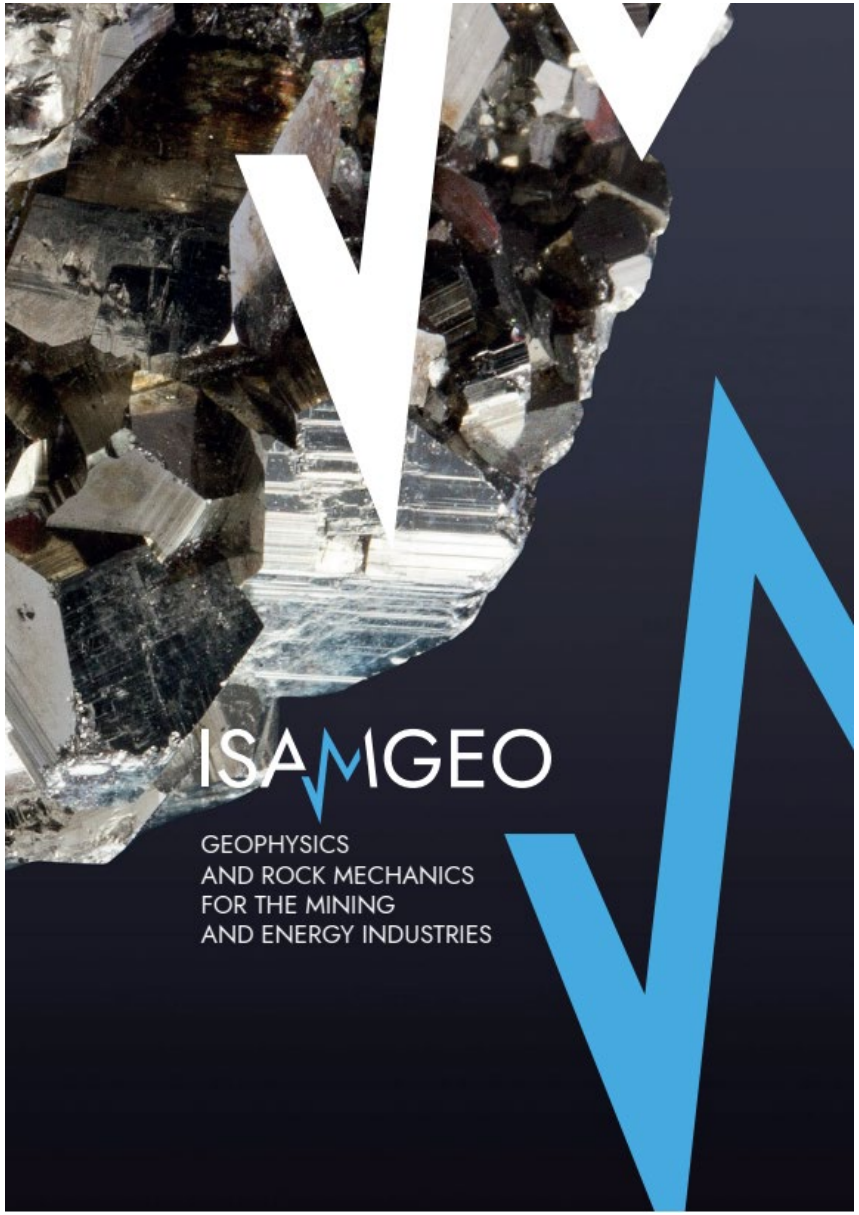
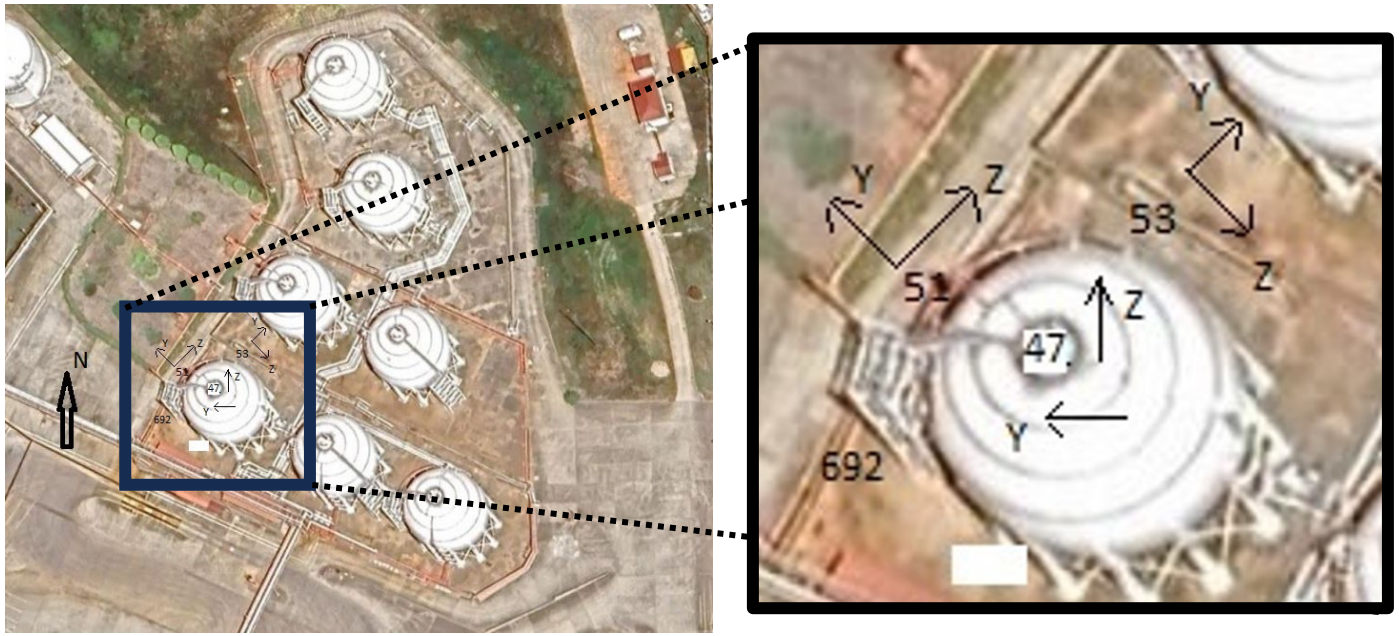


Project I – Pressurized Vessel - Tank 5001 | Data Summary

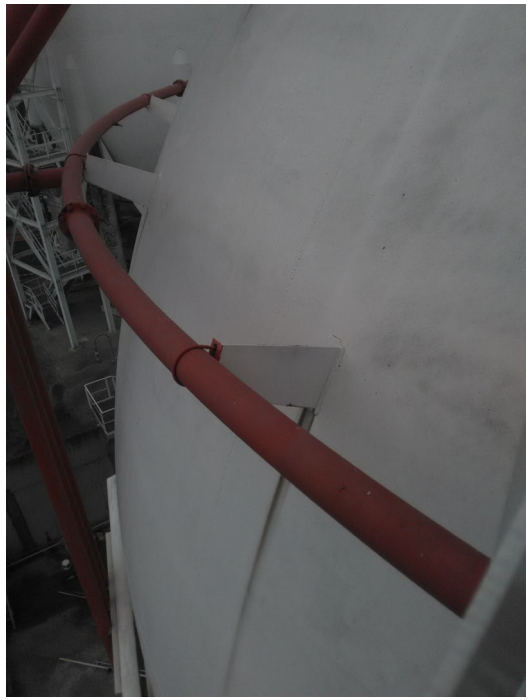
Data recorded from 10th to 20th of November, 2023 in Turkey:

- 1 3C velocimeter : EB692 on the ground on SW corner
- 3 2C accelerometers :
  - SM052 at the tank “equator” N45°W
  - SM053 at the tank “equator” N10°E
  - SM047 at the top of the tank



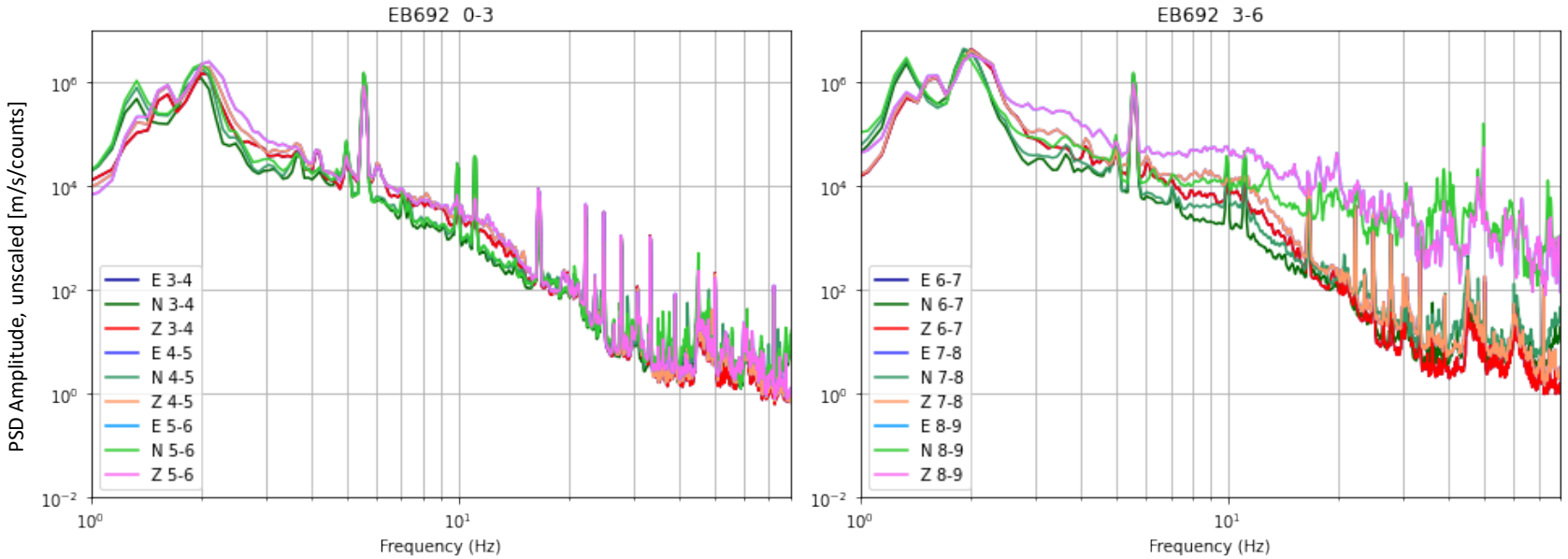
		1107...	1110	1111	1112	1113	1114	1115	1116	1117	1118	1119	1120	Files Read
PO Project	EB692	0	6	6	6	6	9	6	6	6	6	0	6	63
	SM047	0	1	0	5	5	5	3	3	2	0	0	7	31
	SM051	0	5	5	5	5	7	5	5	5	0	0	7	49
	SM053	1	5	5	5	5	7	5	5	5	0	0	7	50

Project I - Tank 5001



Project I - Data Acquisition | EB692

- Sensor placed next to the tank, on the ground
- Objective is to measure the “vibrational input” to the structure
- Both amplitudes and frequency content matter

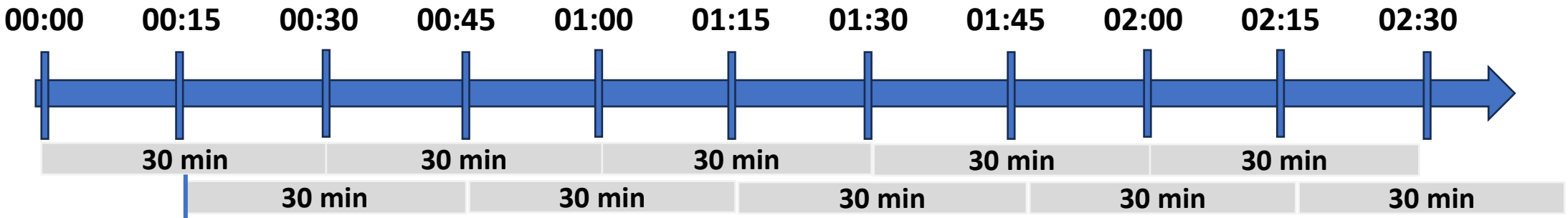


Project I - Data QC | RMS for Ambient Noise Analysis

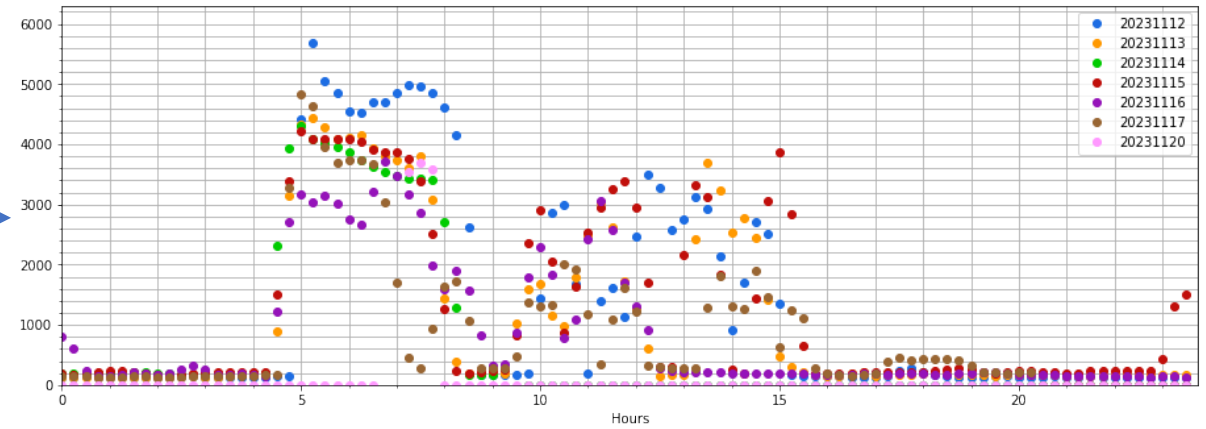
Root Mean Square (RMS) of the stacked data computed over 30 min of data on a sliding window every 15 min

Indicates presence and variation of data amplitude over 30 min of data every 15 min.

Computed from the Fourier Transform of stack data for efficiency



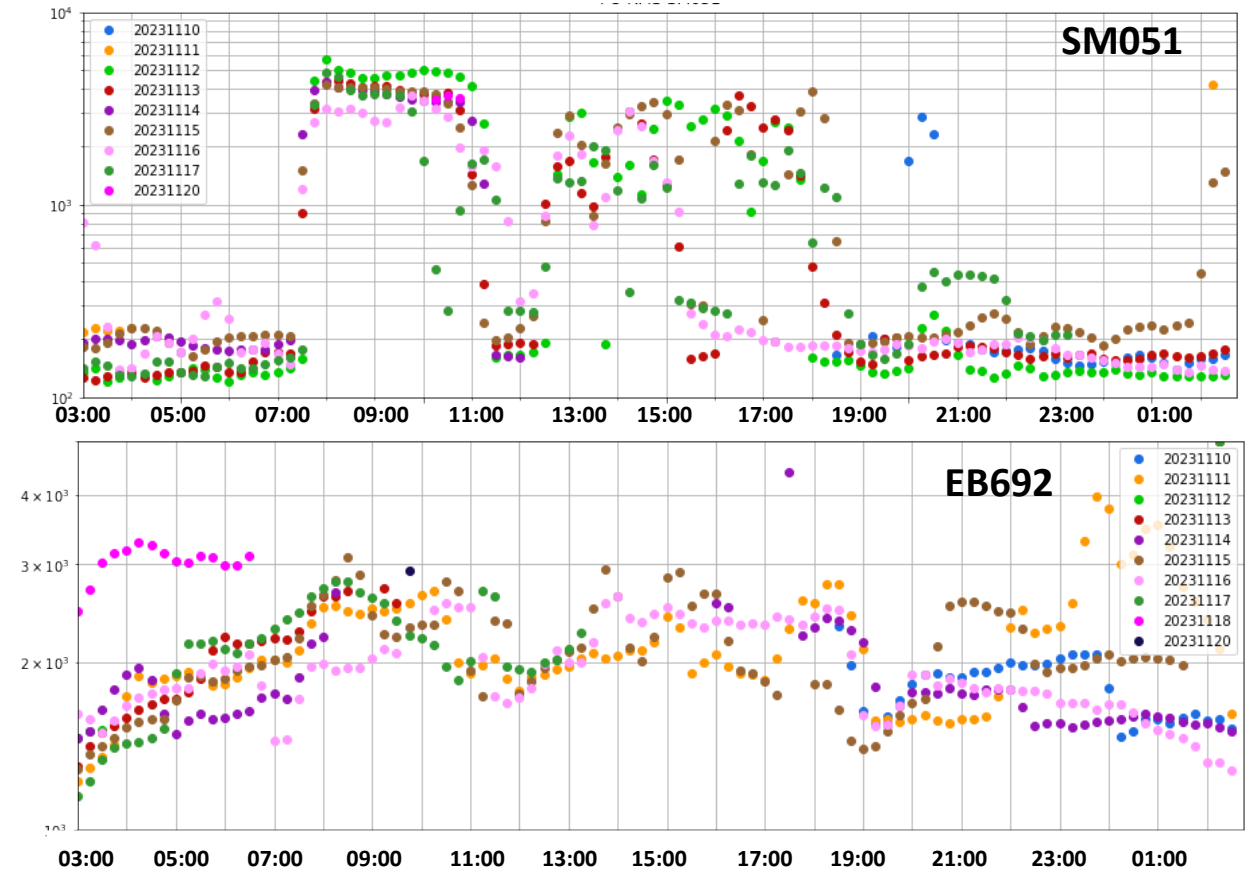
1 RMS point every 15 min



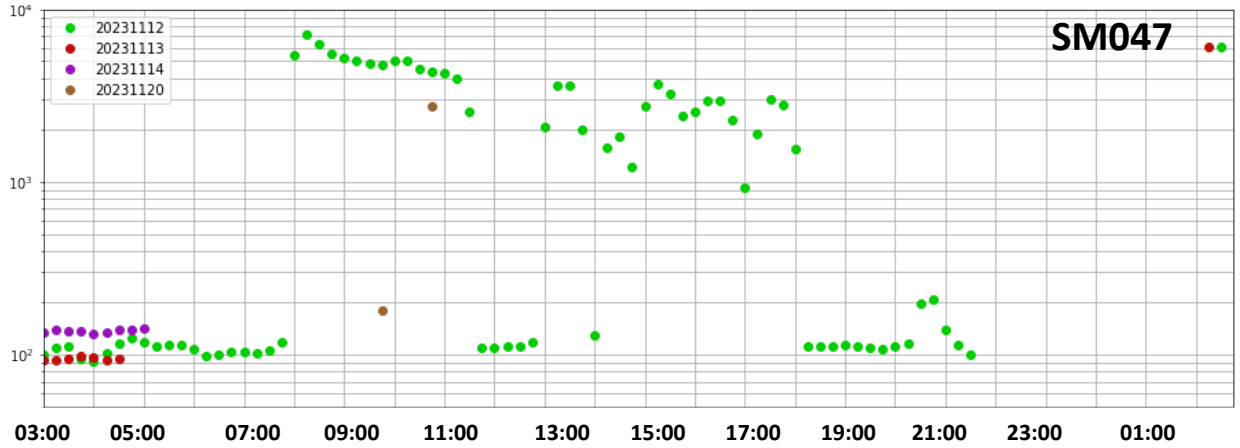
Project I - Data QC | RMS over 24h

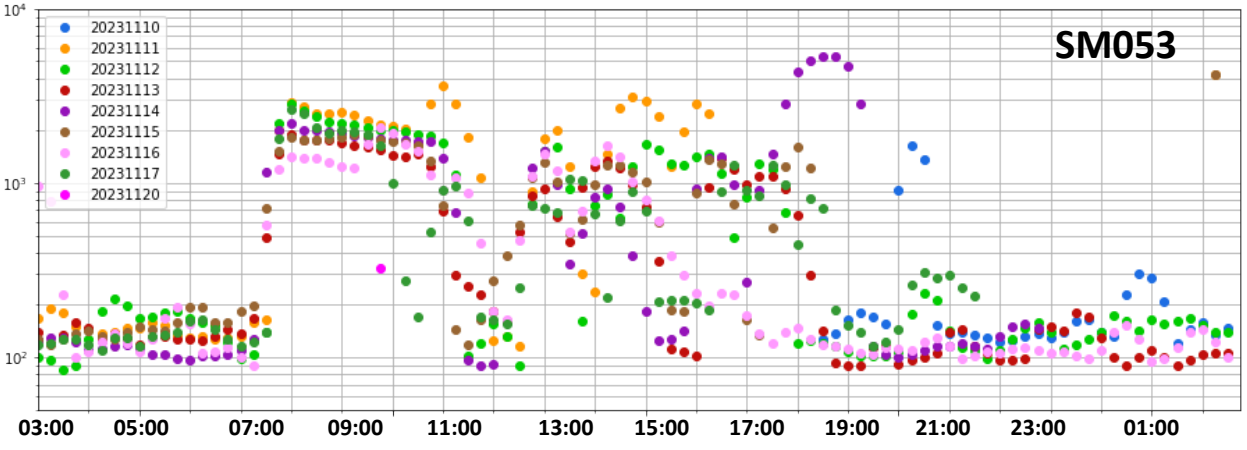
From Nov. 11th to 13th, the tank capacity is **dropping** from 80% to 2%

From Nov. 17th to 19th, the tank capacity is **increasing** from 2% to 80% - Missing data from 17th



Local Time





Local Time

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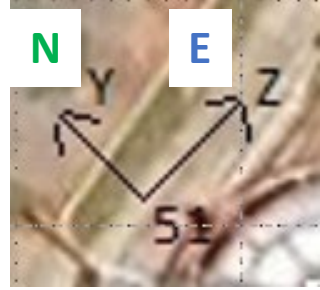
Project I - Data QC | Power Spectral Density

SM051 - 2023-11-13 - Per Component per 12 hours



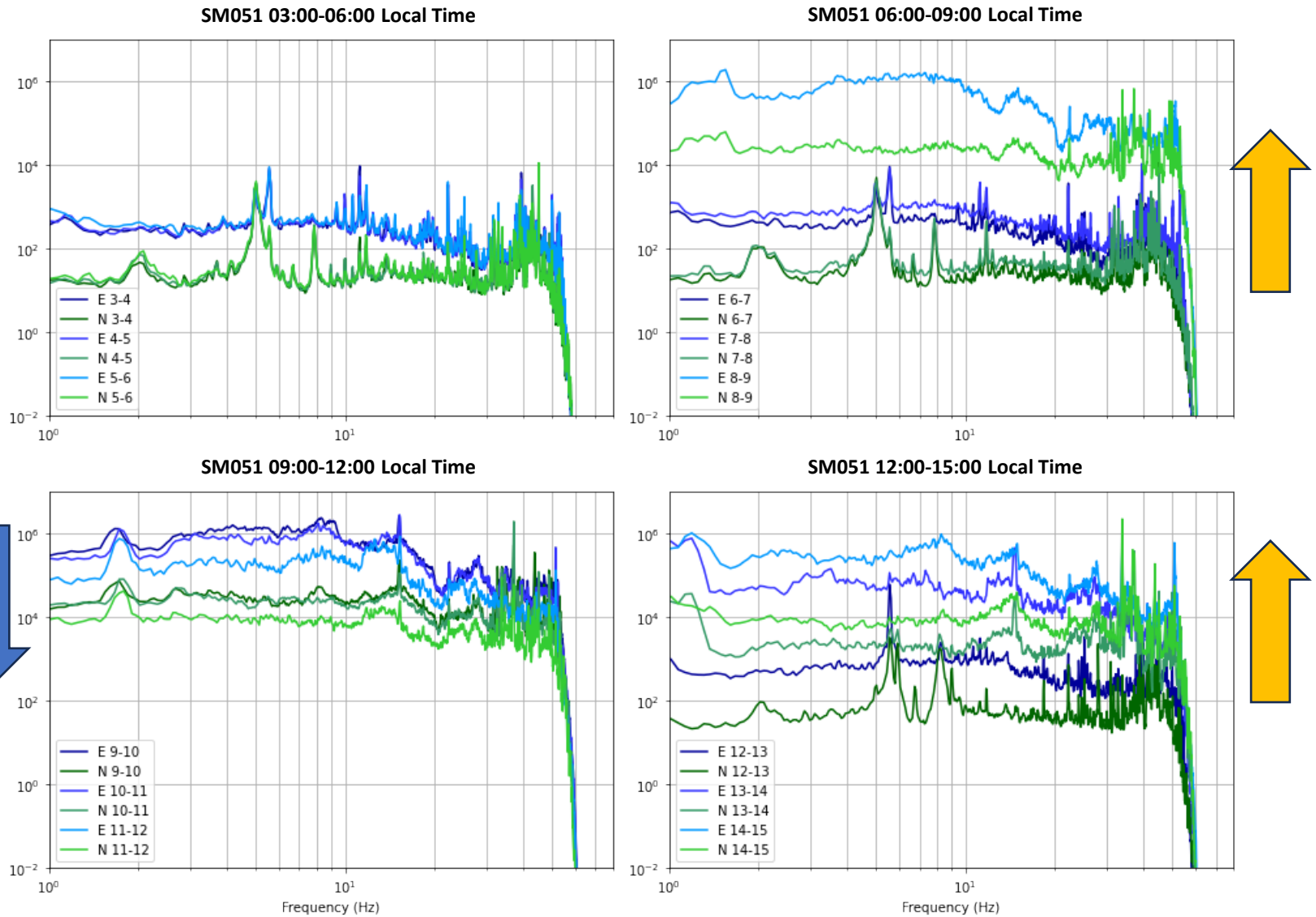
Parallel component in blue picks up consistent higher amplitude

Coherency of signal on both component

Decrease in amplitude over time

Increase in amplitude over time

Increase in amplitude over time



Project I - Modal Analysis

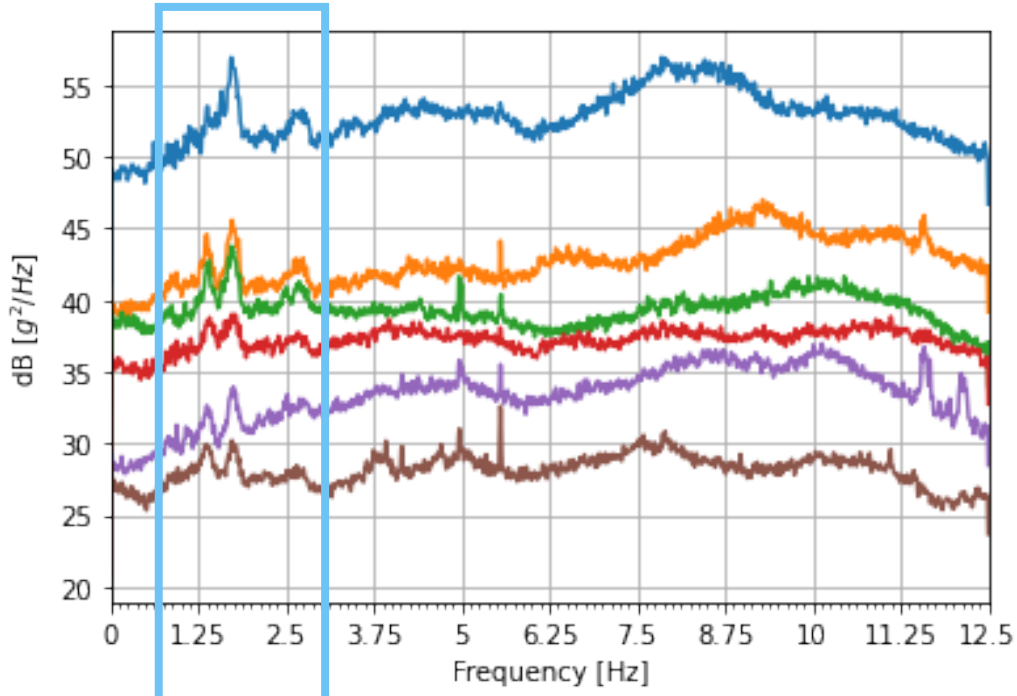
Operational Modal Analysis estimates modal parameters of a structure from measurements of the vibration response in operational condition.

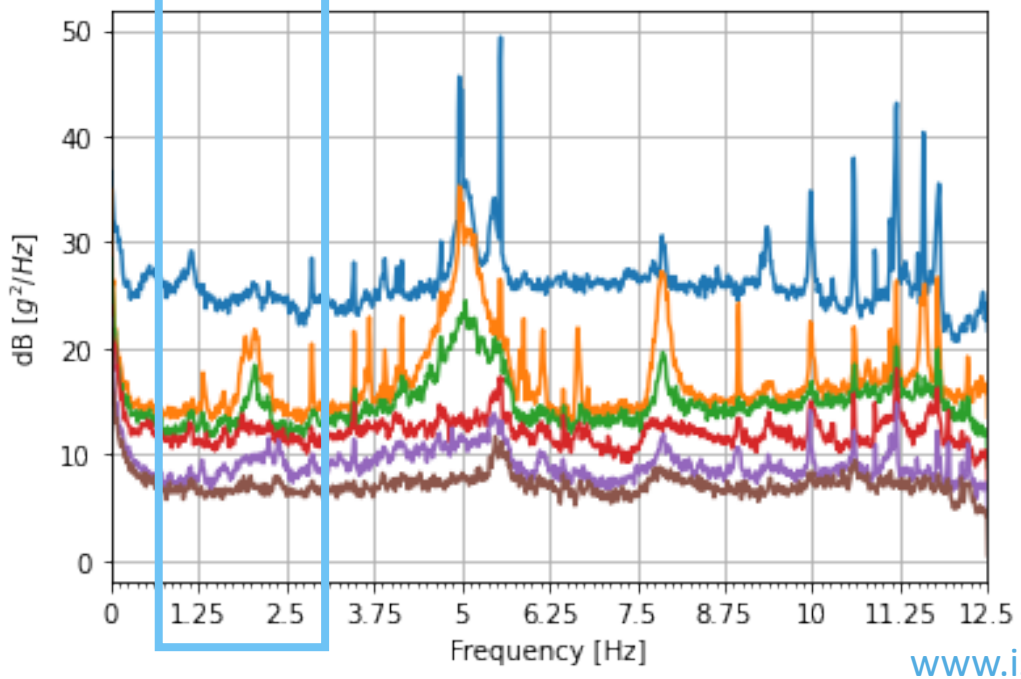
Modal parameters are:

- natural frequencies,
- mode shapes,
- damping ratios

6 Channels of the receivers on the tank are considered together to estimate the main frequency decomposition

Common dominant frequency values on 12 and 13th of Nov are shown around 2 Hz.





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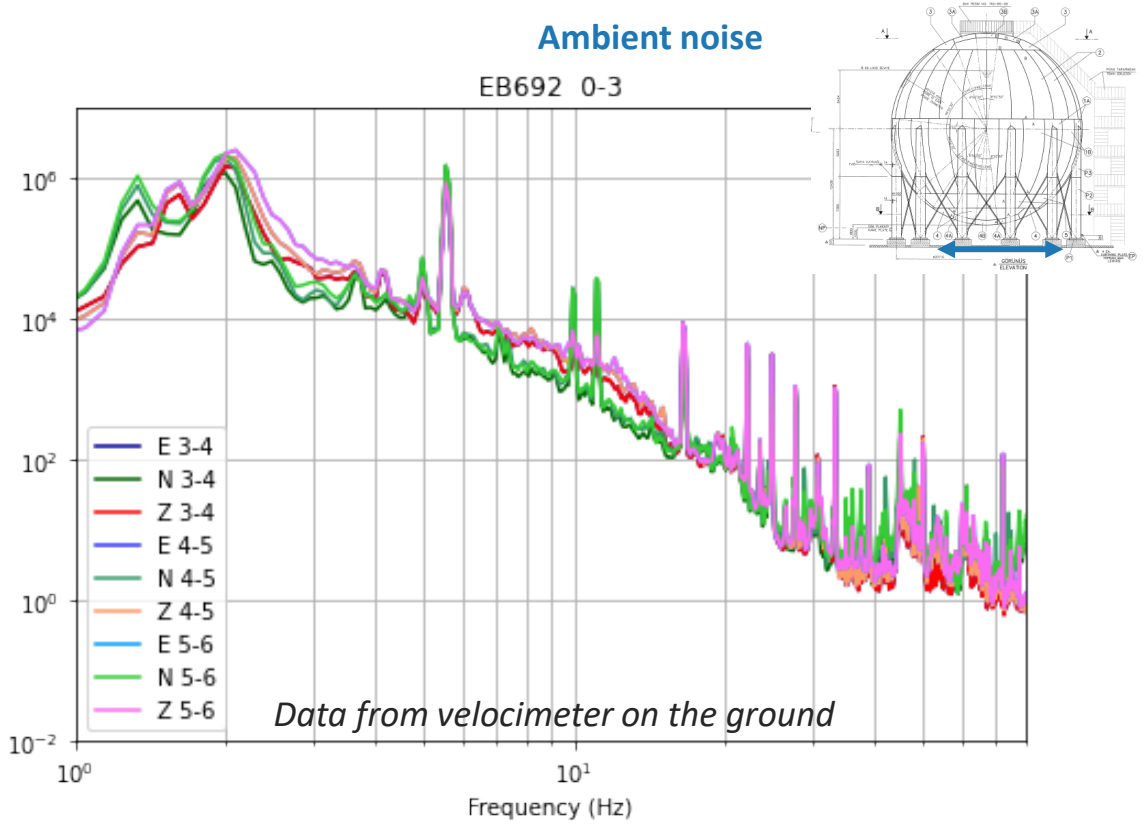
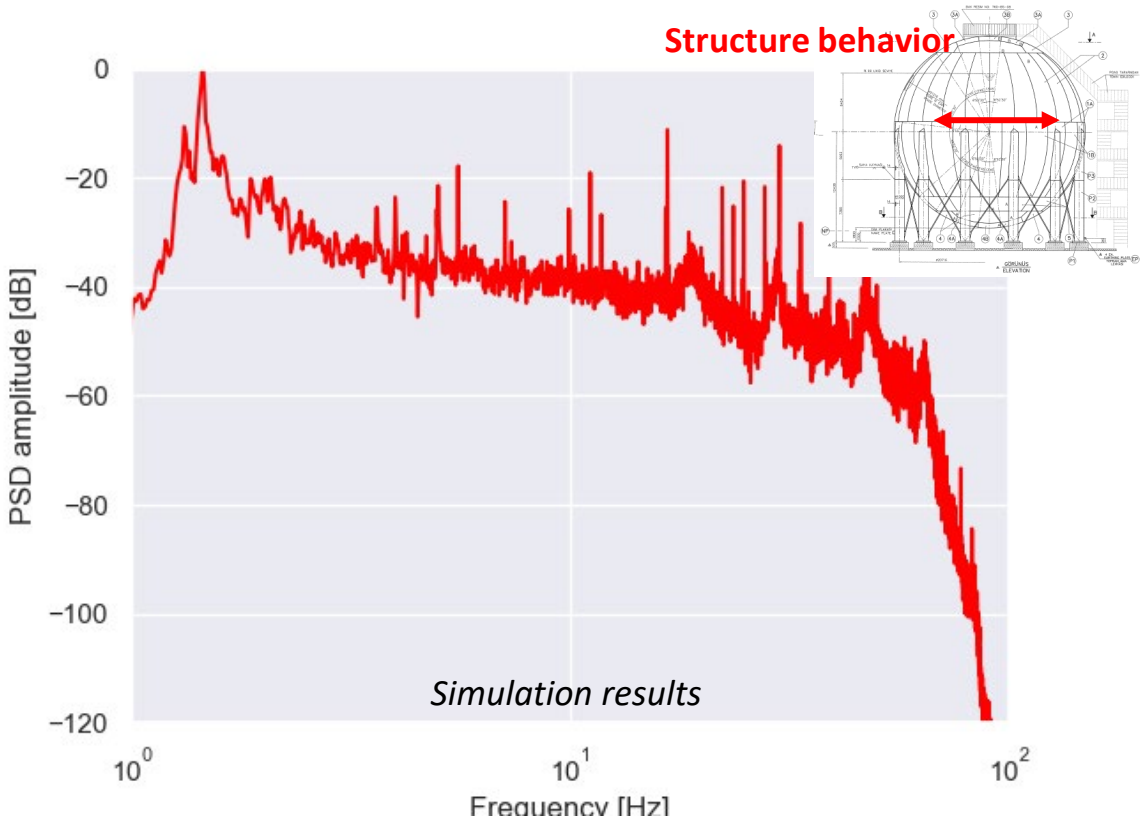
Project I - Effect of Ambient Noise | Multiple Harmonics

OMA assumes ambient noise is **white** and **broadband**





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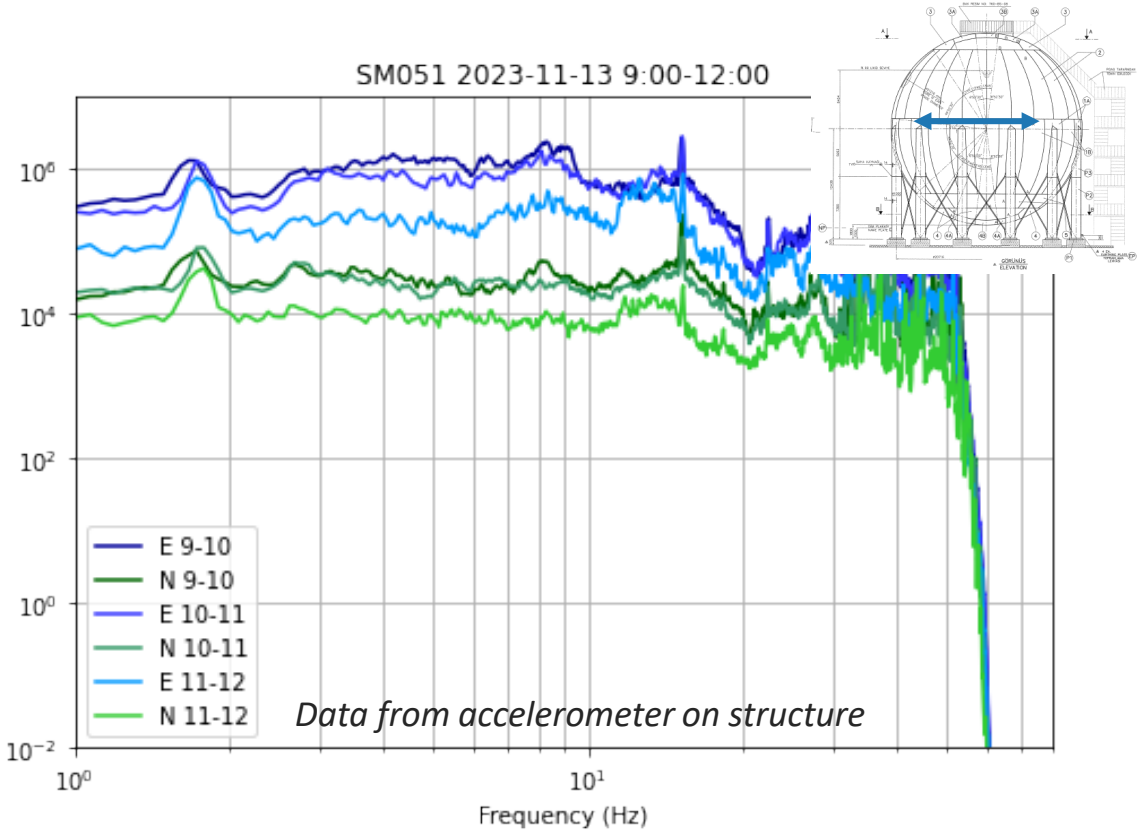
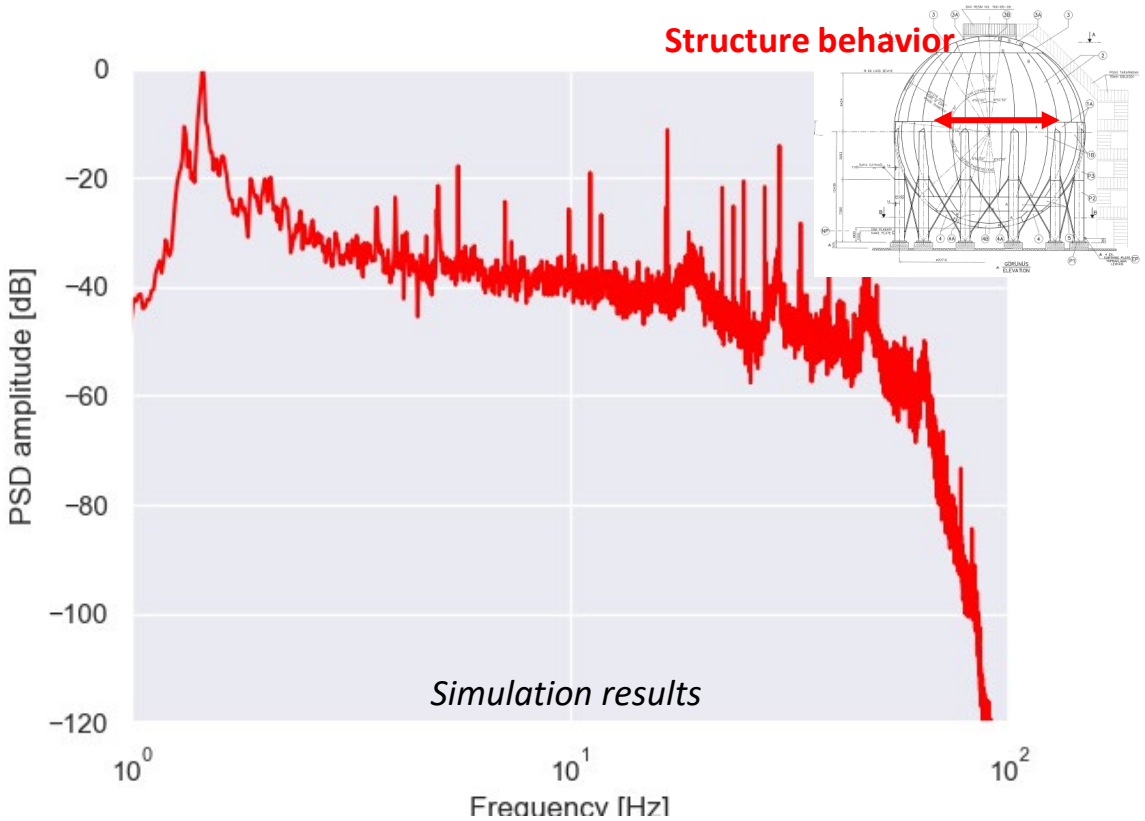
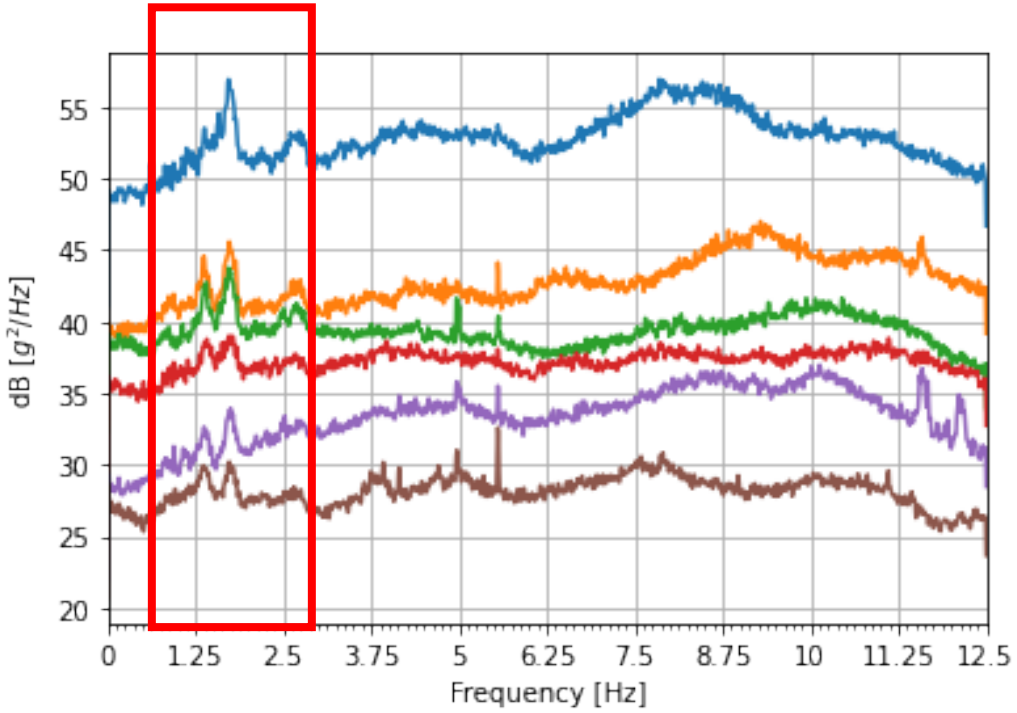
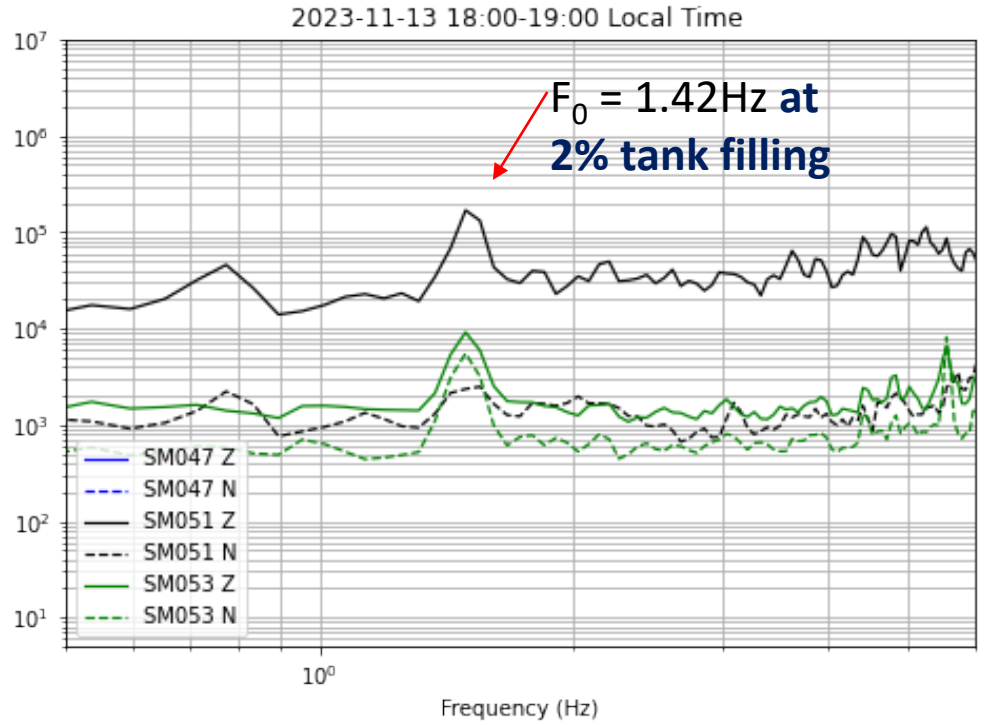




Project I - Data Analysis | Frequency of High Mode



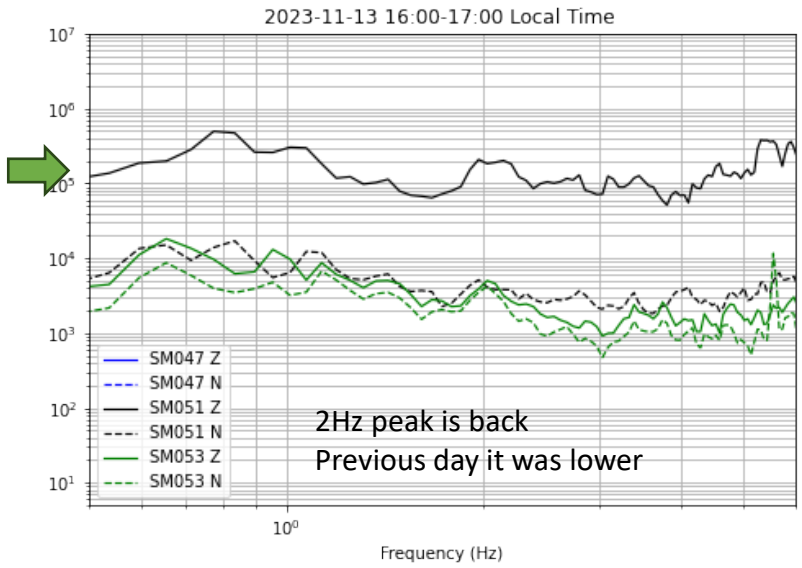
SVD analysis - Processing with pyOMA



Manual inspection of the RAW data

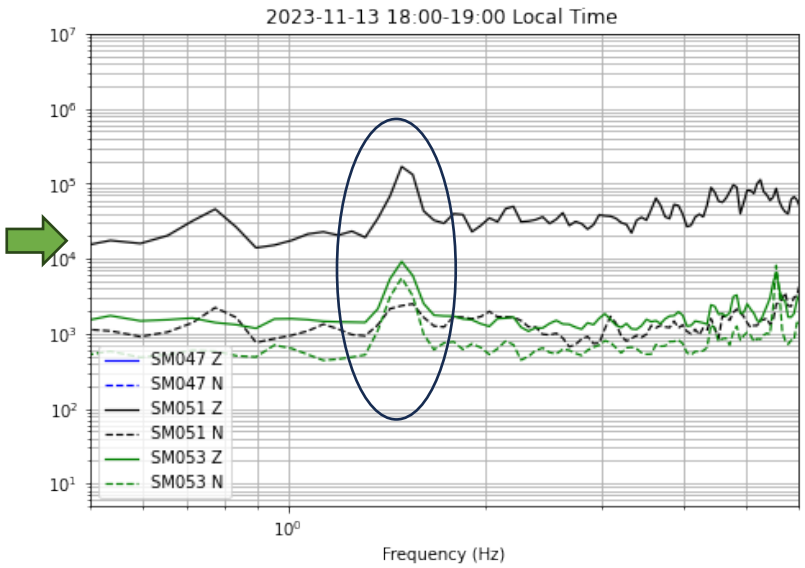
Project I - Data Analysis | Is This Mode Always Visible?

Tank full at <11% - **HIGH** Noise Level



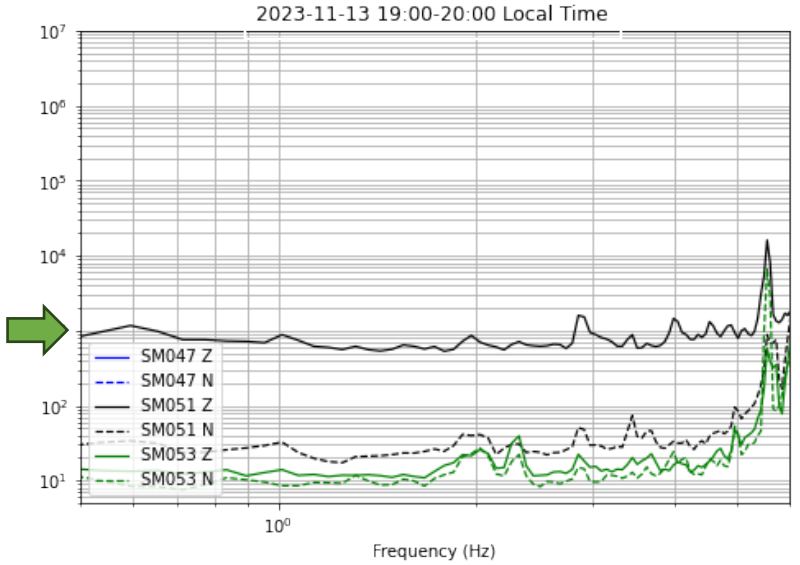
During working hours…
Noise level too high
Mode "hidden"

Tank full at 2% - **LOWER** Noise Level



Late afternoon…
Sufficient energy to trigger mode…
Mode visible!

Tank full at 2% - **LOW** Noise Level



Evening…
Energy in vibration NOT sufficient to trigger the mode

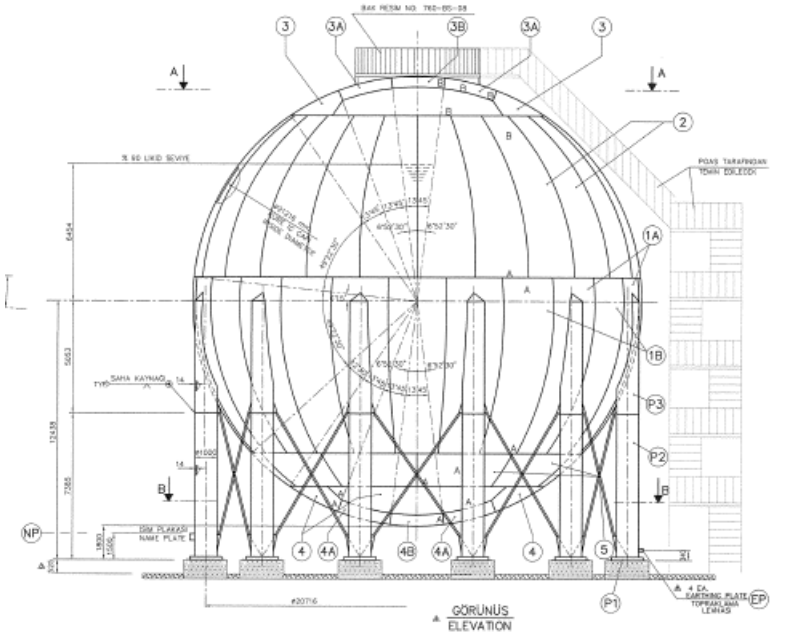
Project I - Modelling | Assumptions

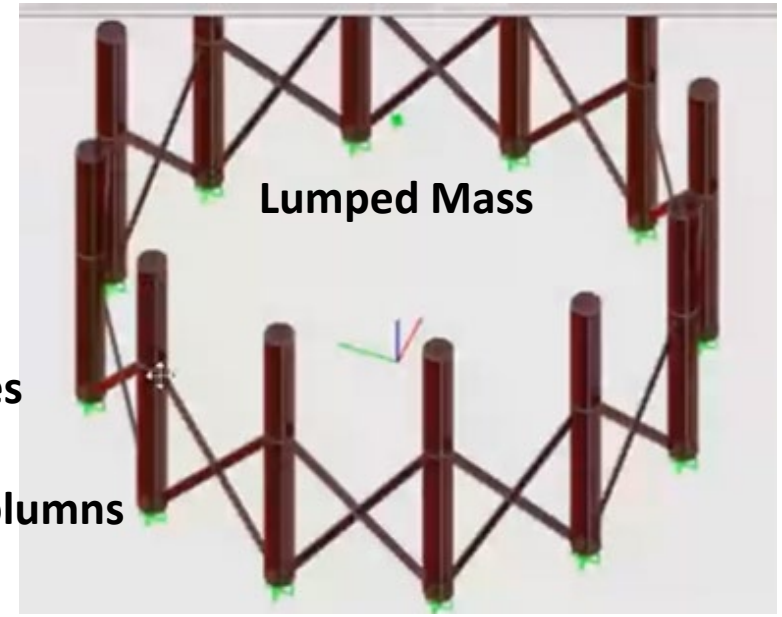
- Model composed of
  - 12 columns of 12 m height with braces, composed of same material
  - 1 lumped mass at centroid of a rigid diaphragm on column tops

- Braces modelled with beam elements welded to columns

- Lumped mass computed with 3 degrees of freedom
  - 2 horizontal planes (X and Y)
  - 1 rotation around vertical axis

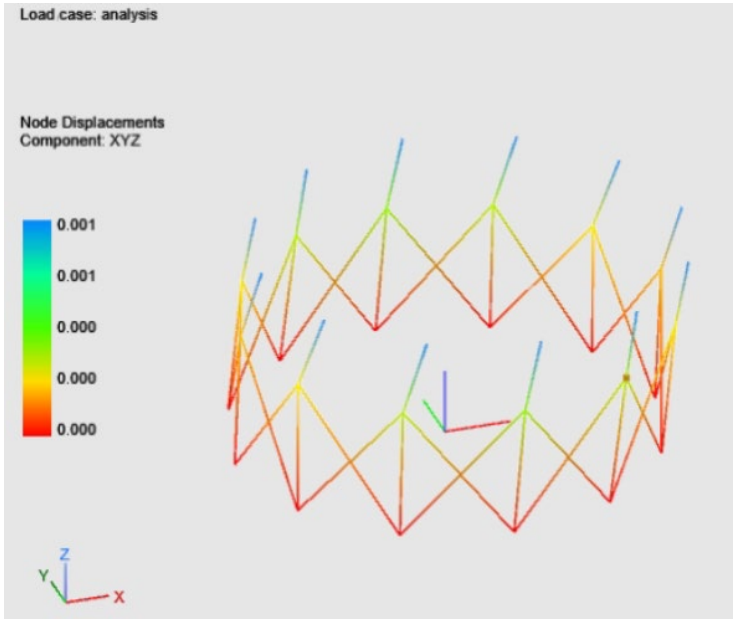
- Assumptions:
  - Model is LINEAR ELASTIC
  - Soil-structure interactions neglected
  - SLOSHING effect is not considered
  - No change in cross-section and stiffness



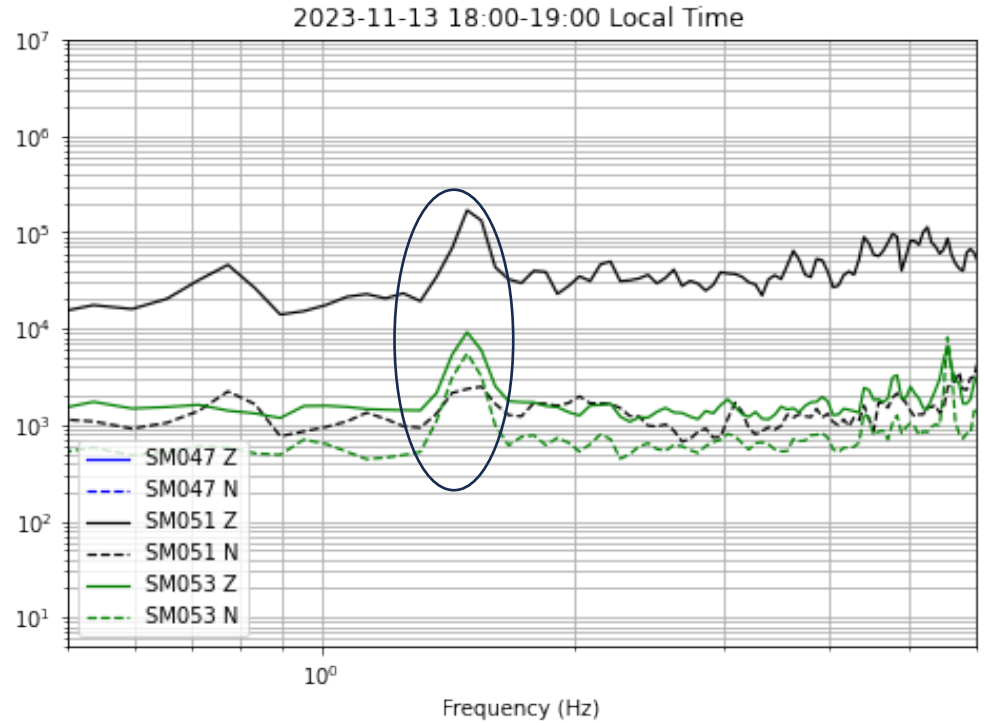


Project I - Modelling vs Data | Frequency of High Mode

F_0 = 1.414Hz **at 2% tank filling**



F_0 = 1.42Hz **at 2% tank filling**



Project I | Summary

Ambient noise used as input for analysis of operational mode for structure

Vibration mode is not always visible:

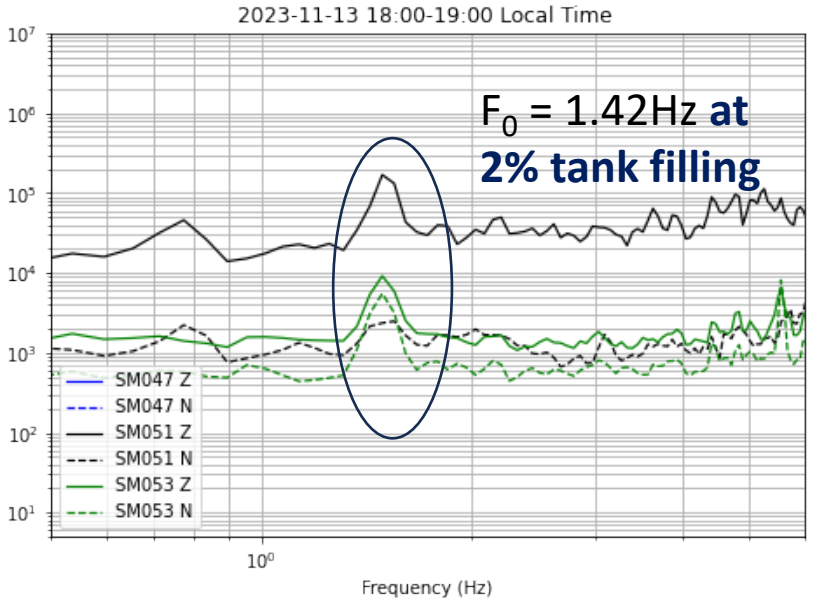
- Need some operational activity to generate vibration in structure
- Too high noise level could mask high amplitude mode at low frequency

Good match between observed and modelled structural mode

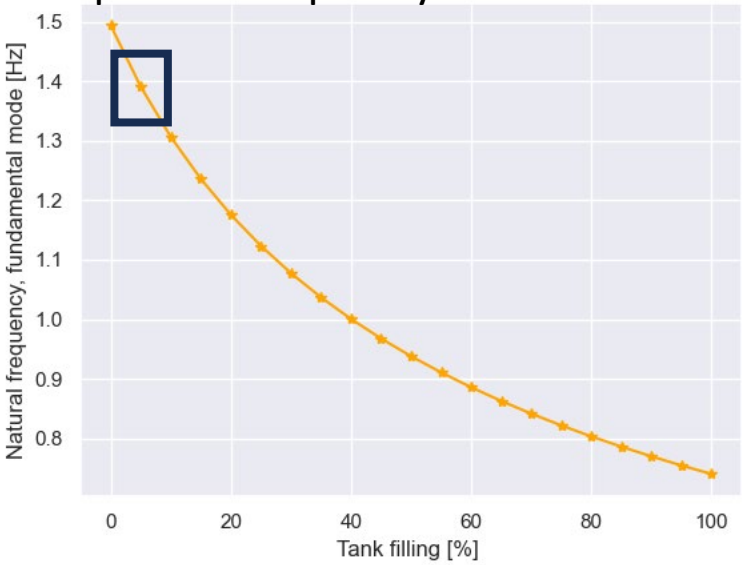
Model shows some decrease in frequency peak of first mode with tank filling – Potential future project idea to monitor complete tank filling/emptying cycle.

Good example of the method application in such context

How to go further with the health structure assessment for major earthquake?
→ Project II



Expected frequency of the first mode



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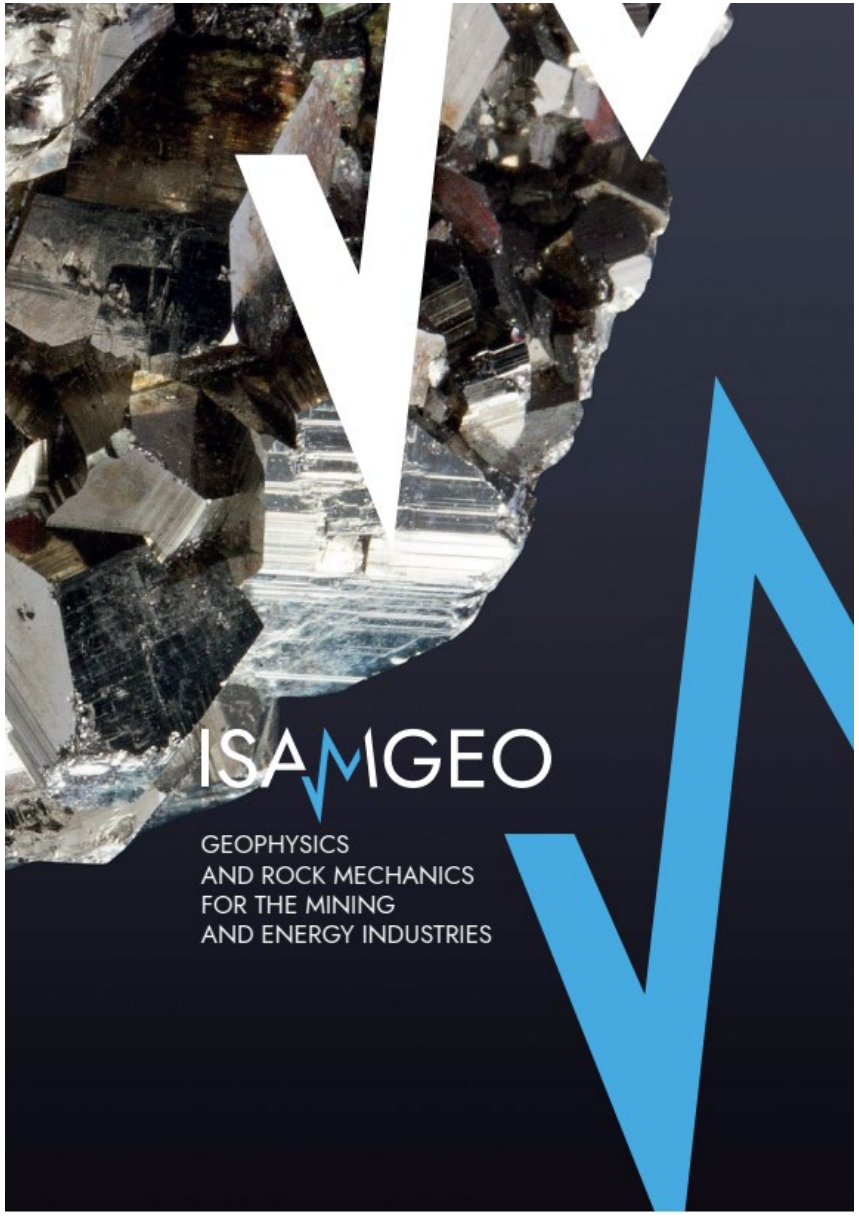


Project II - Critical, High-Risk Buildings | Data Summary

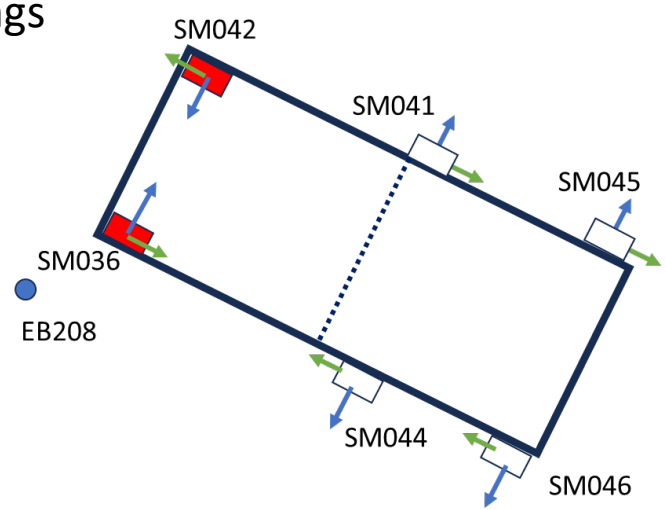
Data recorded from September to December 2023, in Istanbul, Turkey

20 buildings on 9 sites,

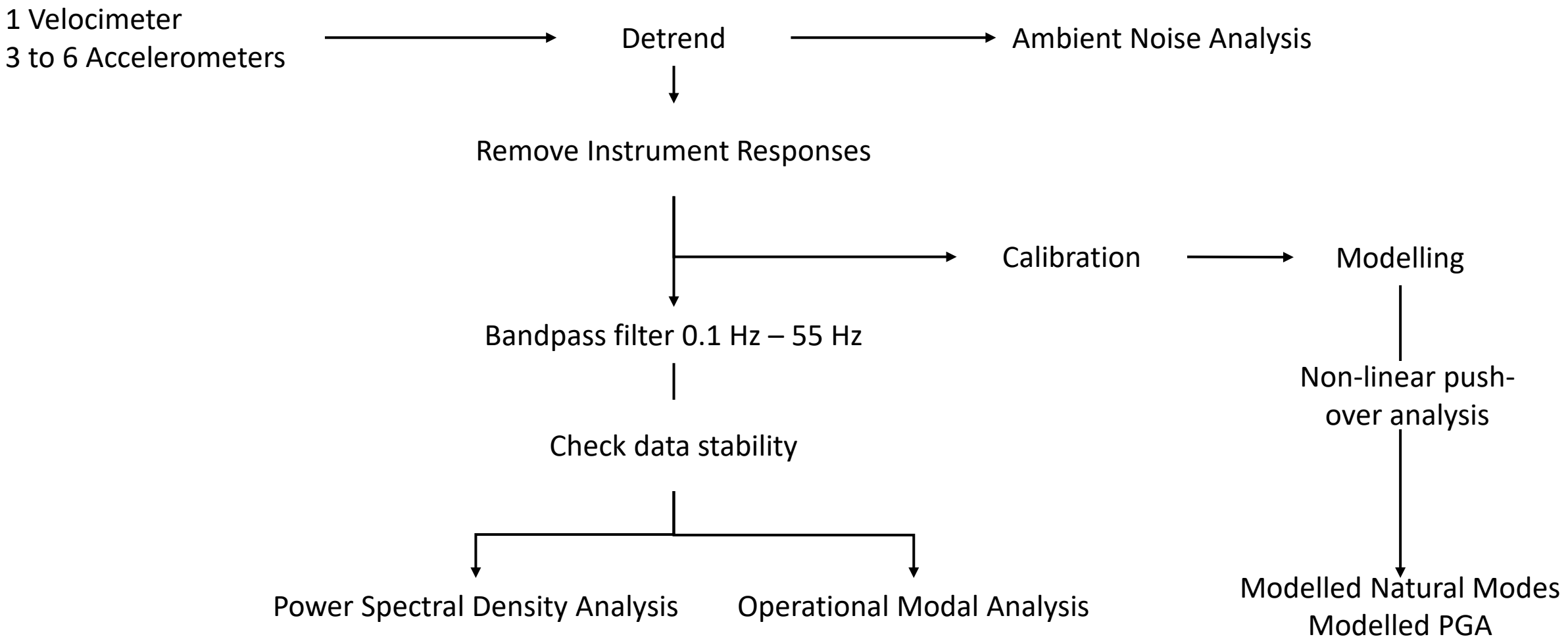
- 3 sites on Asia side with 7 buildings
  - 2 Administrative
  - 5 RMS
- 6 sites on European side with 13 buildings
  - 5 Administrative
  - 8 RMS

Acquisition with 17 receivers:

- 2 velocimeters, deployed on ground near buildings
- 15 accelerometers
  - 3-4 for Admin buildings, deployed inside
  - 5-7 for RMS buildings, deployed 2 inside on pillars and/or outside on walls



Project II - Data & Modelling Workflow



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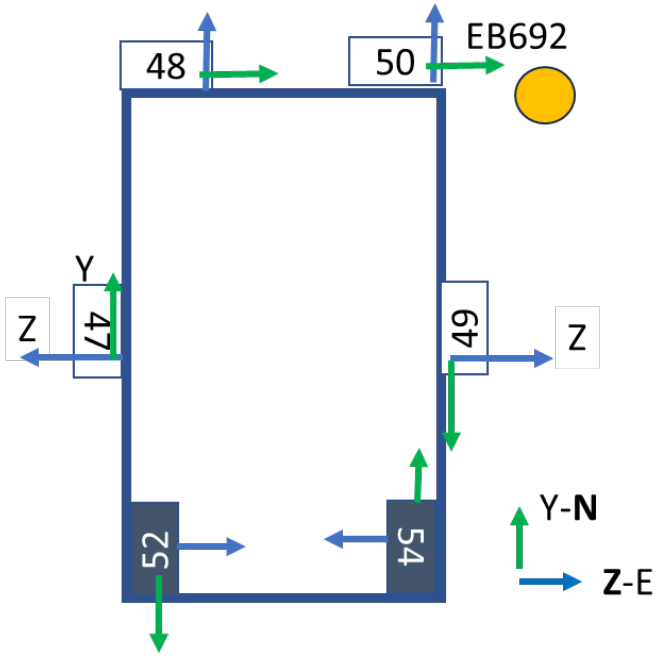
Project II – EU02 Site | Data Analysis on RMS

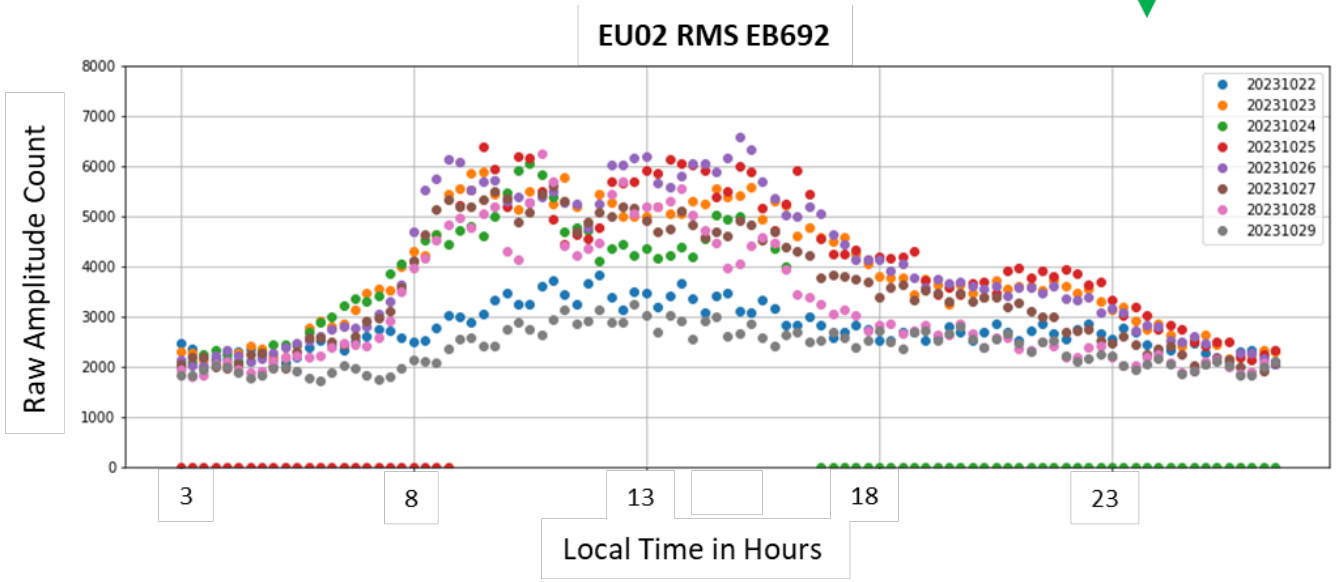
Data recorded from from Oct. 23rd to Oct.30th, 2023 with

- 1 velocimeter
- 6 accelerometers
  - 2 inside on steel pillars
  - 4 outside on reinforced concrete walls

Ambient noise indicate changes of activities between

- Days and nights are well marked
- Decrease in operational noise on Sundays 22 and 29
- Activity break at midday





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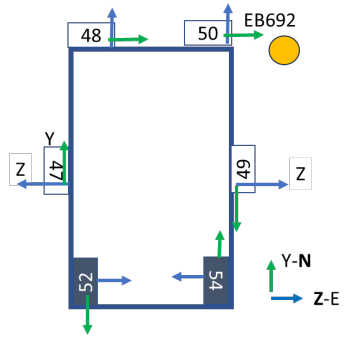
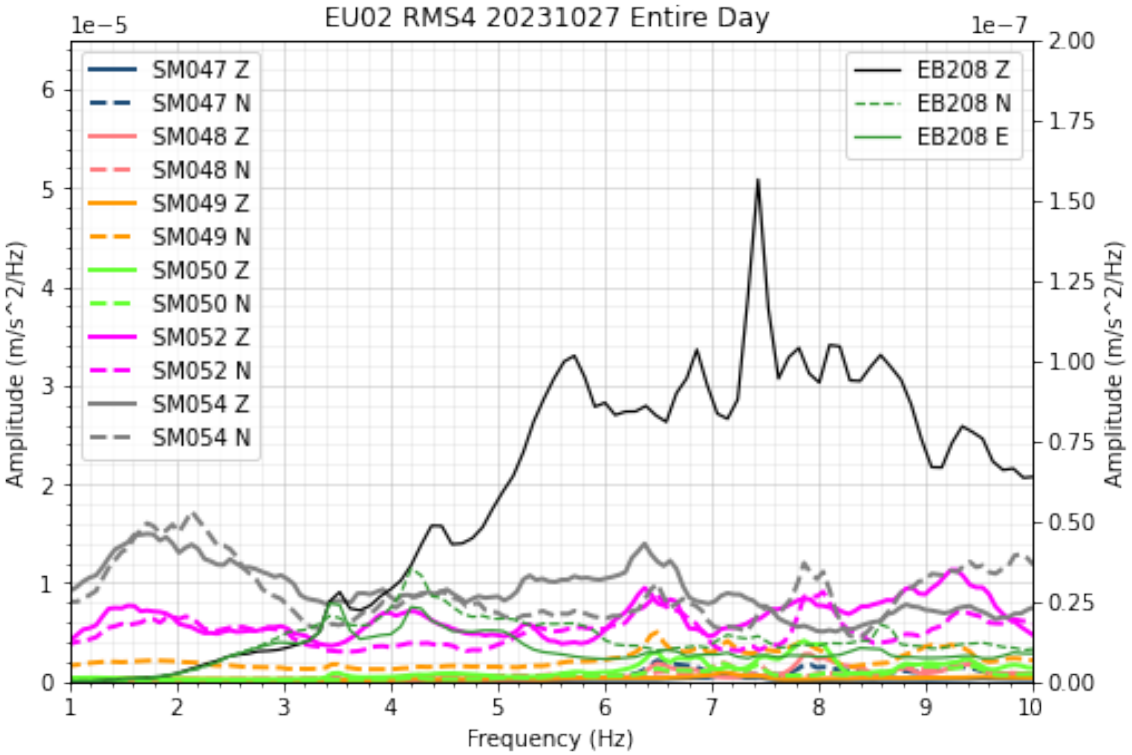
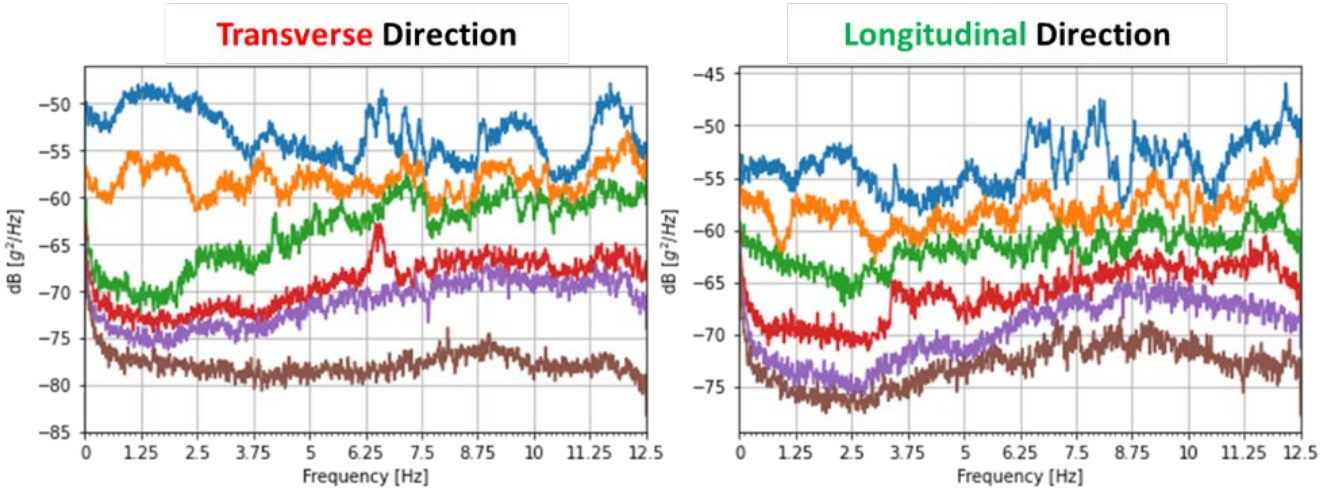


Power Spectral Density provides frequency peaks, refined by Frequency Domain Decomposition

Power Spectral Density



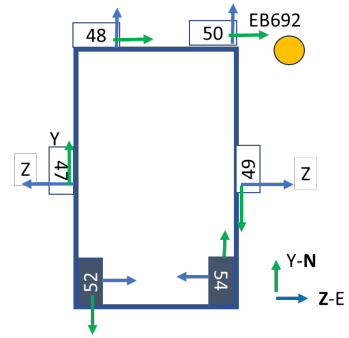
Frequency Domain Decomposition

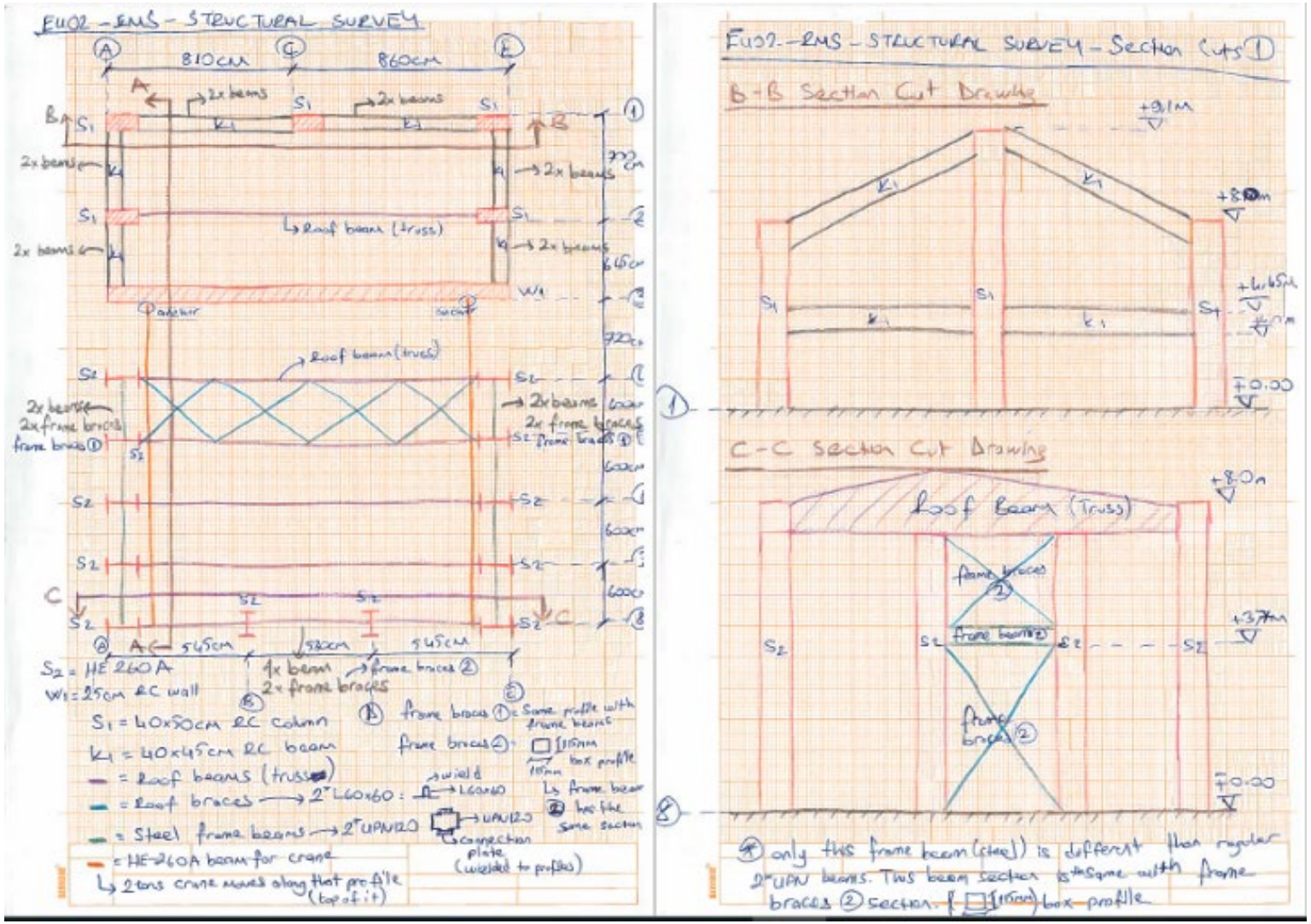


Dag Pasquale Pasca, Angelo Aloisio, Marco Martino Rosso et al., PyOMA and PyOMA_GUI: A Python module and software for Operational Modal Analysis. SoftwareX (2022) 101216, https://doi.org/10.1016/j.softx.2022.101216.

Project II – EU02 Site | Modelling on RMS

The modeling of a building starts from structure design and survey of dimensions and materials

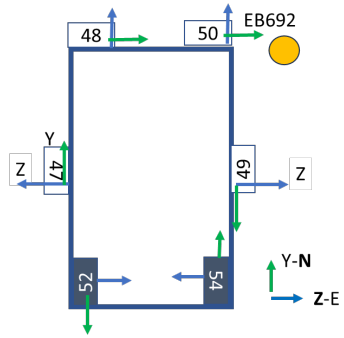




Beams

Columns

Project II – EU02 Site | Finite Element Modeling

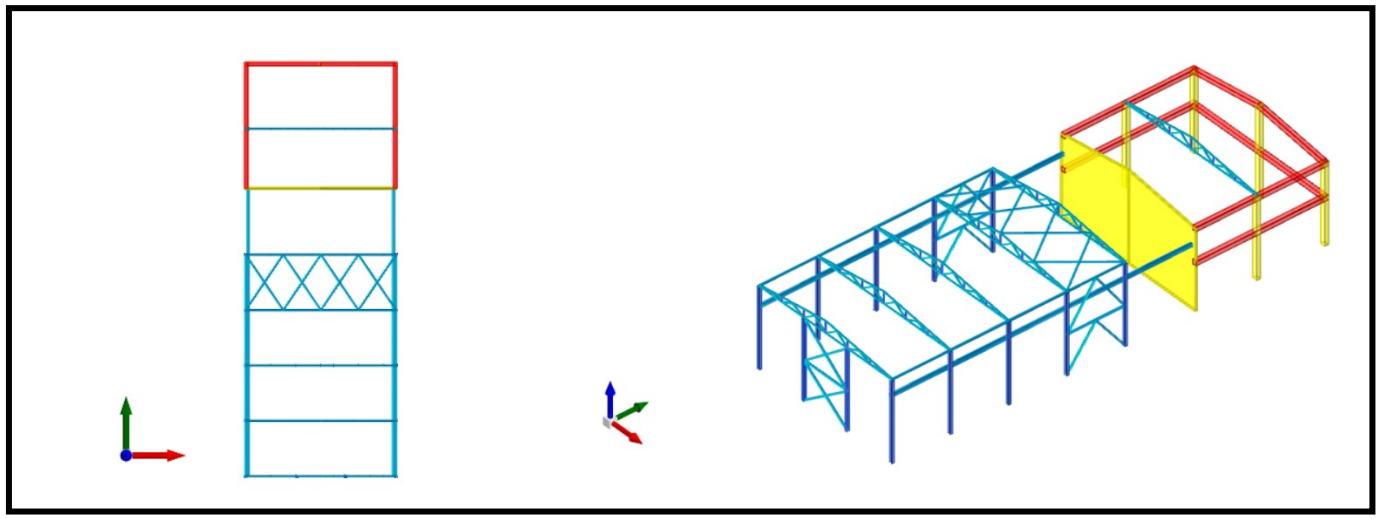


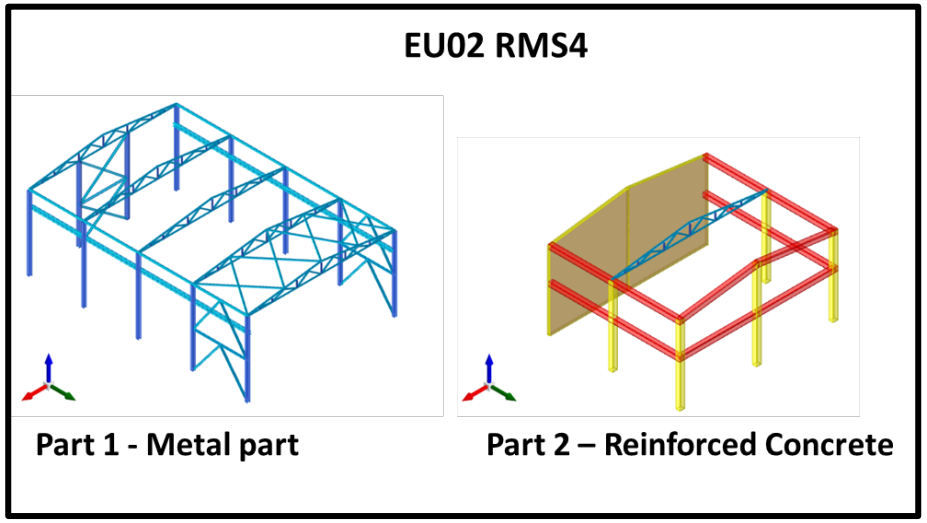
The structural elements of the building consists of

- reinforced concrete,
- Steel columns and beams.

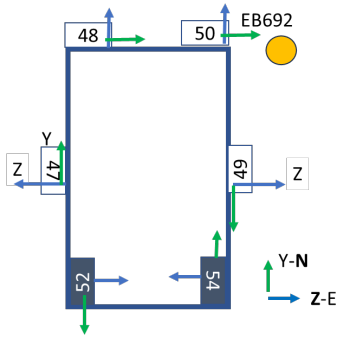
Represented in the finite element method (FEM) using one-dimensional frame elements.

The floor slab consist of reinforced concrete with a thickness of 15 cm.





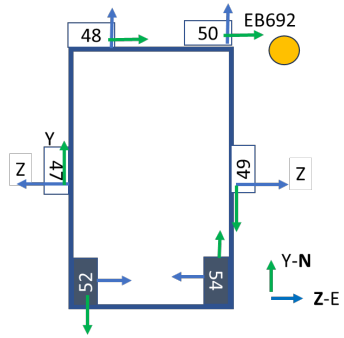
Project II – EU02 Site | Finite Element Modeling



Vibration periods of the most significant modes, based on percentage of total excited mass are compared with observed data

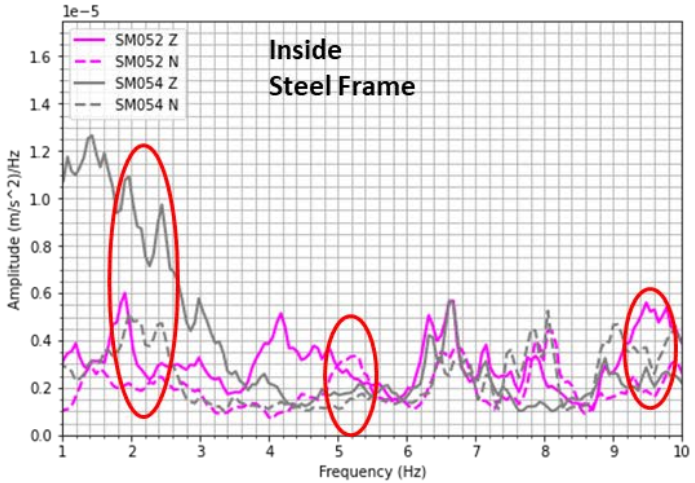
Periodo	Frequency	Massa X	Massa Y	Massa Z	Massa rot. X	Massa rot. Y	Massa rot. Z
4.67	0.21	0.00	0.00	0.00	0.00	0.00	0.00
4.48	0.22	0.00	0.07	0.00	0.12	0.00	0.00
4.27	0.23	0.00	0.04	0.00	0.06	0.00	0.00
1.35	0.74	0.20	0.00	0.00	0.00	0.28	0.04
1.32	0.76	0.02	0.00	0.00	0.00	0.03	0.01
1.26	0.80	0.02	0.00	0.00	0.00	0.03	0.01
0.99	1.01	0.00	0.02	0.00	0.03	0.00	0.00
0.73	1.37	0.00	0.02	0.00	0.03	0.00	0.00
0.67	1.48	0.00	0.02	0.00	0.02	0.00	0.00
0.46	2.18	0.00	0.02	0.00	0.02	0.00	0.00
0.43	2.30	0.00	0.33	0.00	0.38	0.00	0.02
0.41	2.41	0.00	0.01	0.00	0.01	0.00	0.00
0.40	2.49	0.20	0.00	0.00	0.00	0.26	0.30
0.37	2.68	0.00	0.11	0.00	0.10	0.00	0.01
0.27	3.65	0.00	0.05	0.00	0.07	0.00	0.00
0.27	3.67	0.03	0.00	0.00	0.00	0.03	0.11
0.27	3.77	0.00	0.01	0.00	0.01	0.00	0.00
0.26	3.86	0.00	0.04	0.00	0.05	0.00	0.00
0.23	4.31	0.00	0.01	0.00	0.01	0.00	0.00
0.20	5.06	0.00	0.07	0.00	0.05	0.00	0.00
0.13	7.99	0.00	0.01	0.00	0.00	0.00	0.00
0.12	8.15	0.00	0.01	0.00	0.01	0.00	0.00
0.10	9.75	0.04	0.00	0.00	0.00	0.05	0.00

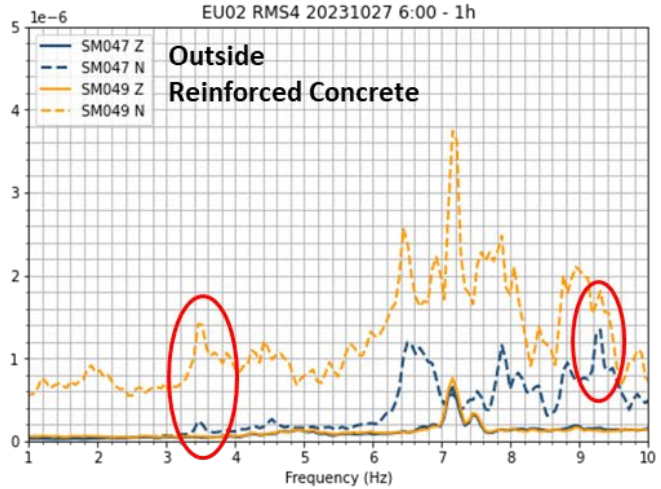
Project II – EU02 Site | Finite Element Modeling

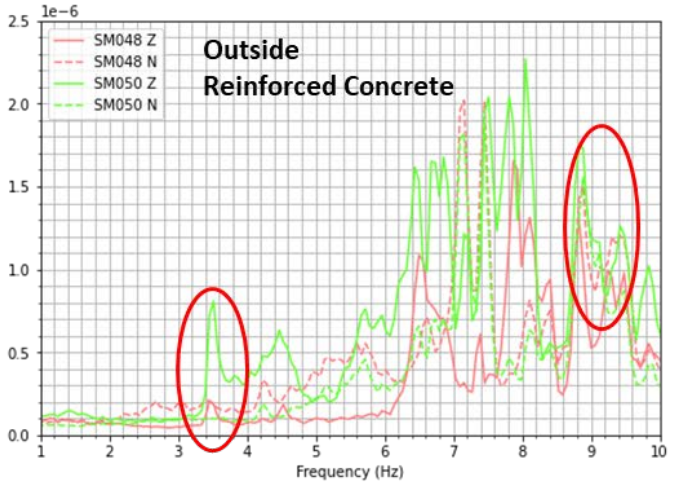


Vibration periods of the most significant modes, based on percentage of total excited mass are compared with observed data

Frequency
0.21
0.22
0.23
0.74
0.76
0.80
1.01
1.37
1.48
2.18
2.30
2.41
2.49
2.68
3.65
3.67
3.77
3.86
4.31
5.06
7.99
8.15
9.75







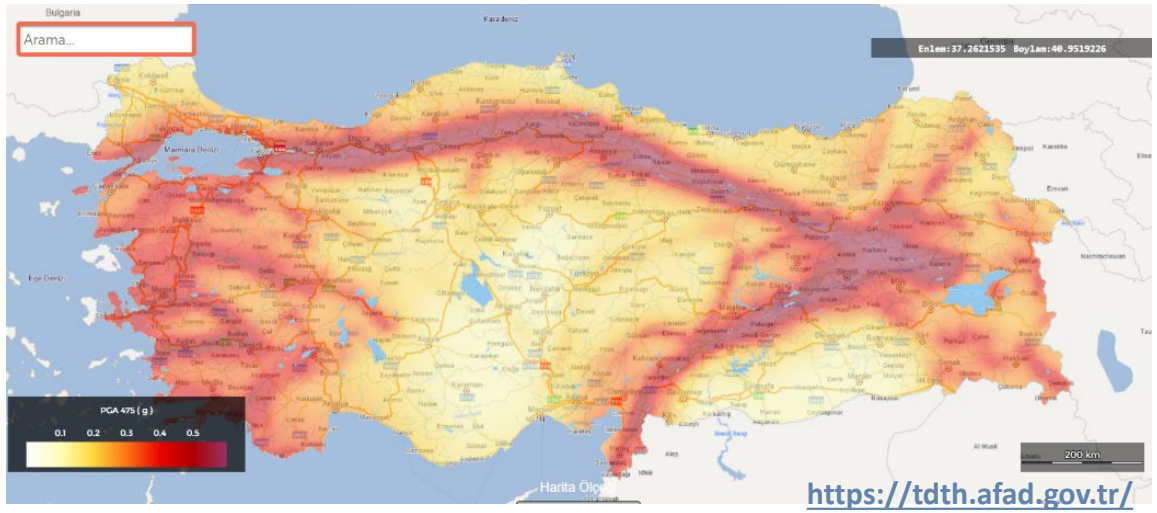
		Peak Frequencies	
		Observed	Modelled
EU02	RMS4		2,3
		2,0	2,5
		2,5	2,7
		3,5	3,7
		4,0	3,9
		5,2	5,1
		6,5	
		8,0	
			9,8
			10,0

Project II – EU02 Site | Risk Analysis

From Turkish Earthquake Hazard Map, **lateral elastic design spectra** for TBEC-2018 (Turkish Building Earthquake Code 2018)

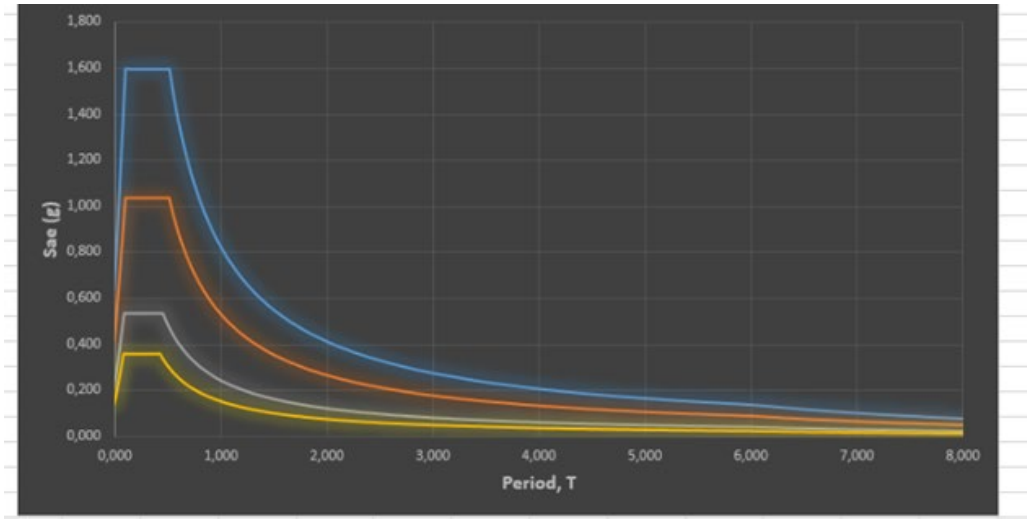
Used for the dynamic modelling analysis.

Turkish Earthquake Hazard Map



EU02

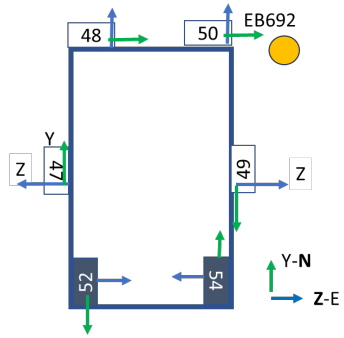
DD-1 DD-2 DD-3 DD-4



Ground Motion Levels (GML) with probability of exceedance in 50 years and return period

- DD1: 02% - 2475 years
- DD2: 10% - 475 years
- DD3: 50% - 72 years
- DD4: 68% - 43 years

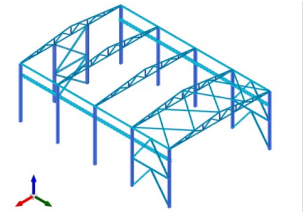
Project II – EU02 Site | Non-Linear Push-Over



Estimate the collapse mechanisms

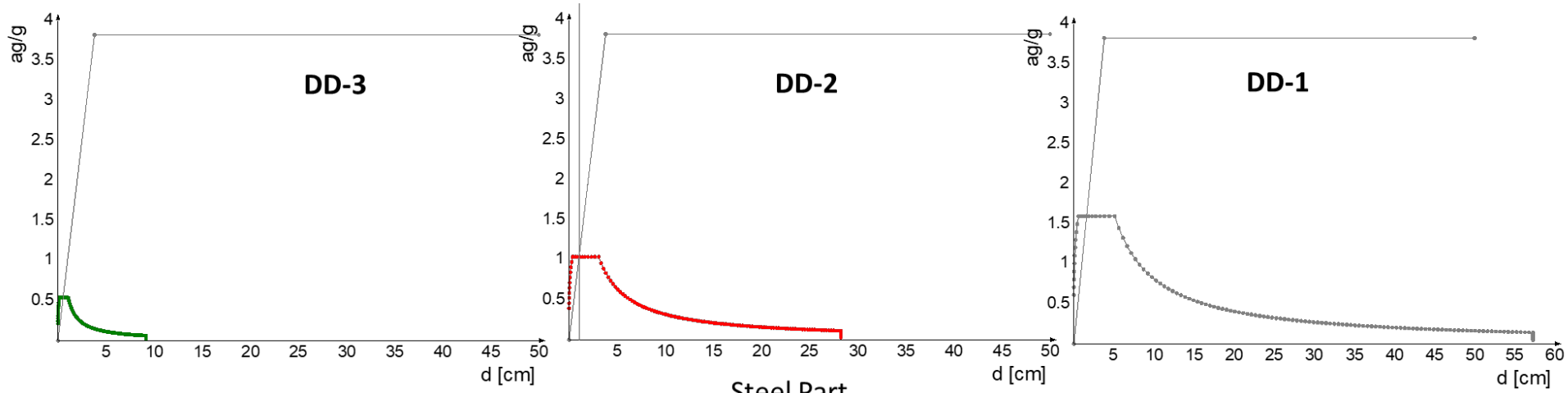
Capacity Curves against Lateral Elastic Design

Provide Peak Ground Acceleration (PGA) at which plasticity occurs in 1 or 2 directions.



Part 1 - Metal part

Steel Part

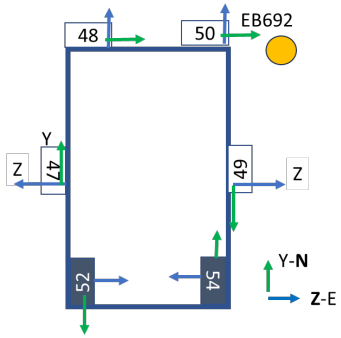


Steel Part

EU02 RMS

For the steel part, not necessary to scale the project spectrum to find the PGA for transition from elastic to plastic field
Even under maximum expected seismic event, DD-1 spectrum, the structure remain intact.

Project II – EU02 Site | Non-Linear Push-Over



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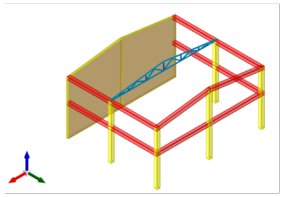
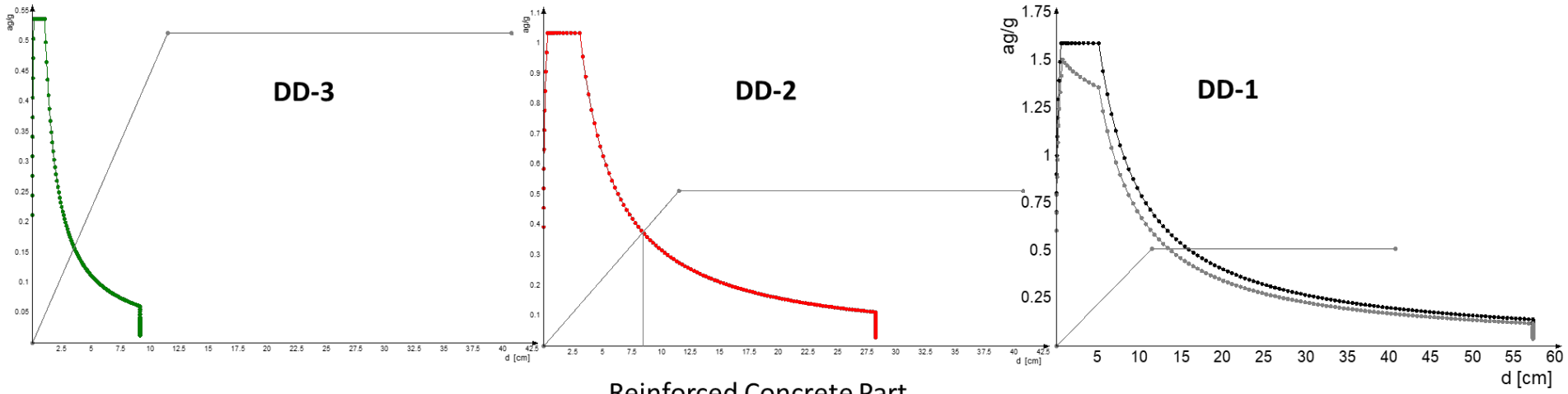


Part 2 – Reinforced Concrete

Reinforced Concrete Part



Reinforced Concrete Part

EU02 RMS

For the reinforced concrete part, plateau of scaled spectrum is at a value of 1.400g, the value of spectrum DD-1.

The PGA, calculated by considering 40% of this value, thus results in 0.560 g.

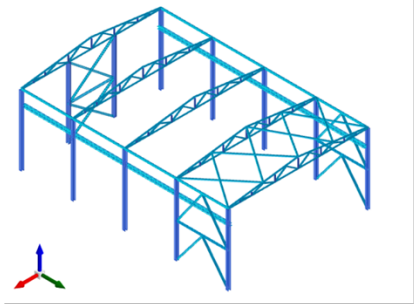
Project II | Summary

Method applied to critical, high-risk buildings on 20 buildings across 9 sites.

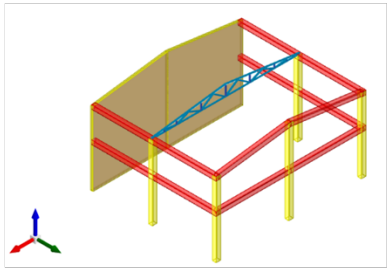
Data analysis serves the modelling calibration for the building modelling.

The analysis provides information on which buildings or which parts of the buildings are more at risk.

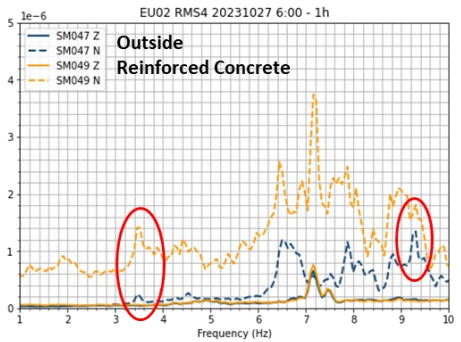
EU02 RMS4

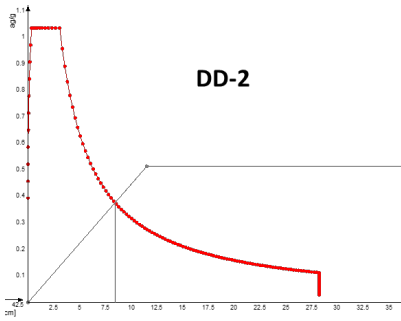


Part 1 - Metal part



Part 2 – Reinforced Concrete





Reinforced Concrete Part

EU02 RMS

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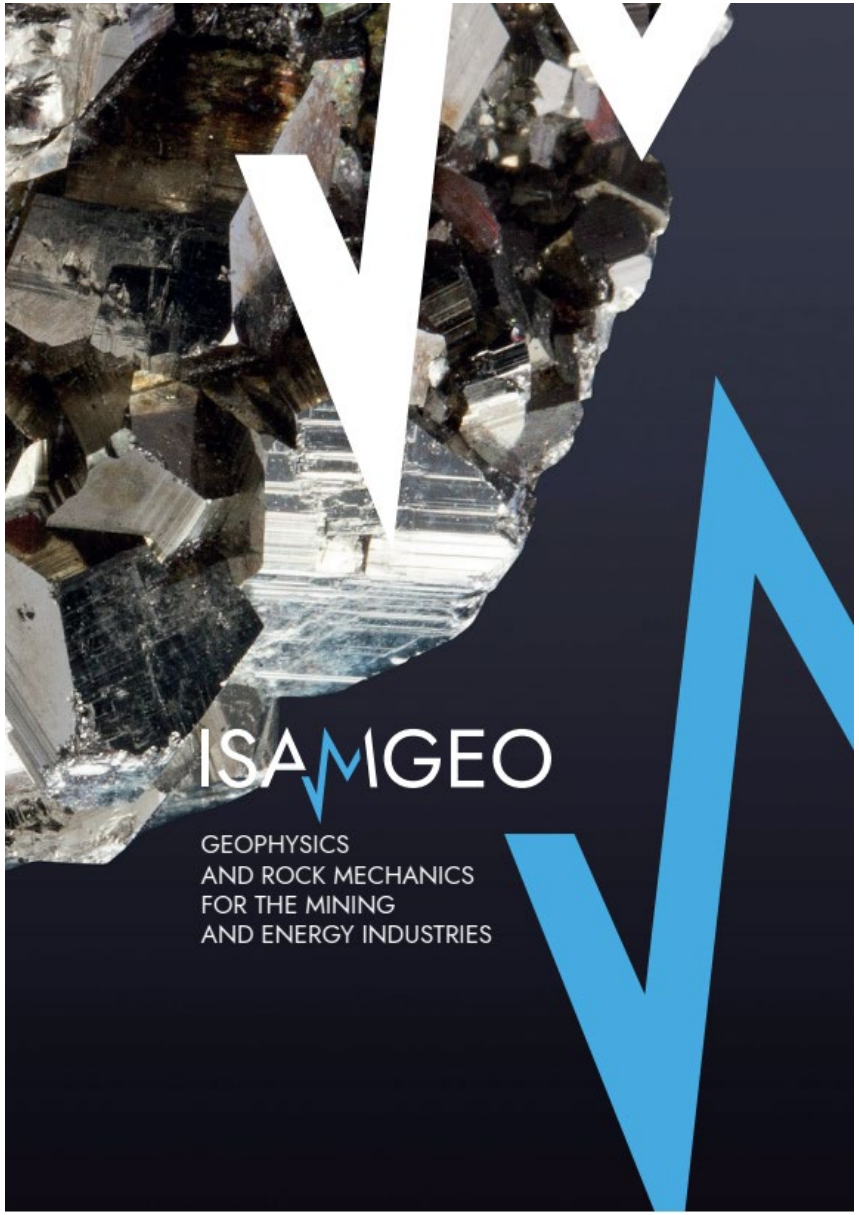
Summary

- Passive Monitoring of Building
  - Structural Health Monitoring
  - Operational Modal Analysis
- Project I – Pressurized Vessel
  - Example of Method Application
- Project II – Critical, High-Risk Buildings Analysis
  - Example of Structural Health Assessment for major earthquake



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Thank you!

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