



Advances in Seismic Structural Health Monitoring

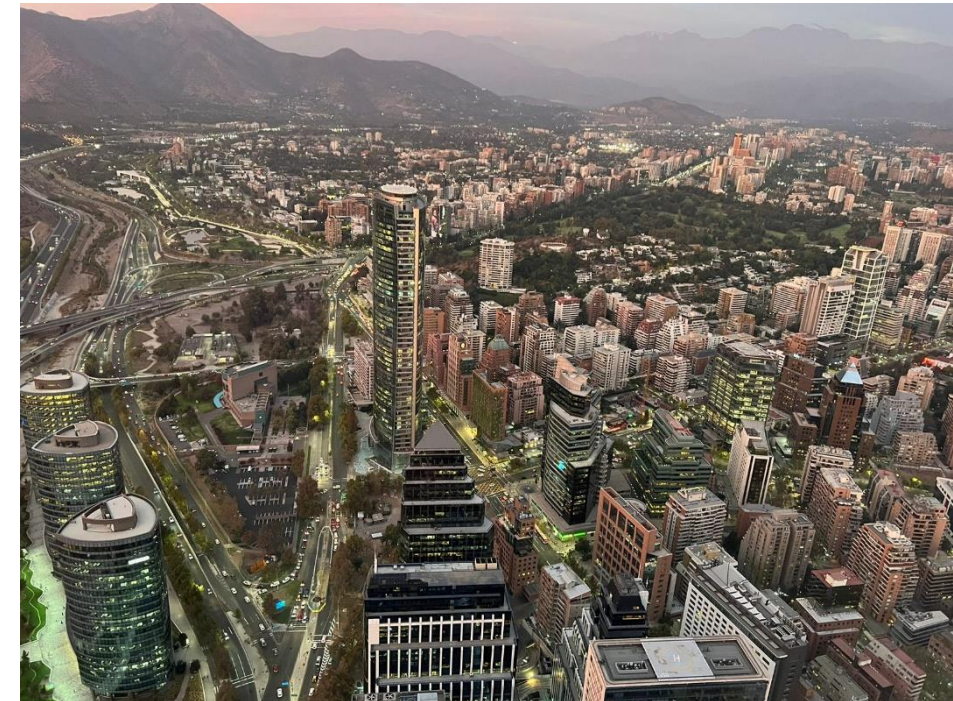
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University of Chile**

**Past President COSMOS
www.strongmotion.org**

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**May 7
IOMAC**



Acknowledgement

Students (many years)

Felipe Alarcón, Miguel Aros, Julio Basualto, Joaquín Bilbao, Rodrigo Carreño, Alejandro Castillo, Tomás Espinoza, Andrés Ferrada, Matías Garrido, Andres Garreau, Wladimir González, Raúl Henríquez, Ernesto Jiménez, Erick Inga, Gustavo Lagos, Pablo León, Patricio Lazcano, Felipe Norambuena, Álvaro Pino, Patricia Porcél, Javier Ramírez, Nicolas Riveros, Felipe Tamayo, Pilar Toledo, Perla Valdez, Pastor Villalpando, Tomas Yáñez, Giacomo Zonno, ...

Engineers

- Emilio Peña
- Pastor Villalpando
- Carlos Poblete

Professors

- Rafael Aguilar
- Enrique López Droguett
- Joao Santos
- Viviana Meruane
- Carlos Ventura
- Hamed Ebrahimian
- Xavier Brunetaud
- Sylvie Treuillet

USGS ShakeMap : OFFSHORE MAULE, CHILE
 Sat Feb 27, 2010 06:34:14 GMT M.8.8 S35.85 W72.72 Depth: 35.0km ID:2010tfan

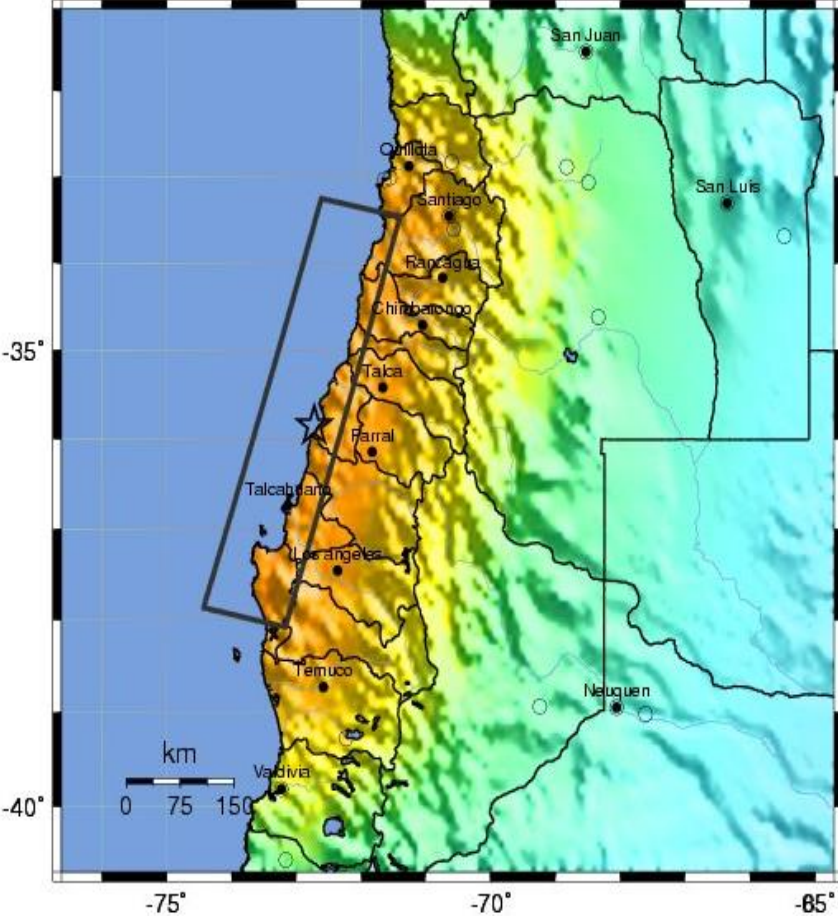
CHILE 2010 Mw=8.8

Strongly Shaken Area: 600 x 200 km
Large Permanent Ground Displacements
Large Energy Release Areas / Asperities

8.000.000 People affected.

Infraestructura Stock

10.000 Buildings 3 story or more
12.000 Bridges, overpass and footbridges
(most of them in affected area)
150 Hospitals
151 Ports



Map Version 6 Processed Sat Feb 27, 2010 01:40:36 PM MST - NOT REVIEWED BY HUMAN

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Schools
Water
Energy

..
230.000 Destroyed Houses

Extensive Damage



3.000 Engineers

4 Month for preliminary review of damage infrastructure

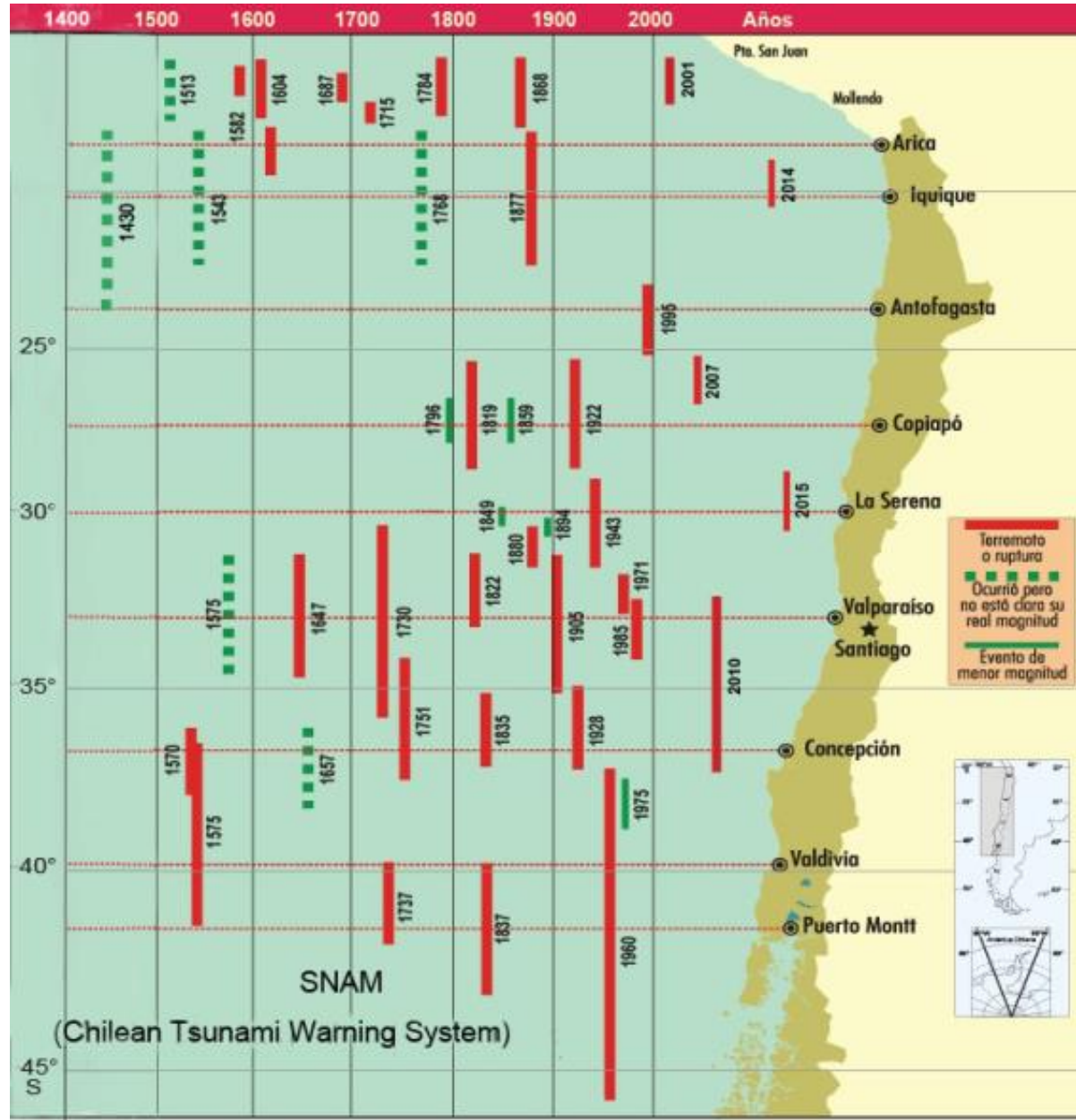
... More than 90 relevant aftershocks



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CHILE A HISTORY OF LARGE EQ



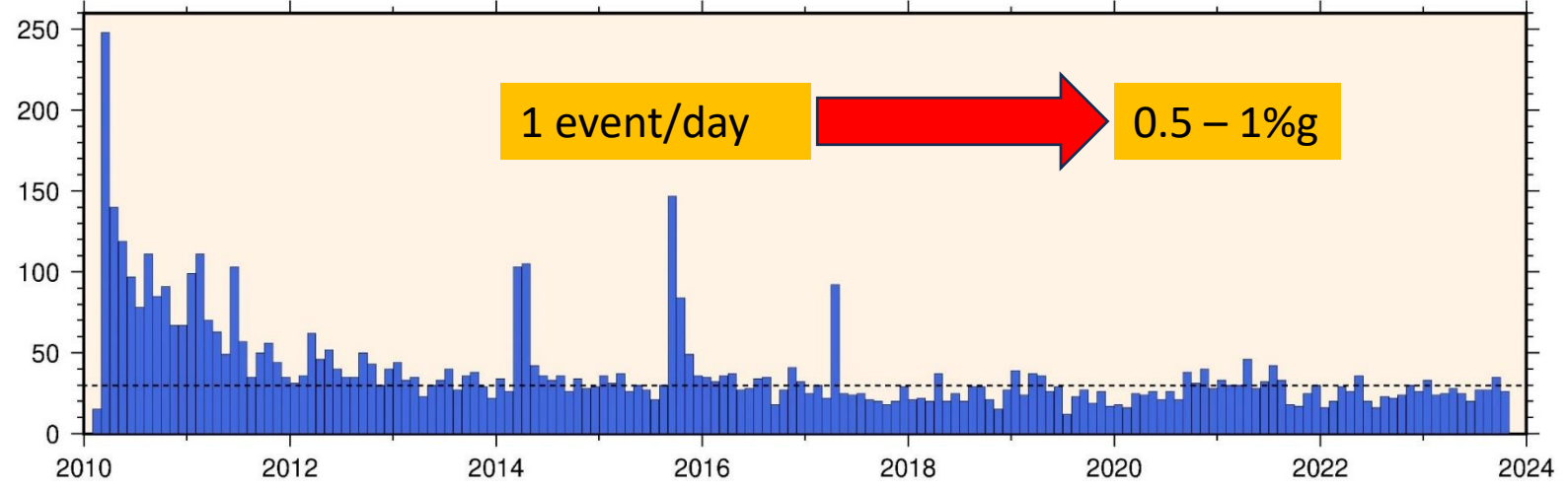
	DATE	MAGNITUDE	APROX LOCATION
1570	Feb.8	8 - 8 1/2	Concepcion
1575	Dec. 16	8 1/2	Valdivia
1604	Nov.24	8 1/2	North de Arica
1647	May. 13	8 1/2	Valparaiso
1657	Mar. 15	8	Concepcion
1730	Jul. 8	8.8	Valparaiso
1737	Dec. 24	7 1/2 - 8	Valdivia
1751	May. 25	8 1/2	Concepcion
1796	Mar. 30	7 1/2 - 8	Copiapo
1819	Apr. 3-11	8.3	Copiapo (3 EQ)
1822	Nov. 19	8 1/2	Valparaiso
1835	Feb.20	8 - 8 1/2	Concepcion
1837	Nov.7	8	Valdivia
1868	Aug.13	8 1/2	Arica
1877	May.9	8	Iquique
1880	Aug. 15	7 1/2 - 8	Illapel
1906	Aug.16	7.9	Valparaiso
1922	Nov.10	8.4	Vallenar
1928	Dec. 1	8.4	Talca
1939	Jan.24	8 - 8.3	Chillan
1943	Abr. 6	8.3	Illapel
1950	Dec. 9	8	Calama
1960	May. 22	9.5	Sur de Chile
1966	Dec. 28	8.1	Taltal
1985	Mar. 3	7.8	Zona Central
1995	Jul. 30	8	Antofagasta
2001	Jun.23	8.4	South Peru
2005	Jun.13	7.8	Tarapaca
2010	Feb.27	8.8	Center-South
2014	Apr. 1	8.2	Iquique
2015	Sep. 16	8.3	Canela Baja

Aprox 1 in 12-15 years

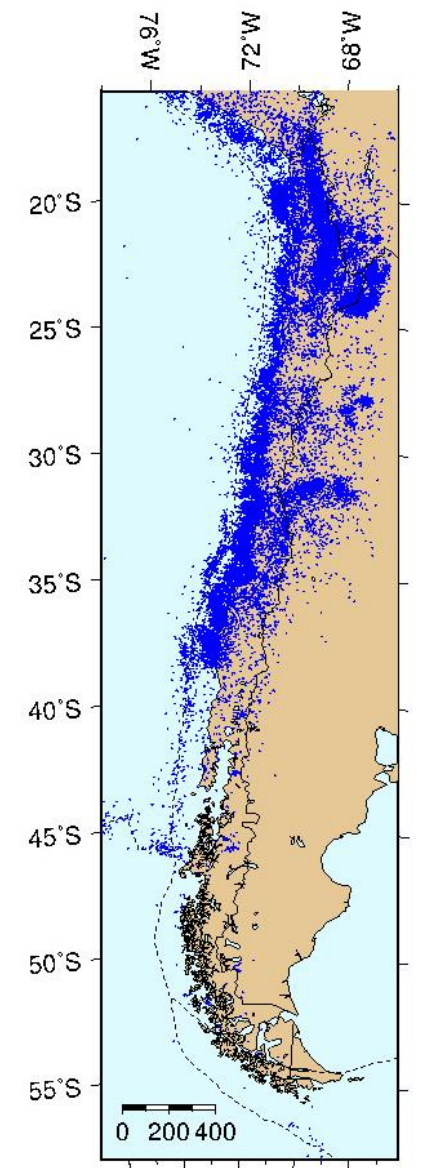
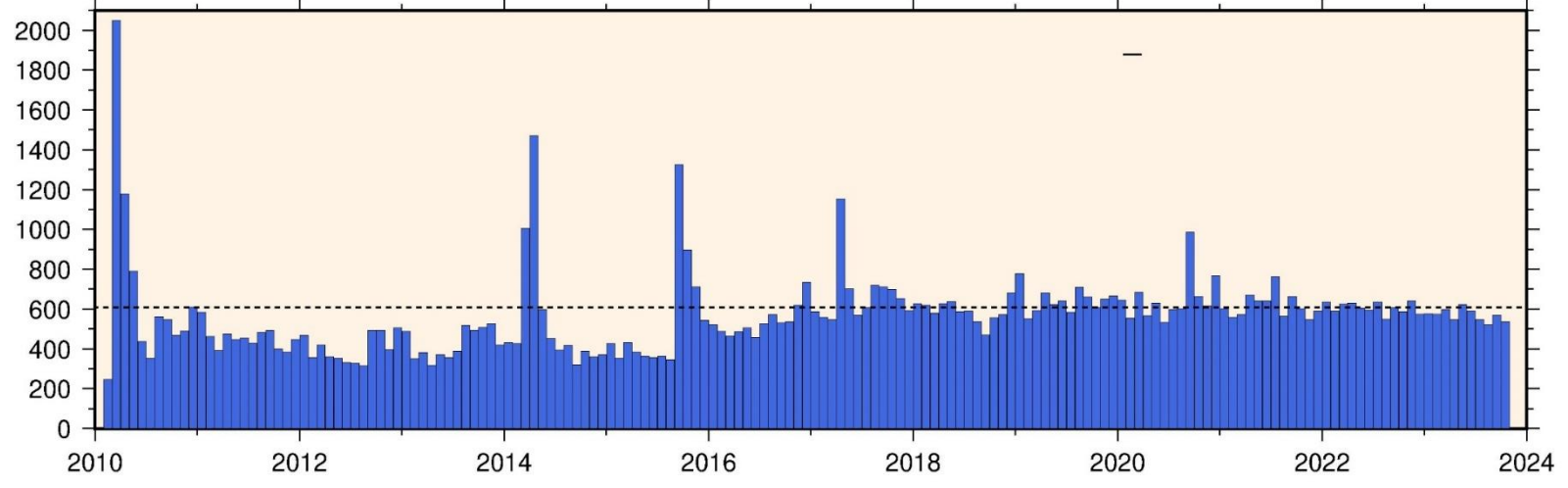
Seismicity of Chile



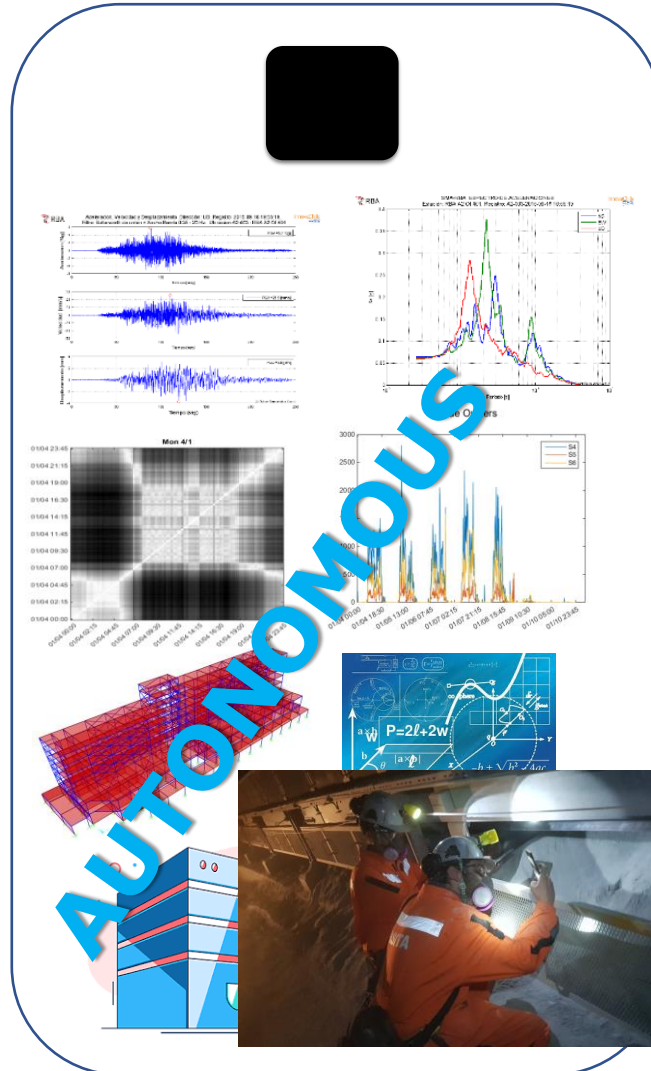
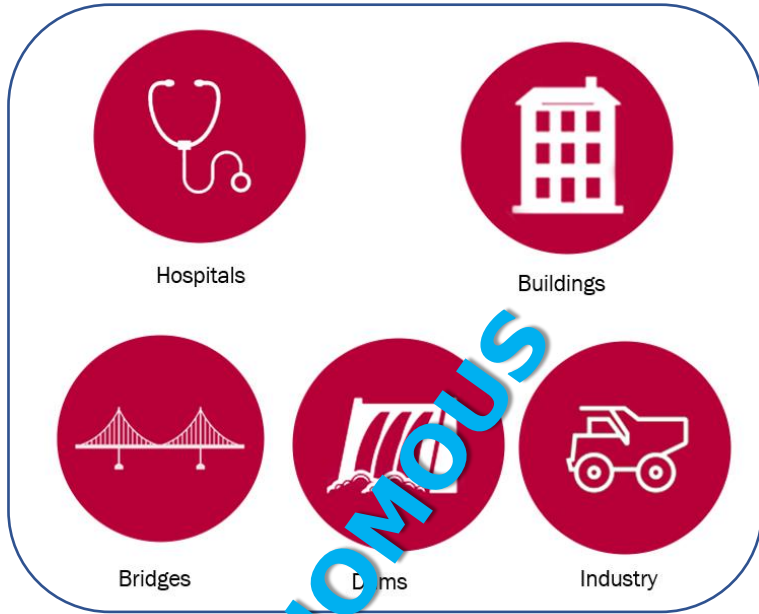
Number of felt earthquakes/month



Total number of events/month (M > 3)



SHM





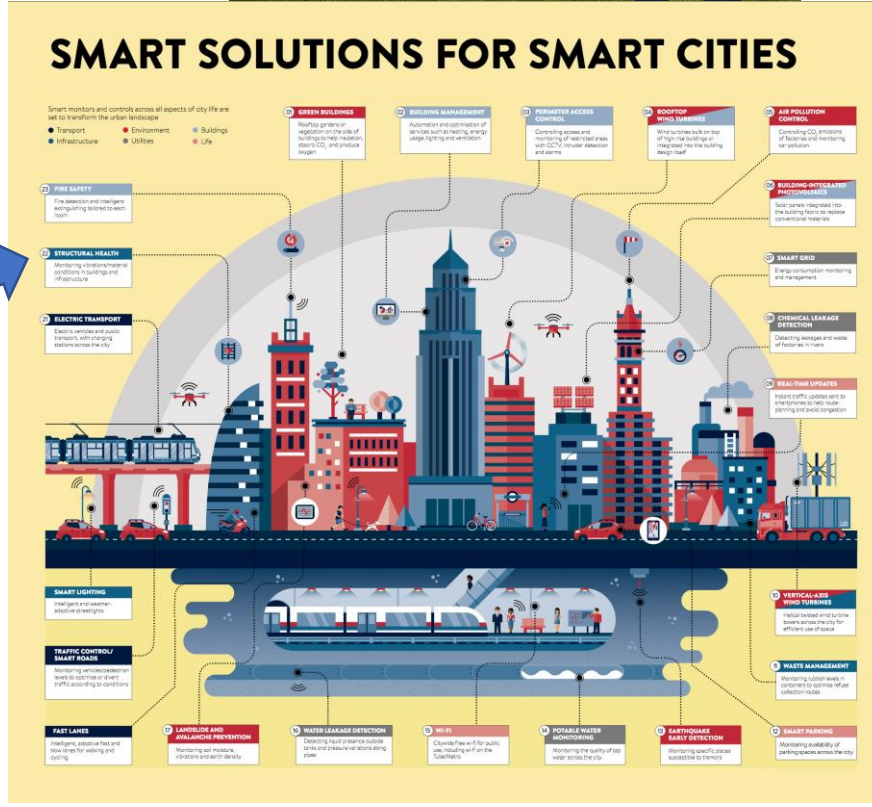
DIGITEX
Kinometrics
Nanometrics
Guralp
Analog
Devices
MicronOptics
Luna
Microsoft
RaspberrySh
ake
FLIR
DJI



22 STRUCTURAL HEALTH

Monitoring vibrations/material conditions in buildings and infrastructure

**WORLD ECONOMIC FORUM JANUARY 9, 2019:
"THIS IS WHAT THE CITIES OF THE FUTURE COULD
LOOK LIKE"**



Are we there yet?

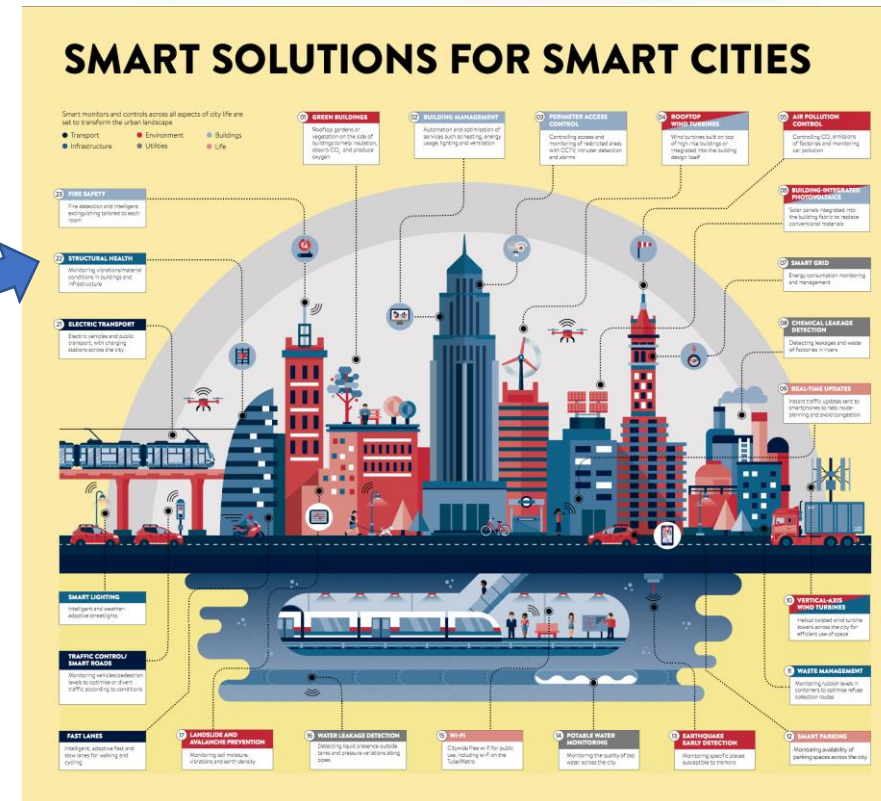
NON SHM Instrumentation

- ☺ • Ground Level EQ Instrumentation.
- ☺ • Early Warning Systems
- ☺ • Real time structural data

Structural Health Status Monitoring

- ☺ • Nuclear
- ☺ • LNG
- ☺ • Dams
- ☺ • Hospitals
- ☺ • Bridges
- ☹ • Data Centers
- ☹ • Office Buildings
- ☹ • Residential

- ☹ • Pipelines



WORLD ECONOMIC FORUM JANUARY 9, 2019:
"THIS IS WHAT THE CITIES OF THE FUTURE COULD LOOK LIKE"

Common Sensor Distribution in Buildings and Objectives

I. Critical Parameters

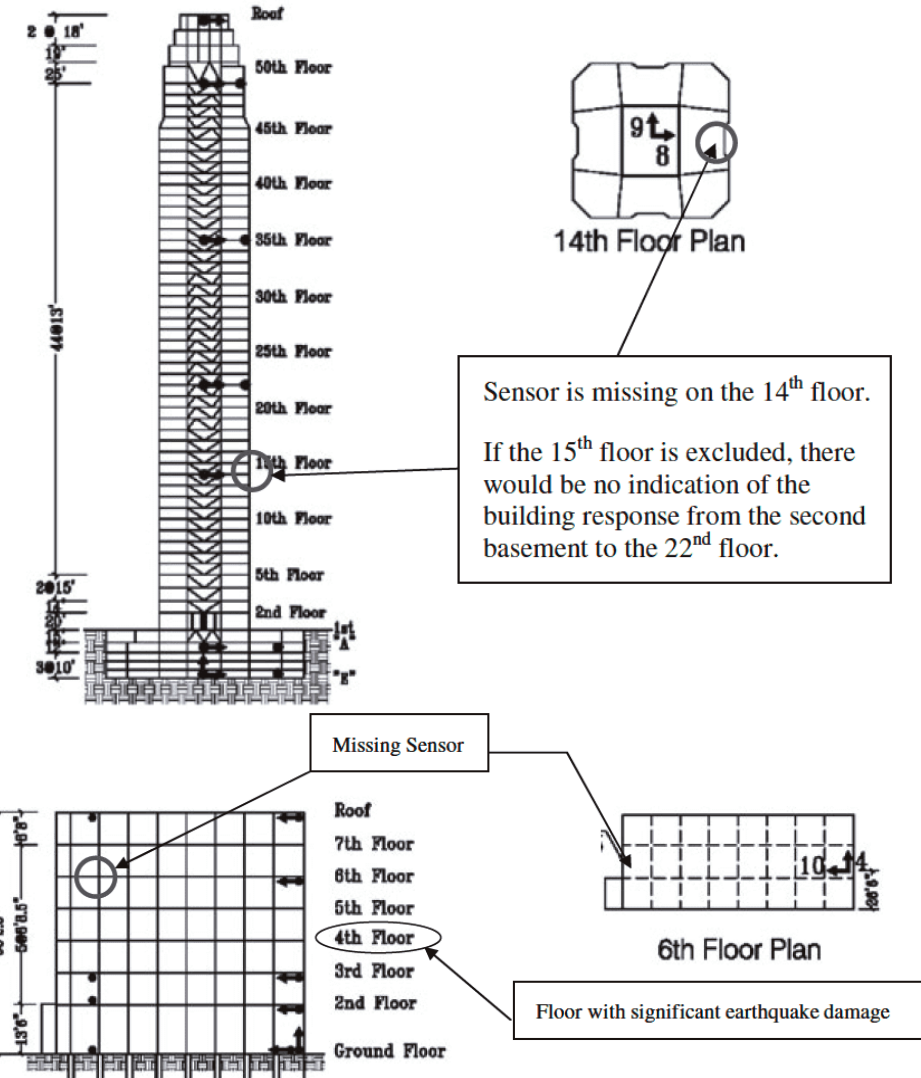
- a. Interstory Drifts
- b. Base shear
- c. Residual drifts

II. Other Important Parameters

- a. Floor acceleration and spectra
- b. Maximum displacements

III. Damage detection

- a. Modal parameters
- b. Hysteresis
- c. CAV, Peak Structural Accel, Vel, Disp.
- d. Many others

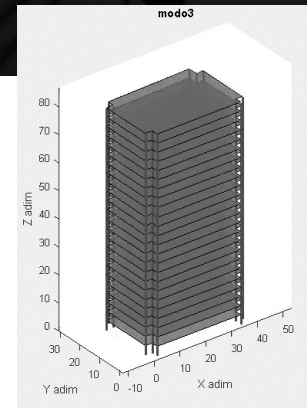
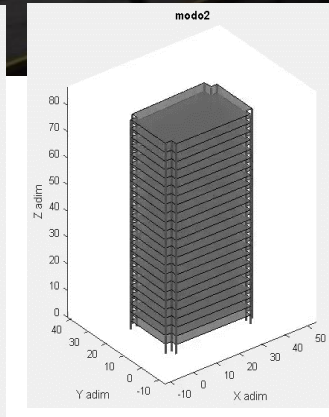
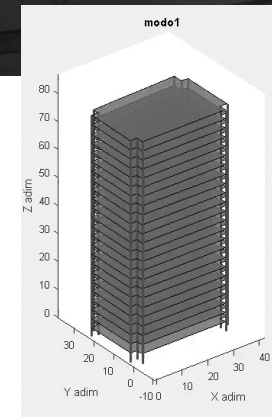
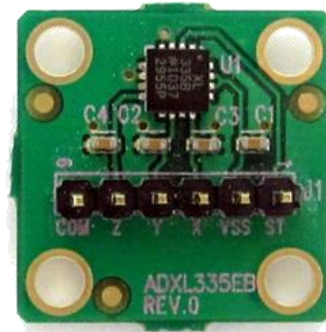


Confronting difficulties

- No Standard Package (black box)
- Instrumentation Cost (initial and maintenance)
- Limited Human Resources
- Limited Instrumentation (permits, cables, modifications)
- Low knowledge/interest of owners/users

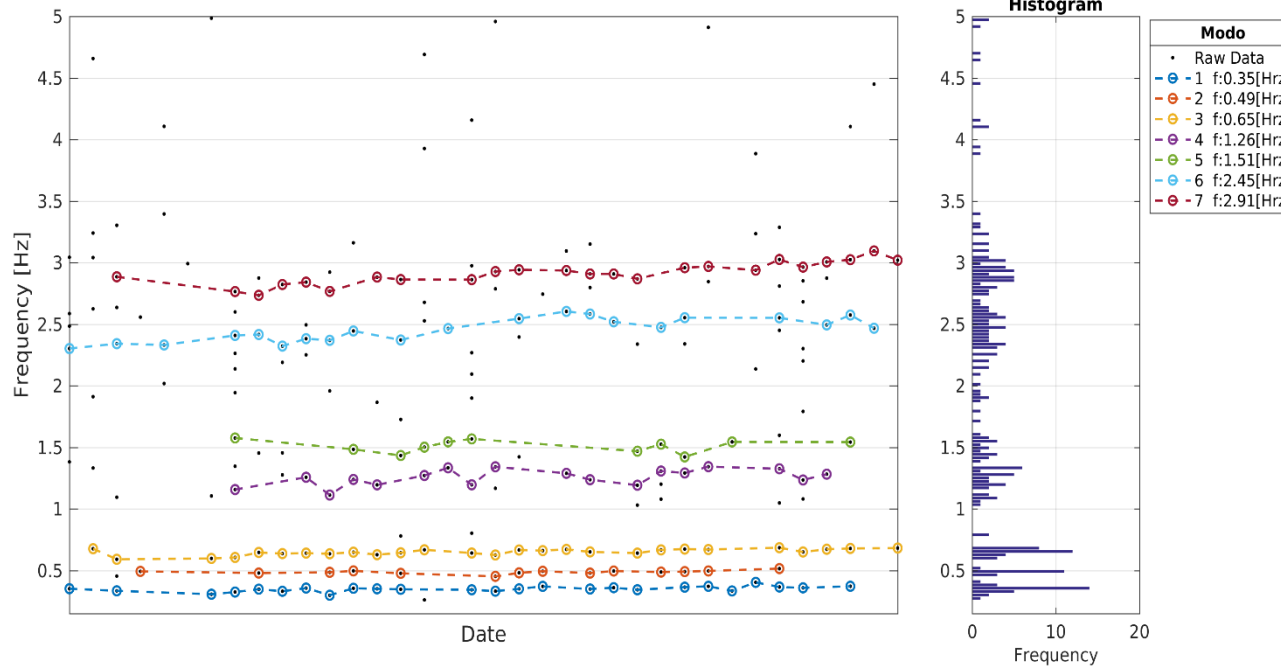
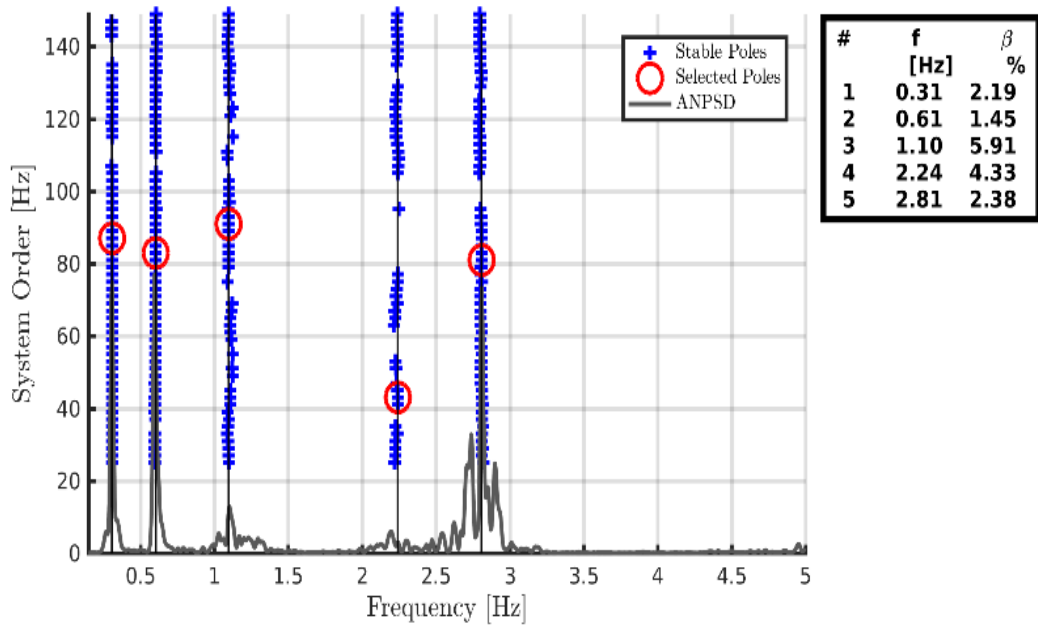
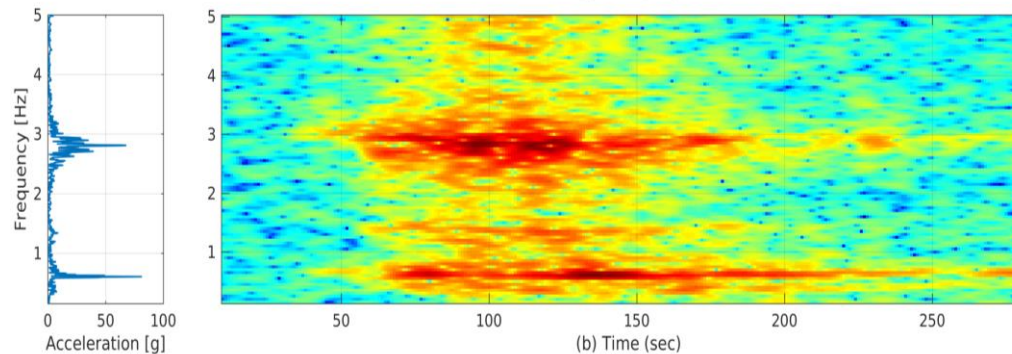
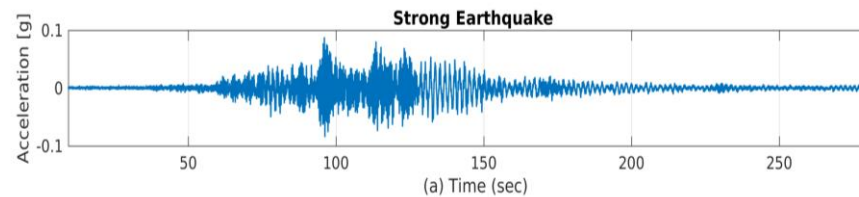
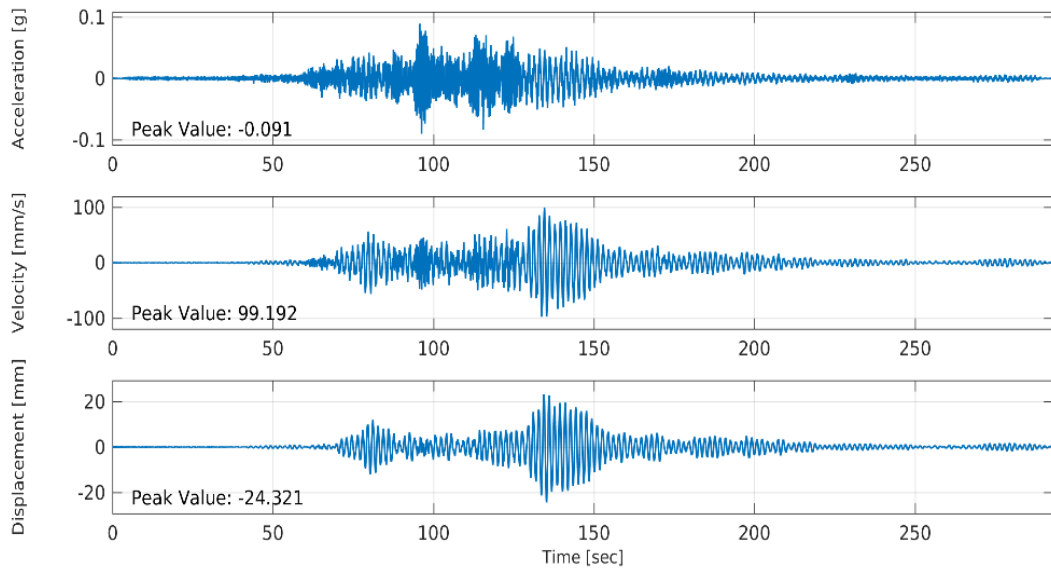
- Can we track modal properties and their variations with limited data (quantity – quality)?

With the support of *Delec Achitects*



Boroschek R., Villalpando P., Peña E. (2019) Building Structural Health Monitoring Under Earthquake and Blasting Loading: The Chilean Experience. In: Limongelli M., Çelebi M. (eds) Seismic Structural Health Monitoring. Springer Tracts in Civil Engineering. Springer, Cham. pp 361-383

EQ

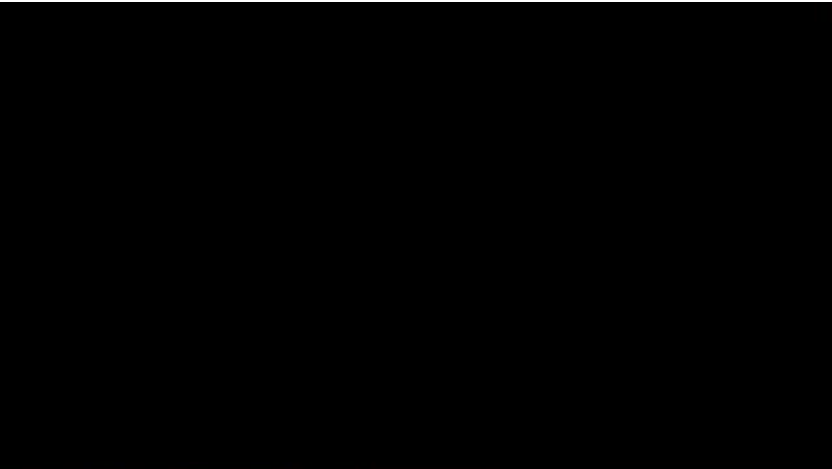


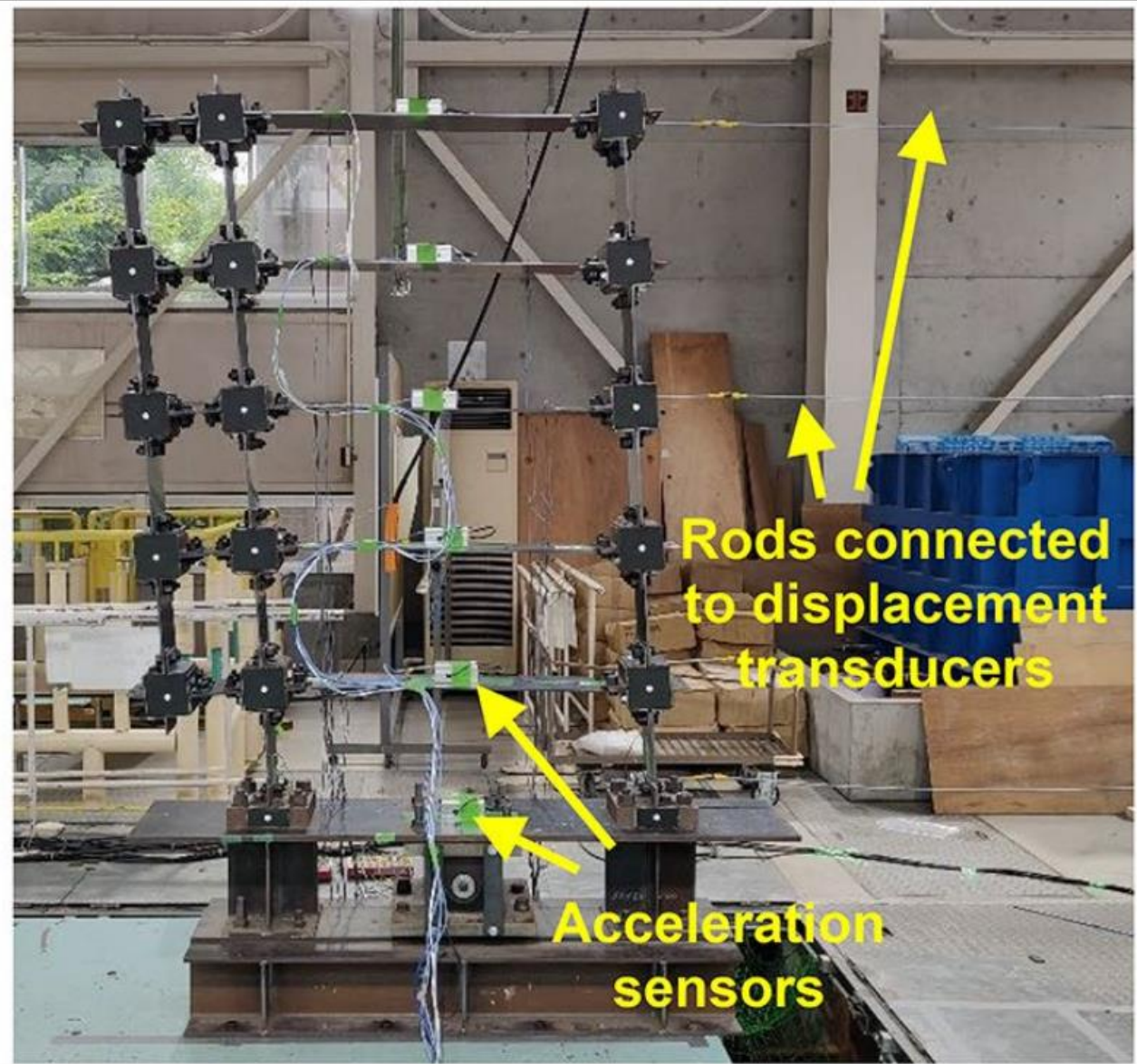
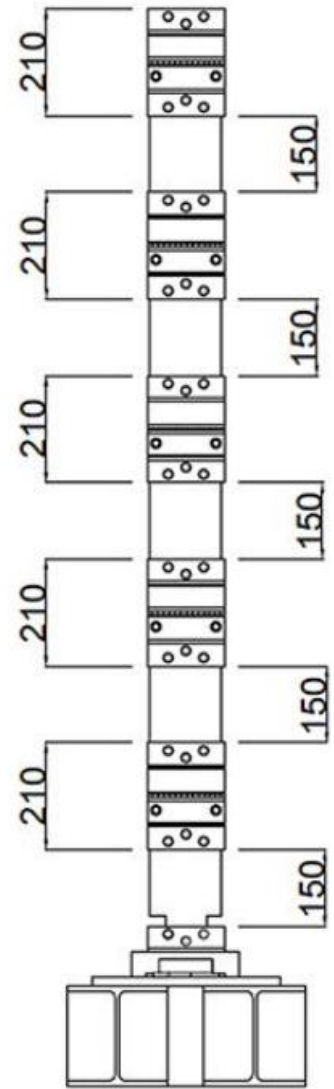
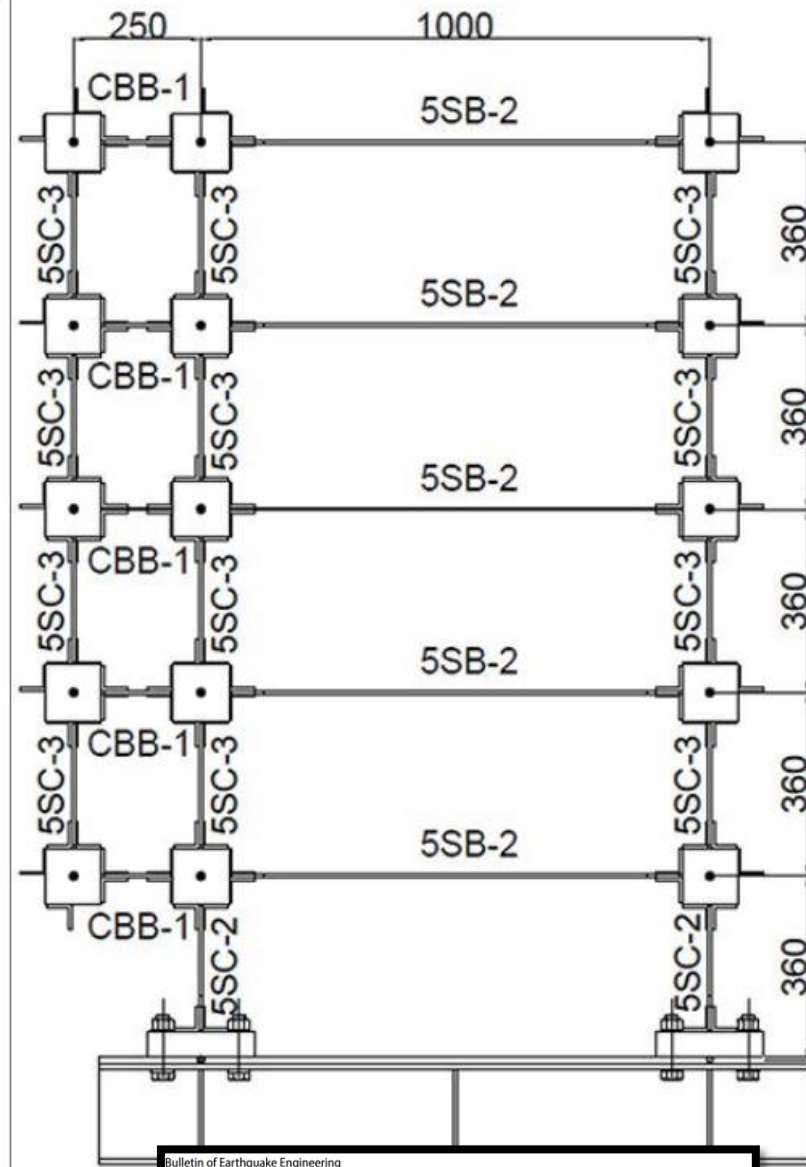
But... Cameras and Videos are everywhere



Most surveilled cities in the world (cameras per square mile):

1. 🇨🇳 Shenzhen: 7,462
2. 🇨🇳 Wuhan: 6,488
3. 🇨🇳 Shanghai: 5,239
- 4-20. 🇨🇳 Different cities of China
21. 🇨🇳 Beijing: 1,500
22. 🇮🇳 Delhi: 1,490
35. 🇰🇷 Seoul: 618
40. 🇸🇬 Singapore: 387
41. 🇮🇳 Hyderabad: 321
44. 🇺🇸 New York: 235
45. 🇷🇺 Moscow: 220
46. 🇬🇧 London: 209
49. 🇧🇩 Dhaka: 141
50. 🇲🇽 Mexico City: 139
56. 🇹🇭 Bangkok: 108
58. 🇺🇸 Los Angeles: 86
59. 🇩🇪 Berlin: 80
60. 🇿🇦 Johannesburg: 72
64. 🇹🇷 Istanbul: 54
68. 🇫🇷 Paris: 41
69. 🇪🇬 Cairo: 39
70. 🇮🇩 Jakarta: 35
76. 🇿🇦 Cape Town: 18
82. 🇦🇺 Sydney: 15
84. 🇧🇷 Rio de Janeiro: 13
86. 🇵🇰 Lahore: 10





Bulletin of Earthquake Engineering
<https://doi.org/10.1007/s10518-025-02142-9>

ORIGINAL ARTICLE

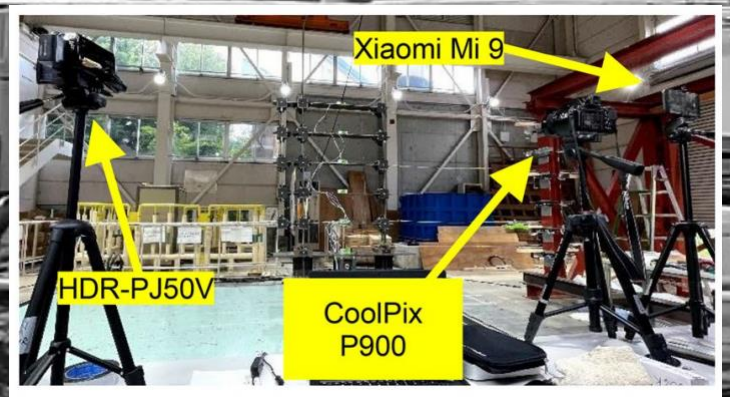
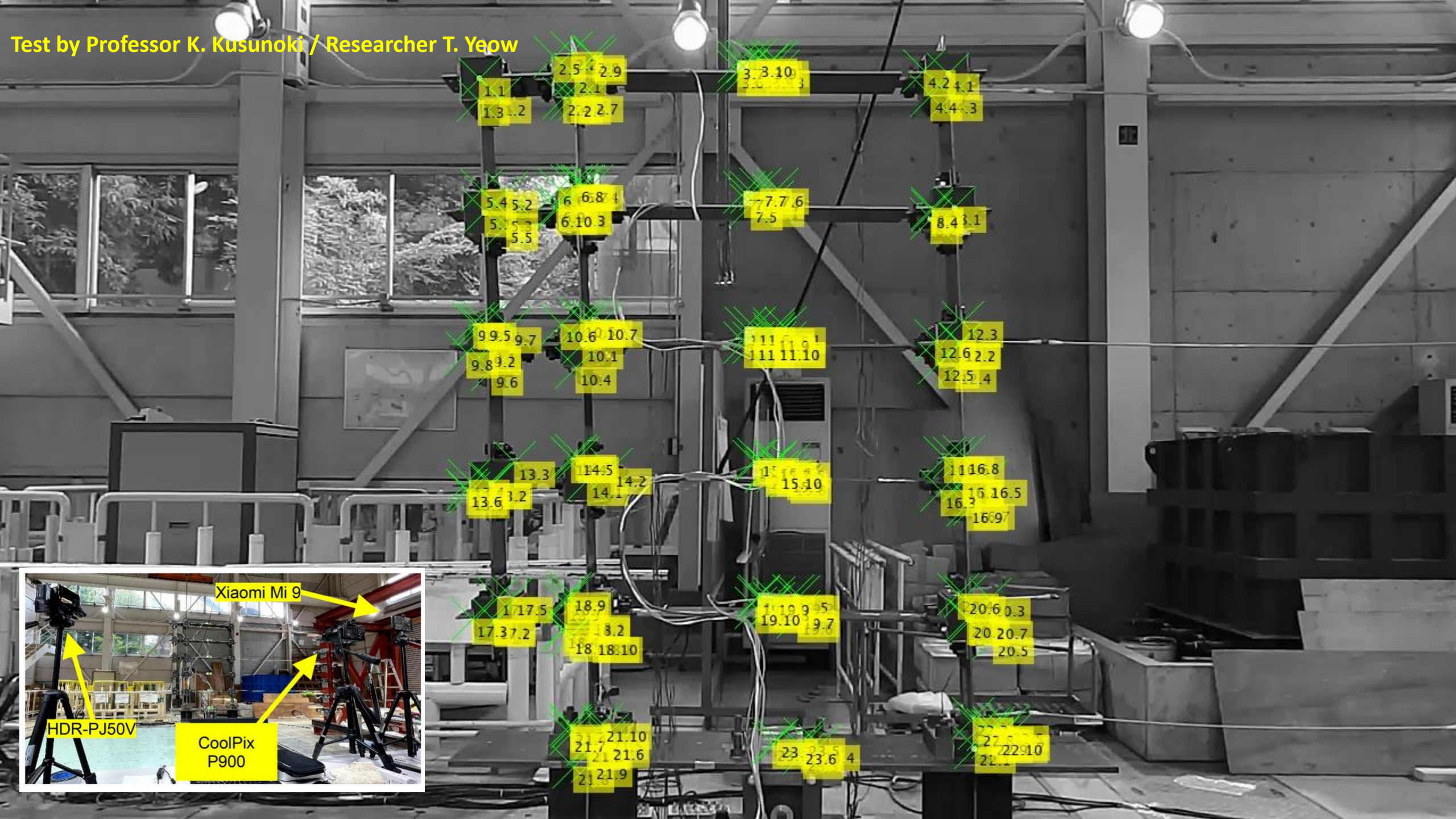
Nonlinear seismic response and residual drift determination combining ground acceleration data with recorded videos

R. Boroschek¹ · T. Yeow² · K. Kusunoki³

Received: 28 December 2024 / Accepted: 4 March 2025
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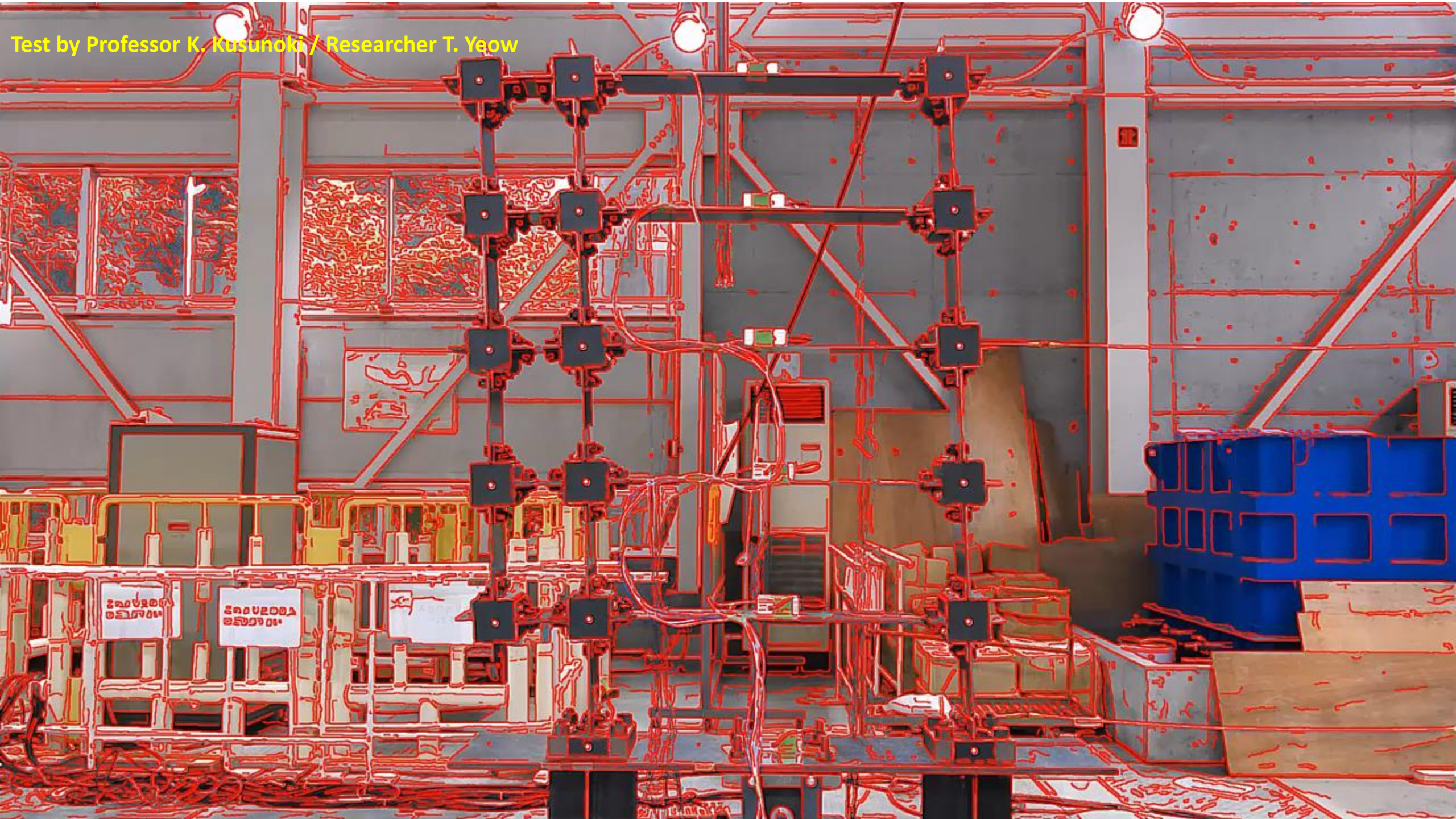
Boroschek, R., Yeow, T. & Kusunoki, K. Nonlinear seismic response and residual drift determination combining ground acceleration data with recorded videos. *Bull Earthquake Eng* (2025).

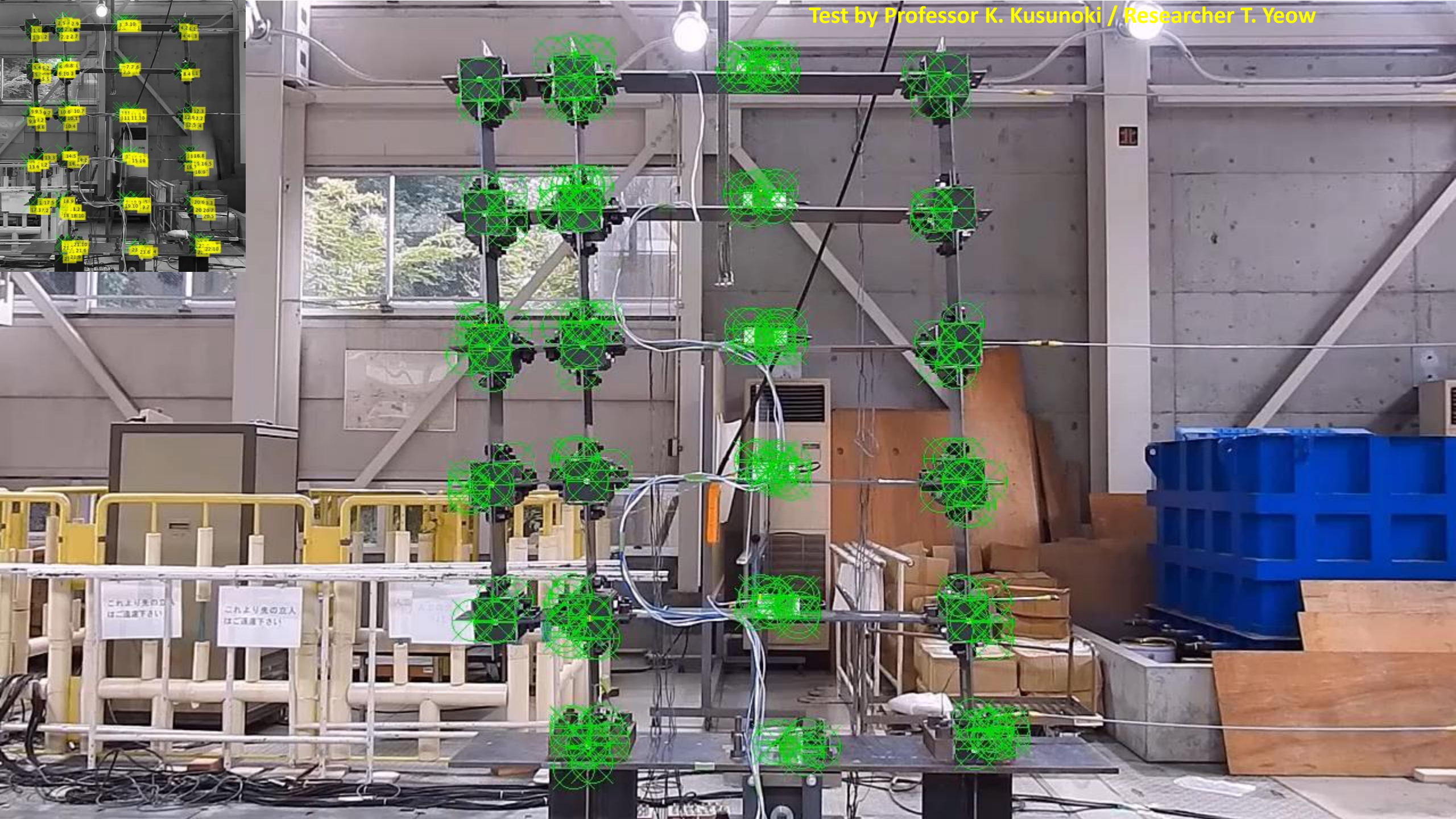
Test by Professor K. Kusunoki / Researcher T. Yeow

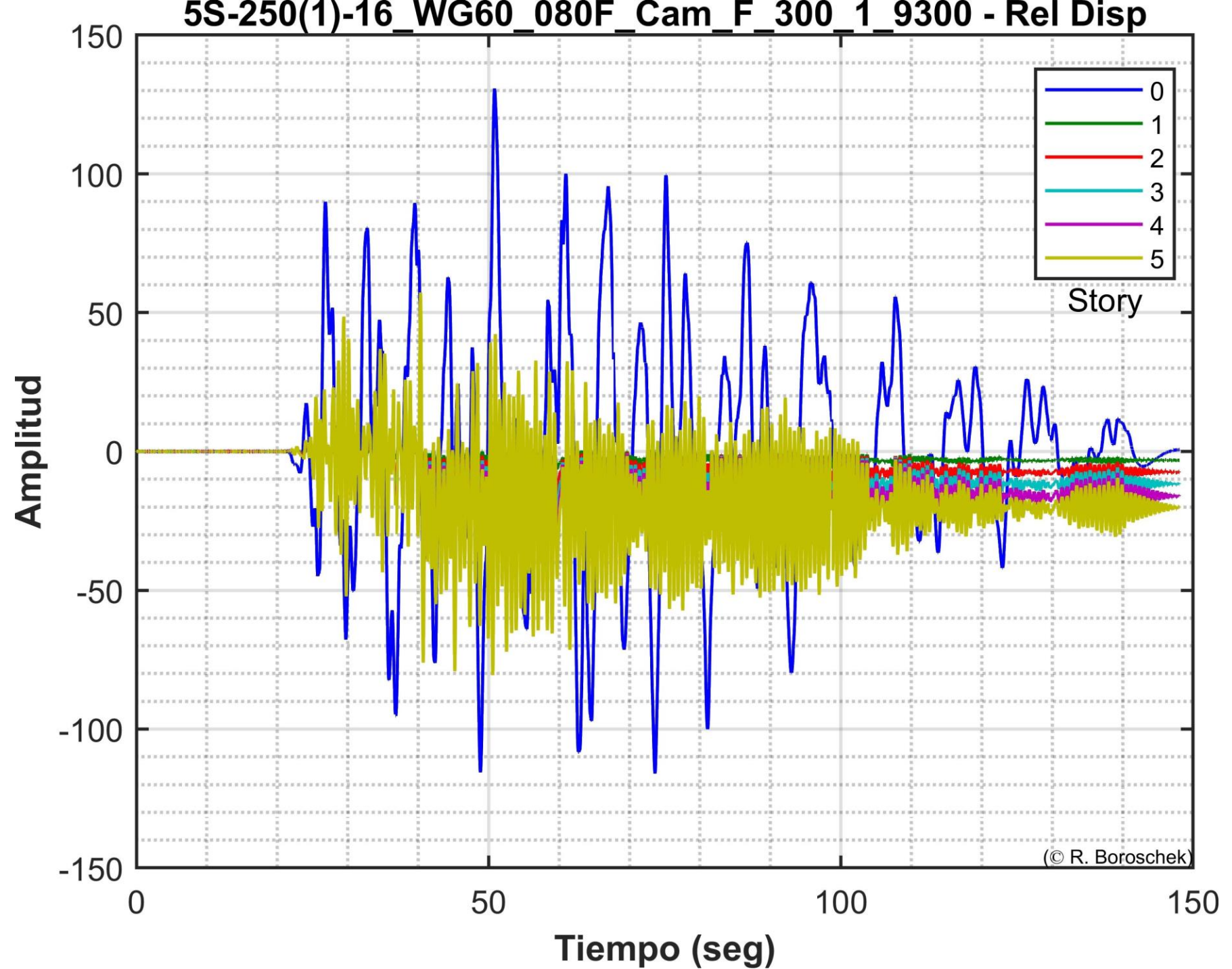
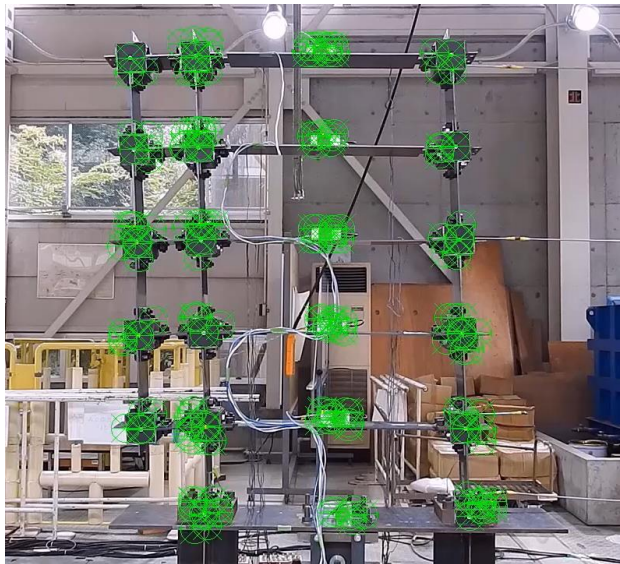


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2	5.4 5.2 5.5 5.3 5.5	6.6 8.4 6.10 3	7.7 6 7.5	8.4 1.1
3	9.9 9.7 9.8 9.2 9.6	10.6 10.7 10.1 10.4	11.1 10.1 11.1 11.10	12.3 12.6 2.2 12.5 4
4	13.3 13.6 3.2	14.5 14.2 14.1	15.10 15.10	16.8 16.16 5 16.97
5	17.5 17.3 7.2	18.9 18.2 18 18.10	19.10 9.5 19.10 9.7	20.6 0.3 20 20.7 20.5
6	21.7 21.7 21.6 21.9	21.10 21.6 21.9	23 23.6 4	22.2 22.9 10 22.1

Test by Professor K. Kusunoki / Researcher T. Yeow

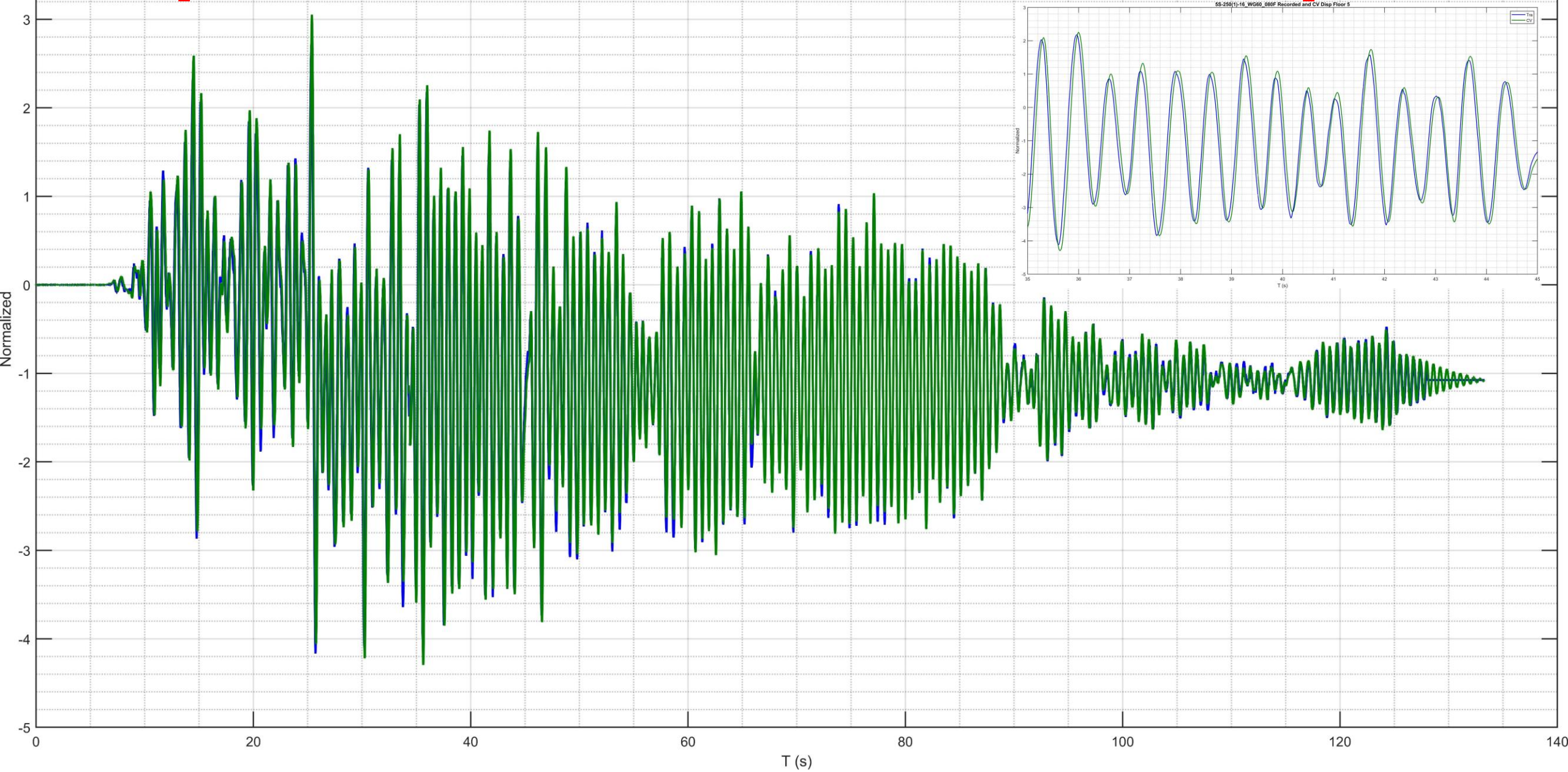






Comparison Transducer and CV Disp F 5

Tra
CV

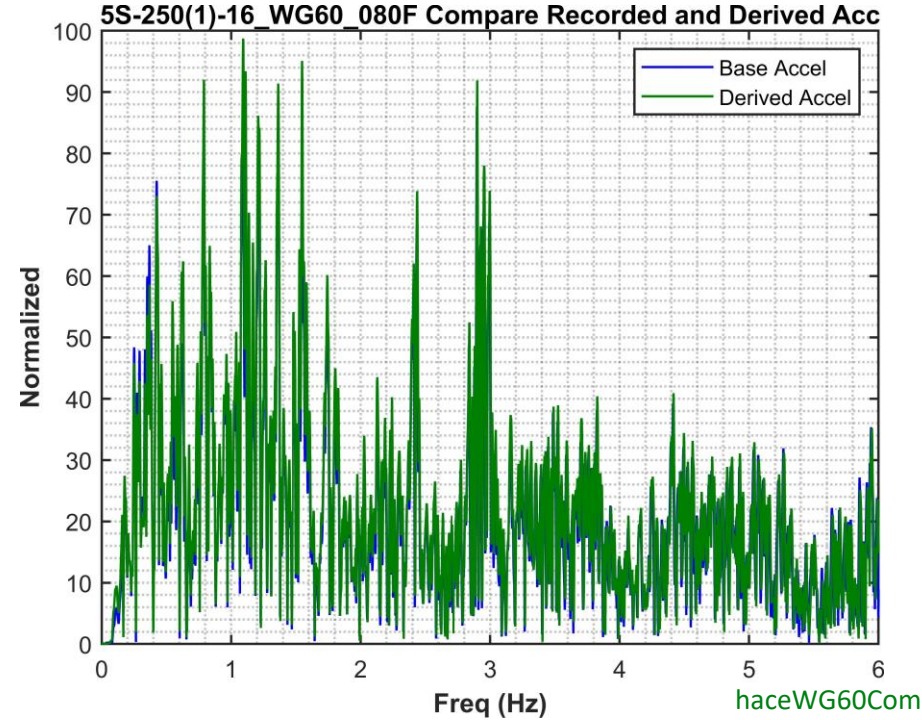
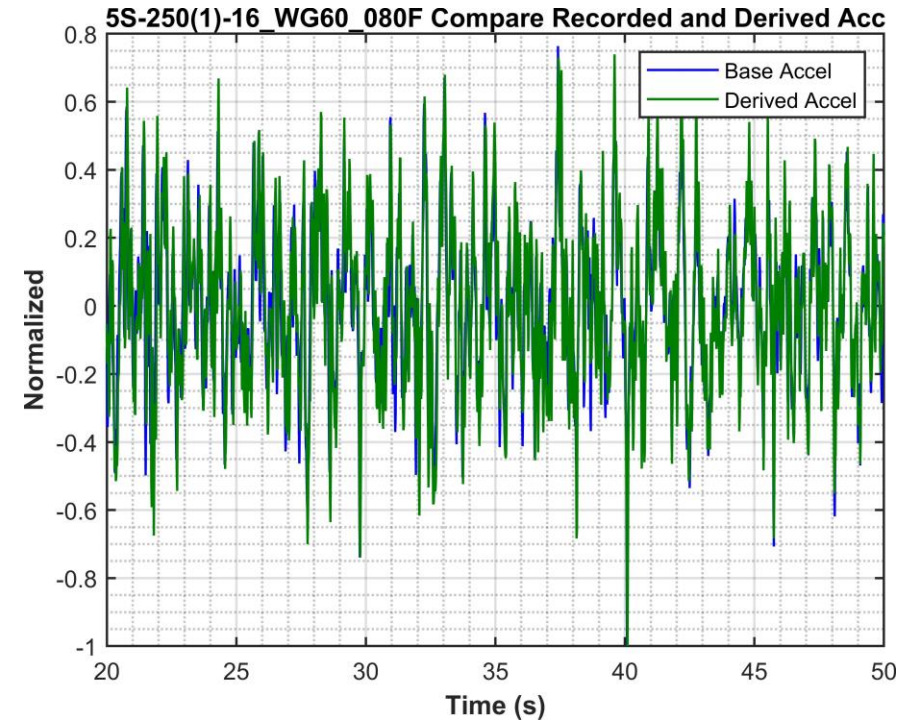
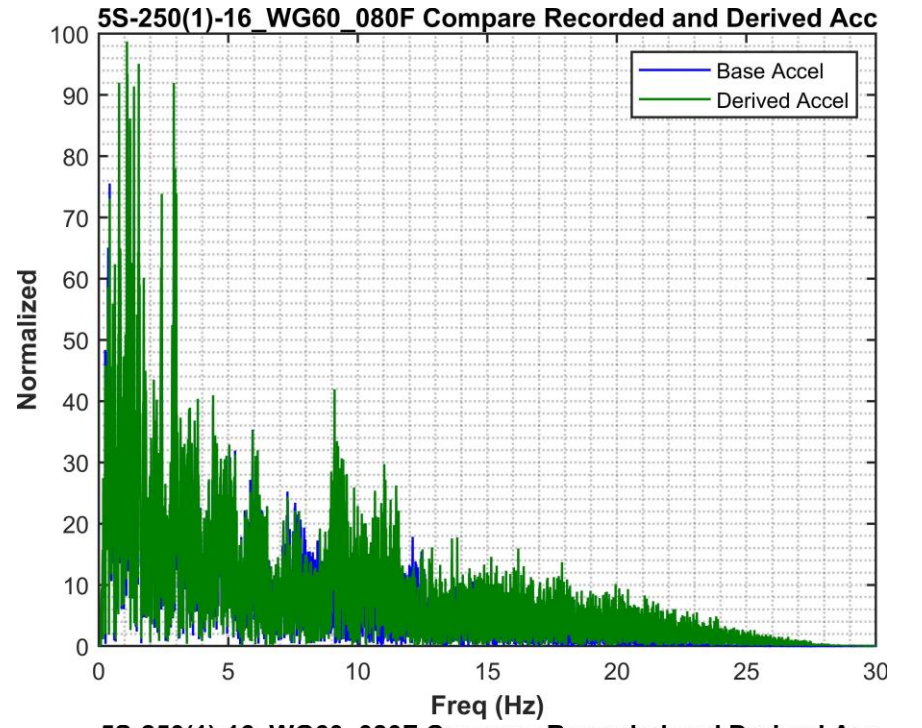
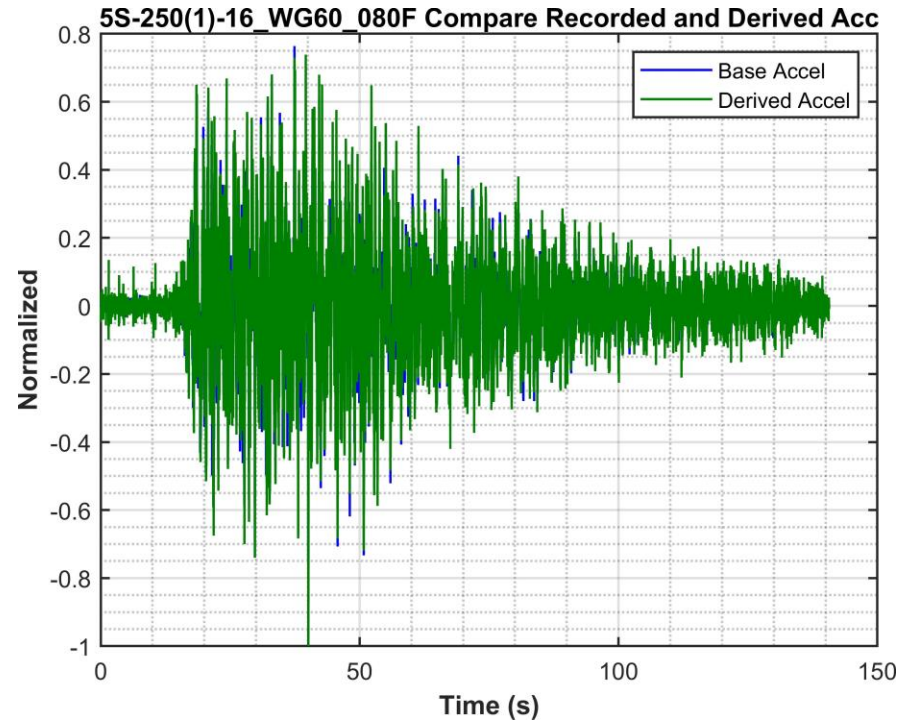


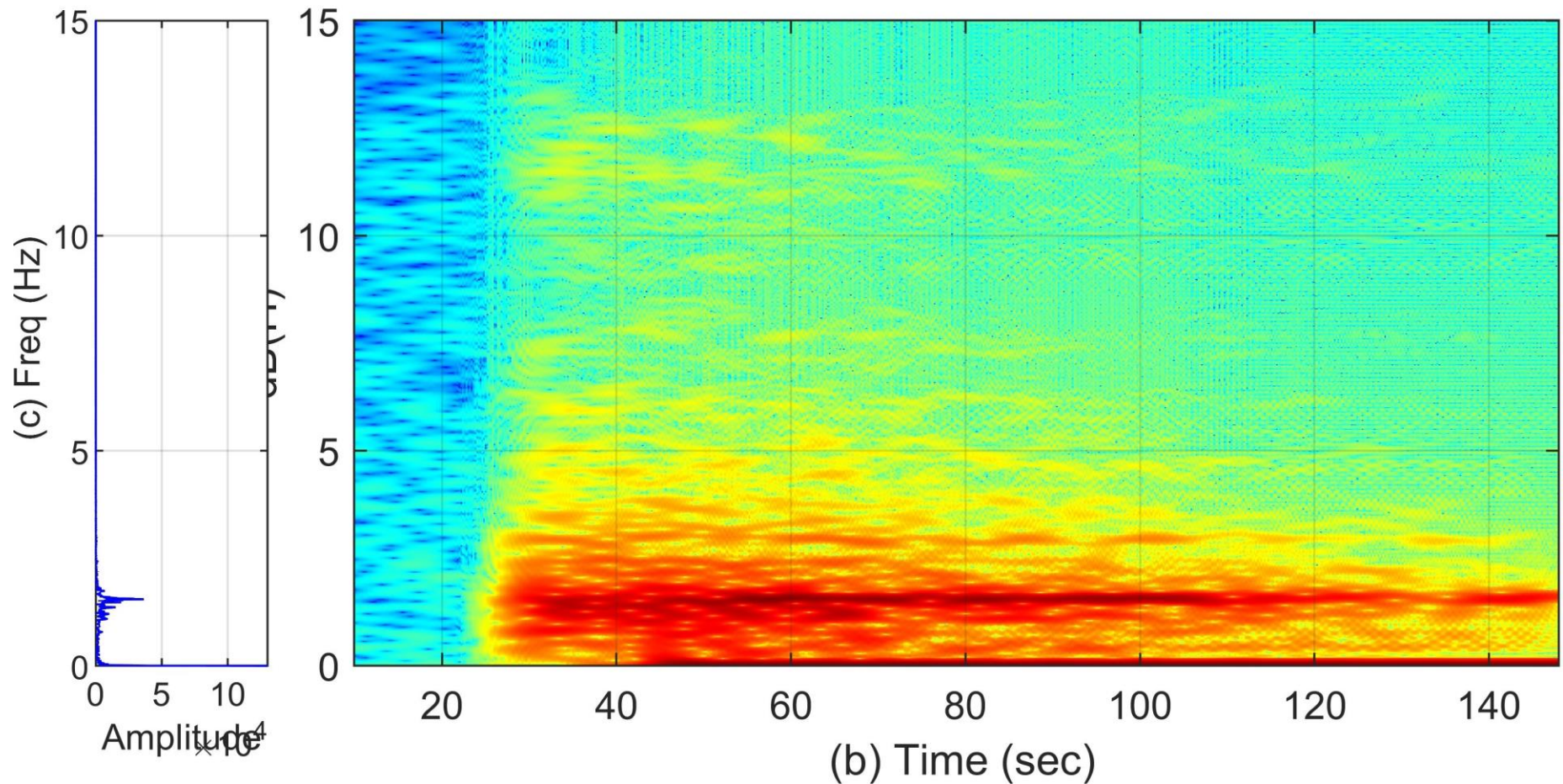
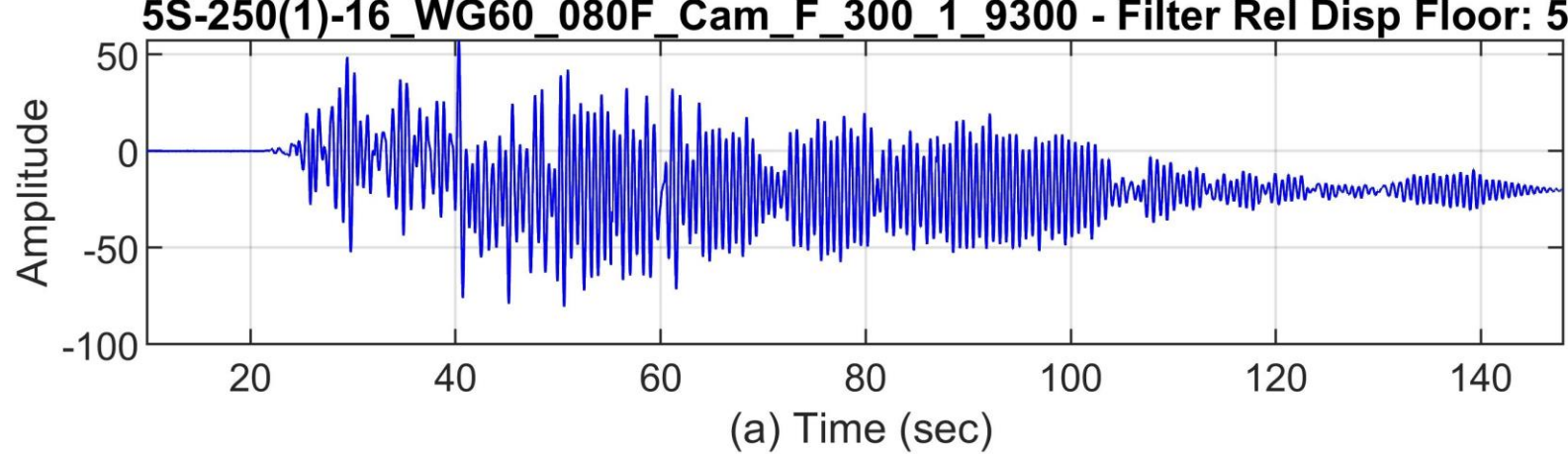
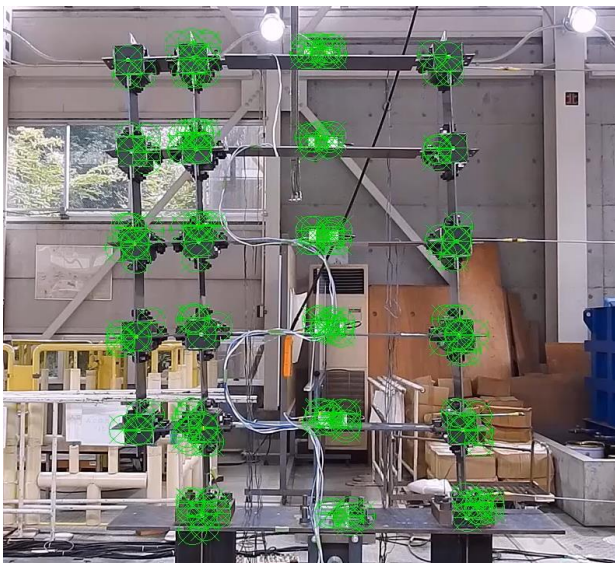
Acceleration Comparison

Base Records

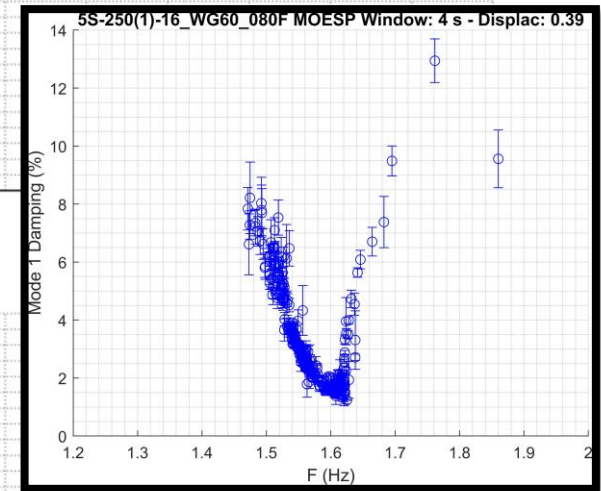
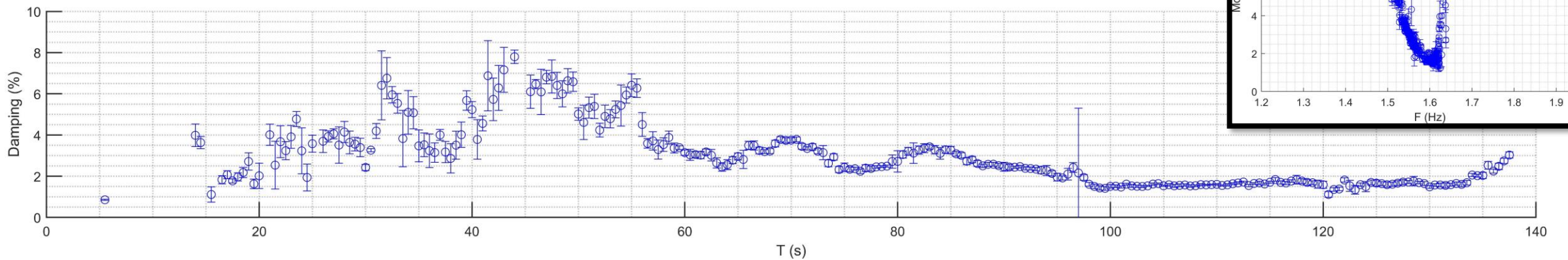
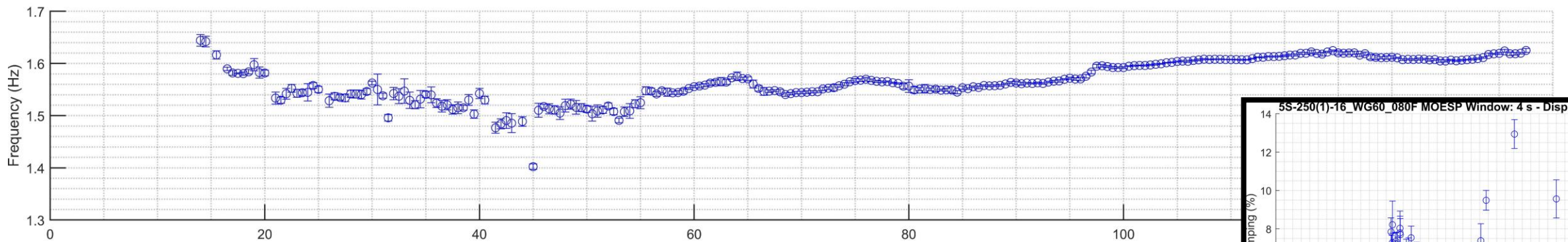
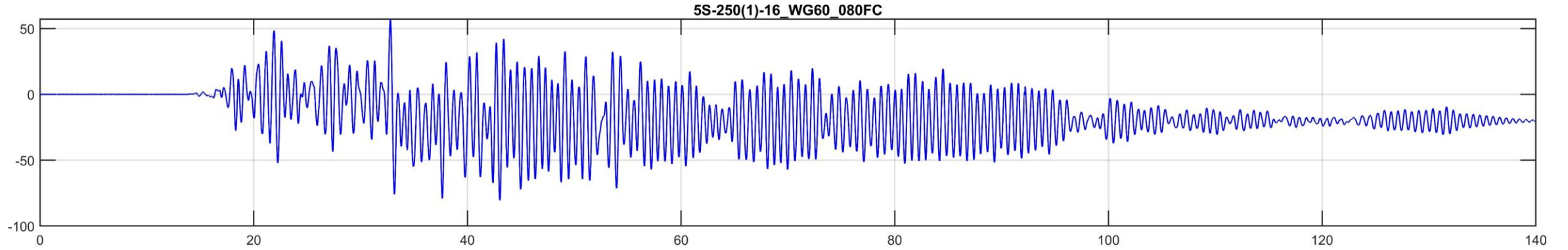
Recorded acceleration is compared with derived acceleration from vision displacements

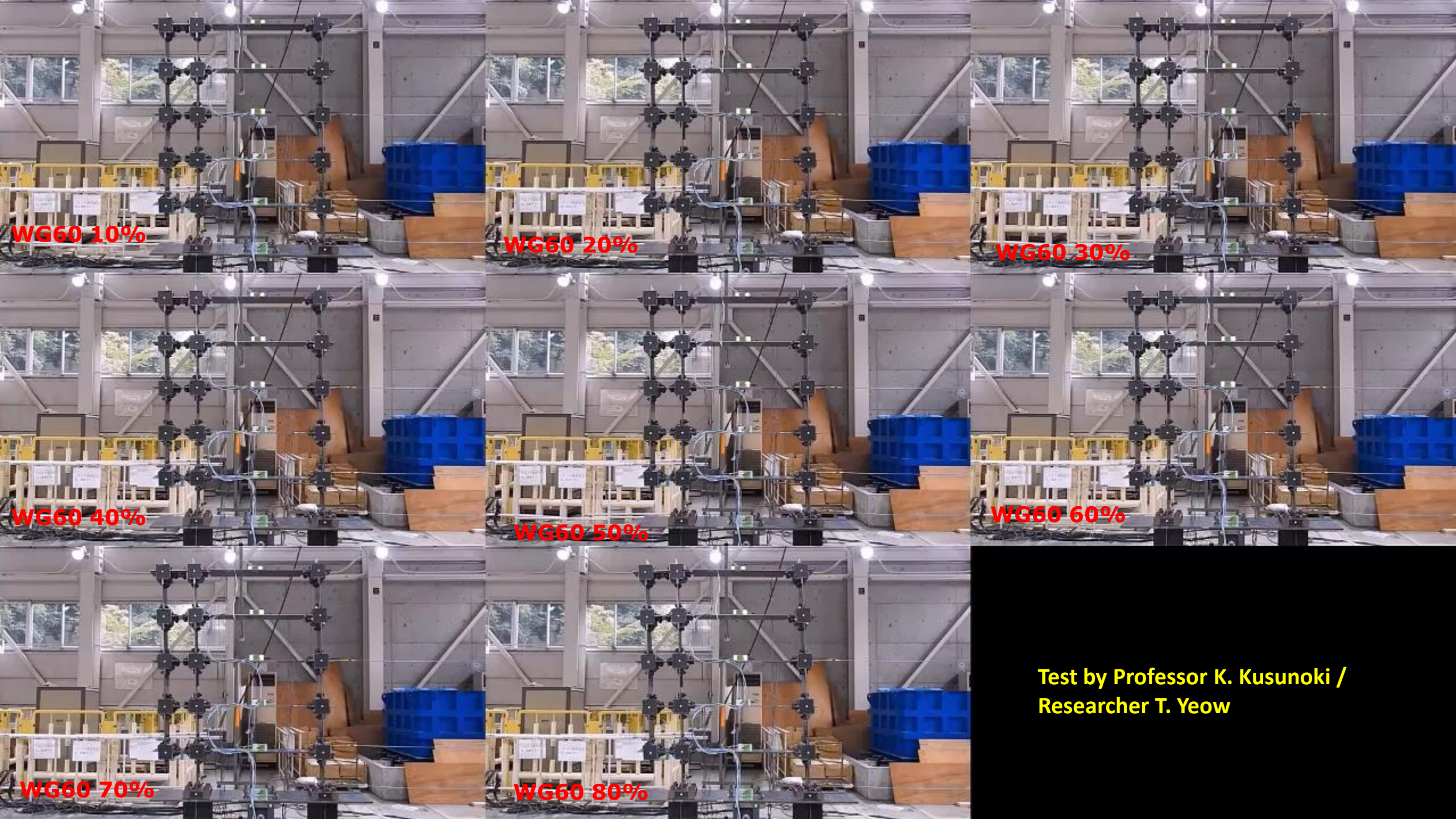
Good agreement is found for the response frequency band.





Time – Freq – Damping Evolution Floor 5 Displacements Window: 5 s MOESP





WG60 10%

WG60 20%

WG60 30%

WG60 40%

WG60 50%

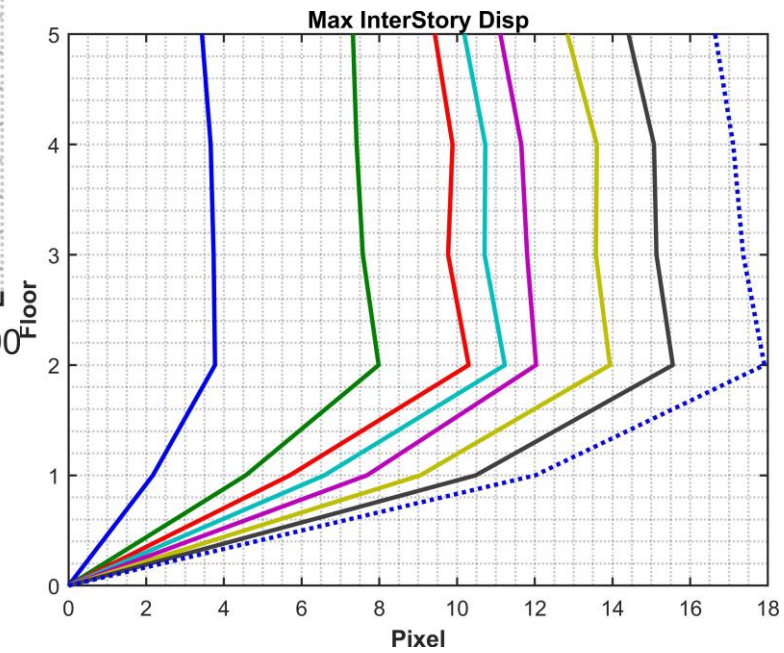
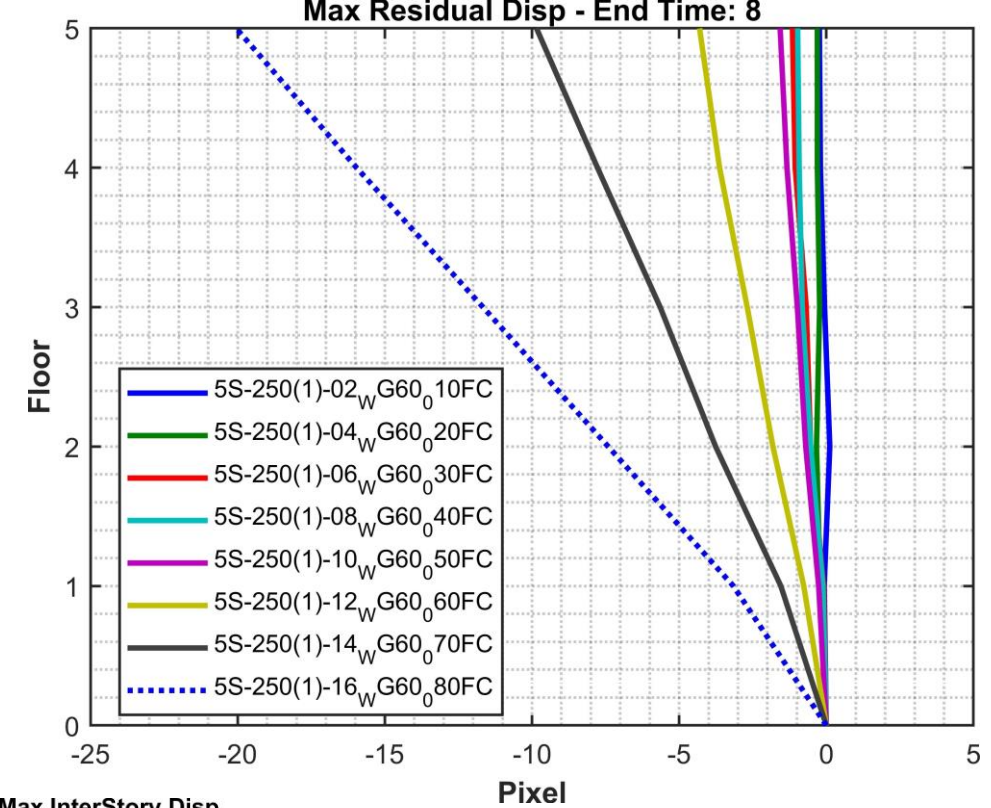
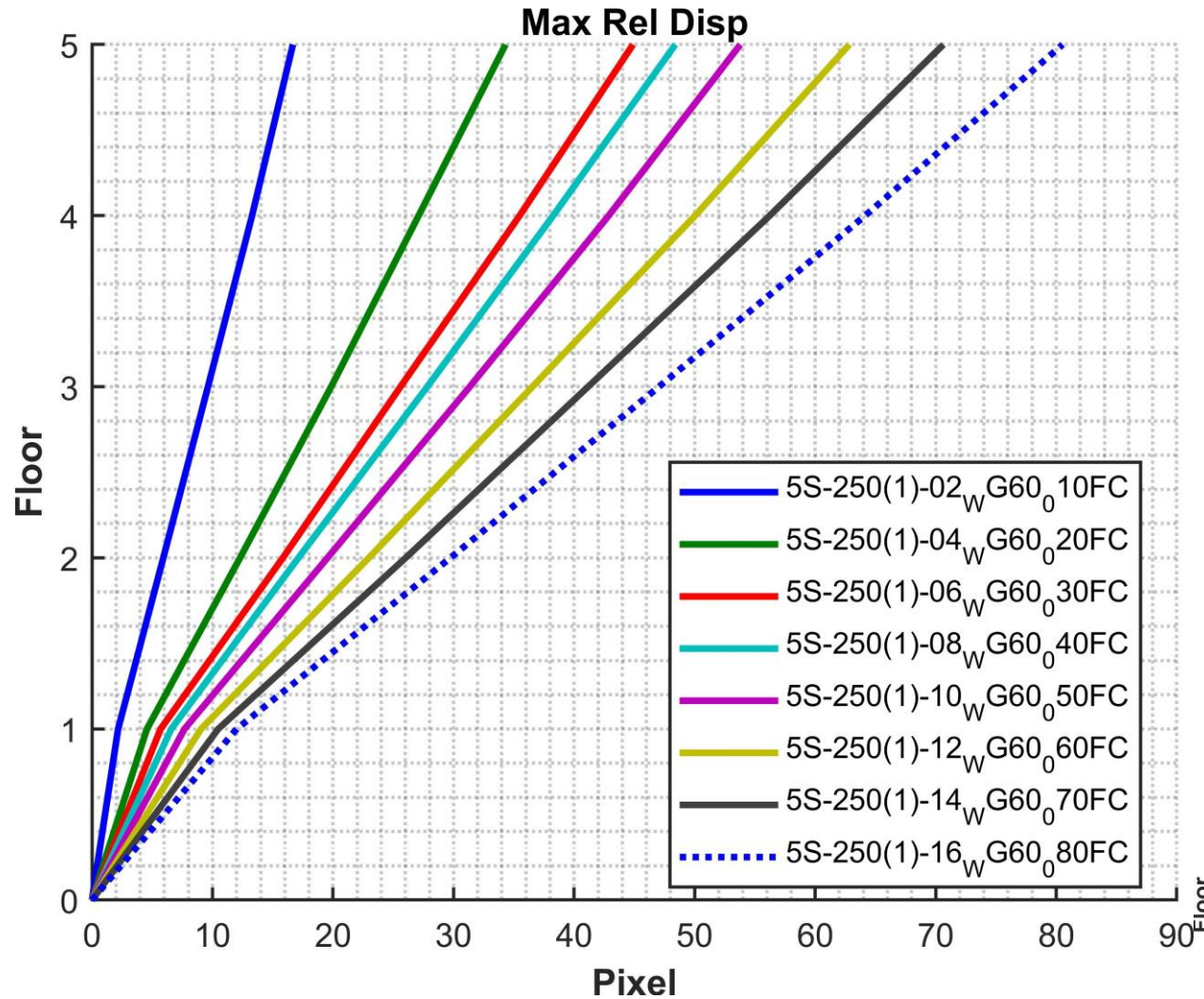
WG60 60%

WG60 70%

WG60 80%

**Test by Professor K. Kusunoki /
Researcher T. Yeow**

Envelopes for all Test WG60F



Total Displacement, Interstory Drift and Residual Displacements increases with demands in each test. The cumulative residual drift for all test will be the summation of results. Residual drift of less than 2 pixels is not robust.

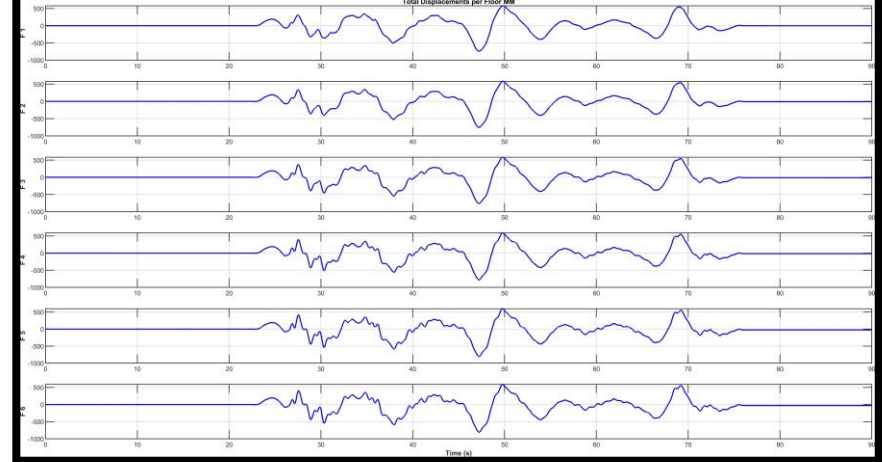


BLIND TEST: video provided by Prof. Kusunoki and Researcher T. Yeow

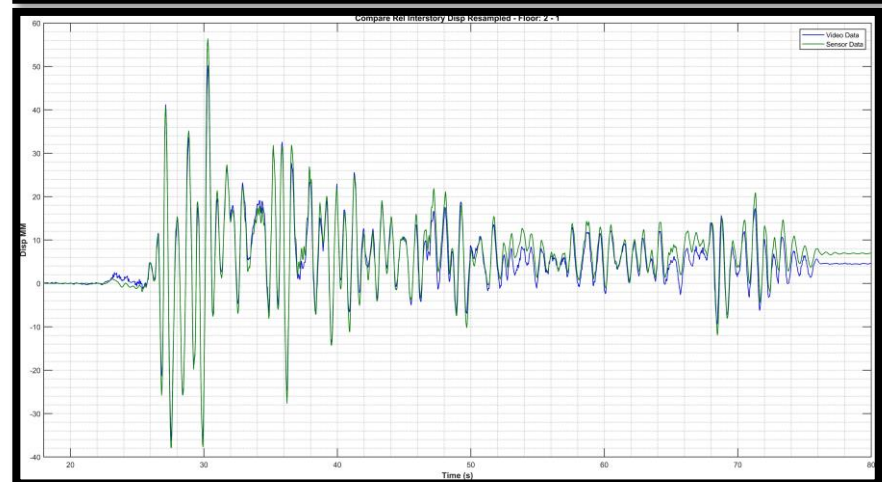
Tatsuya ASAI, Masaomi TESHIGAWARA, Kento YOSHIKAWA, Koichi KUSUNOKI, Eiichi INAI, Takuya NAGAE, Ippei MARUYAMA, Koichi KAJIWARA, Joji SAKUTA, Tsutomu OHTA, et al. YIELD DISPLACEMENT EVALUATION OF RC BUILDINGS EXAMINED BASED ON SHAKING TABLE TEST.



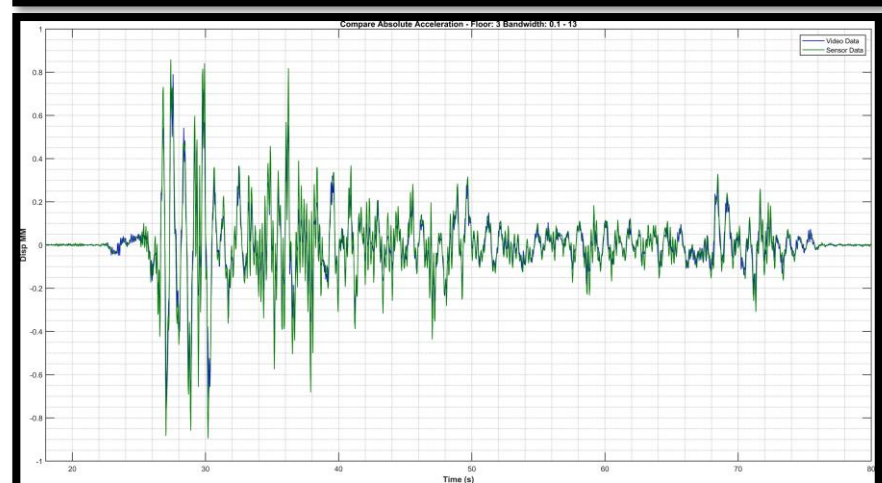
Total Displacement

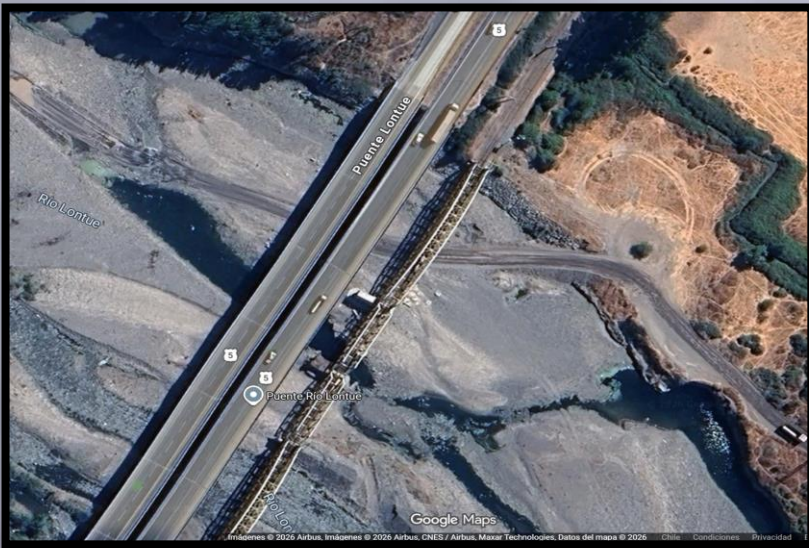


Interstory drift

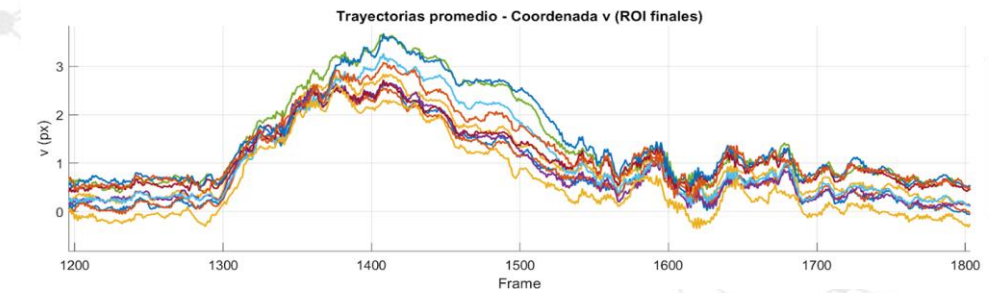
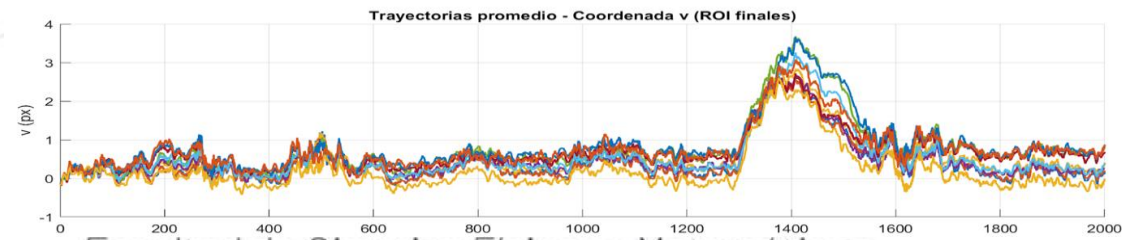
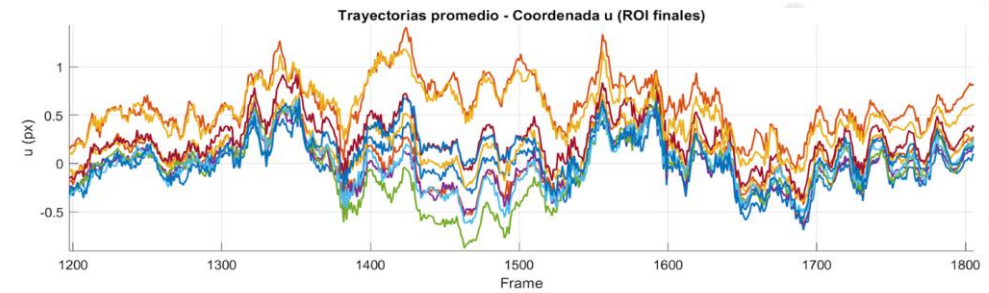
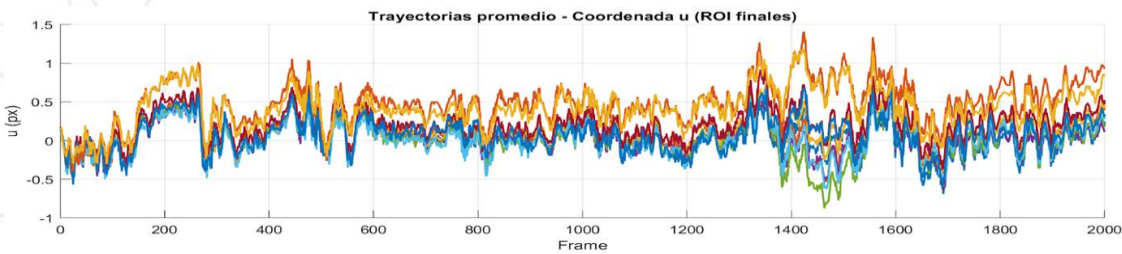
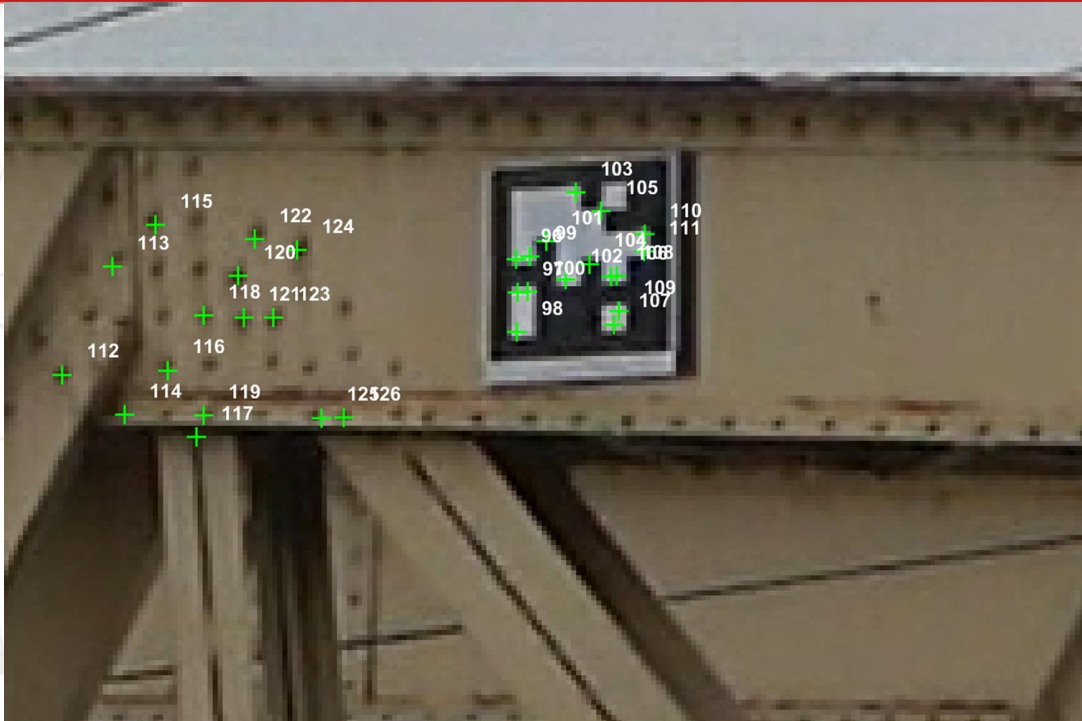


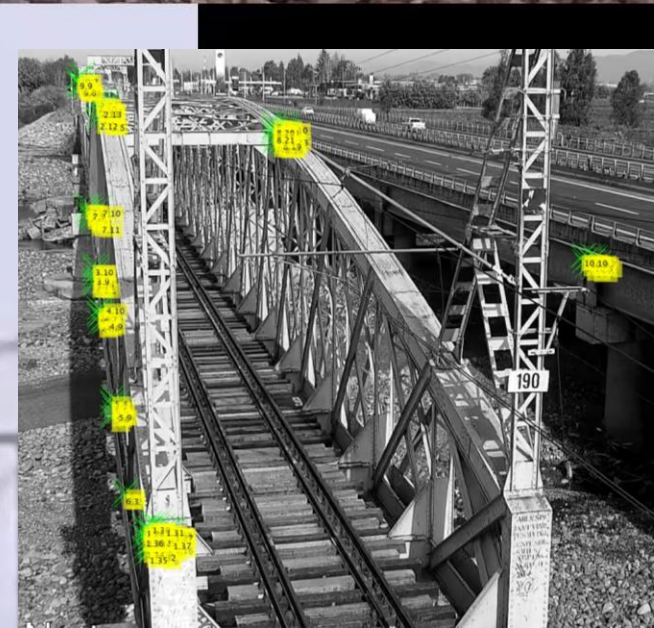
Acceleration





Video Student A. Garreau Prof. R Boroschek

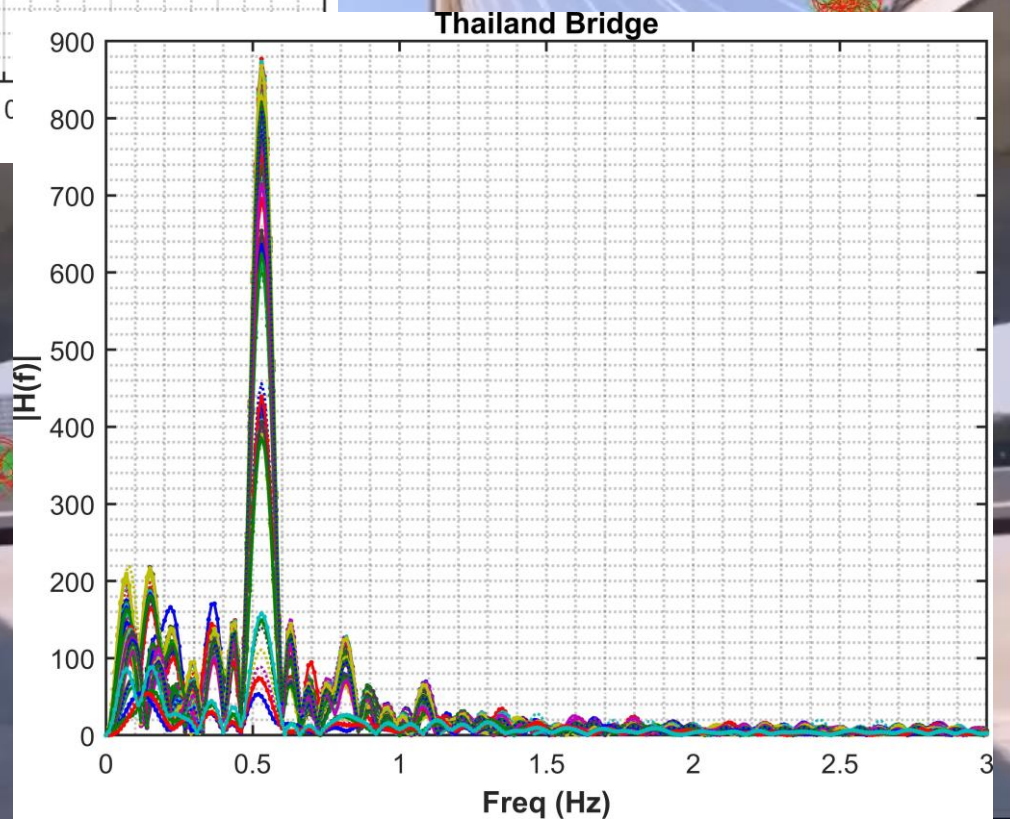
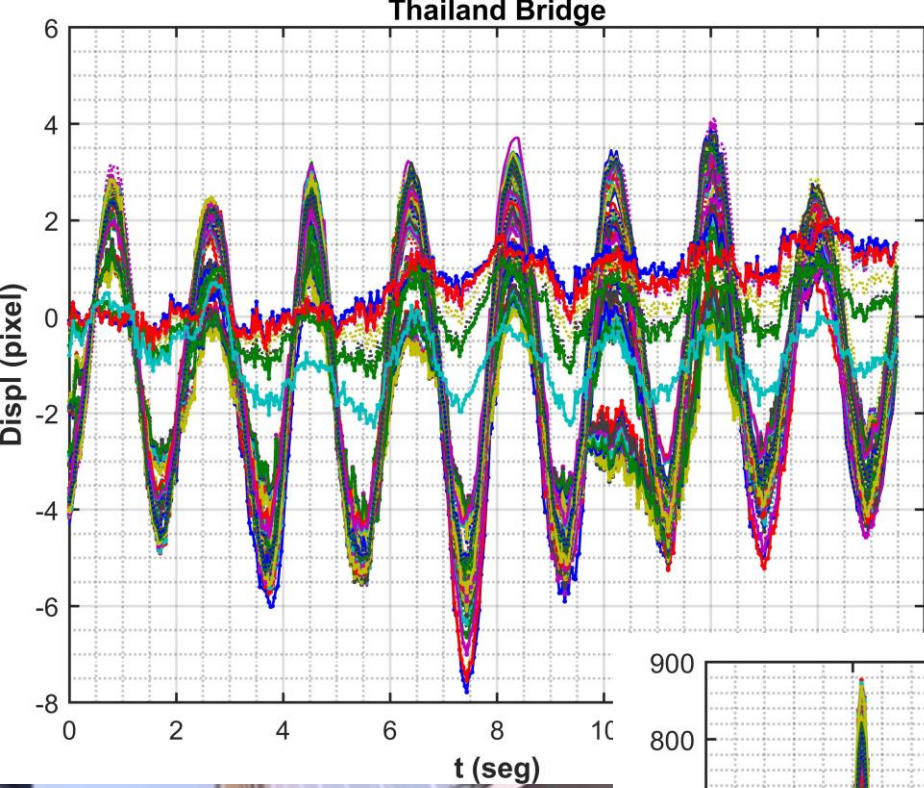


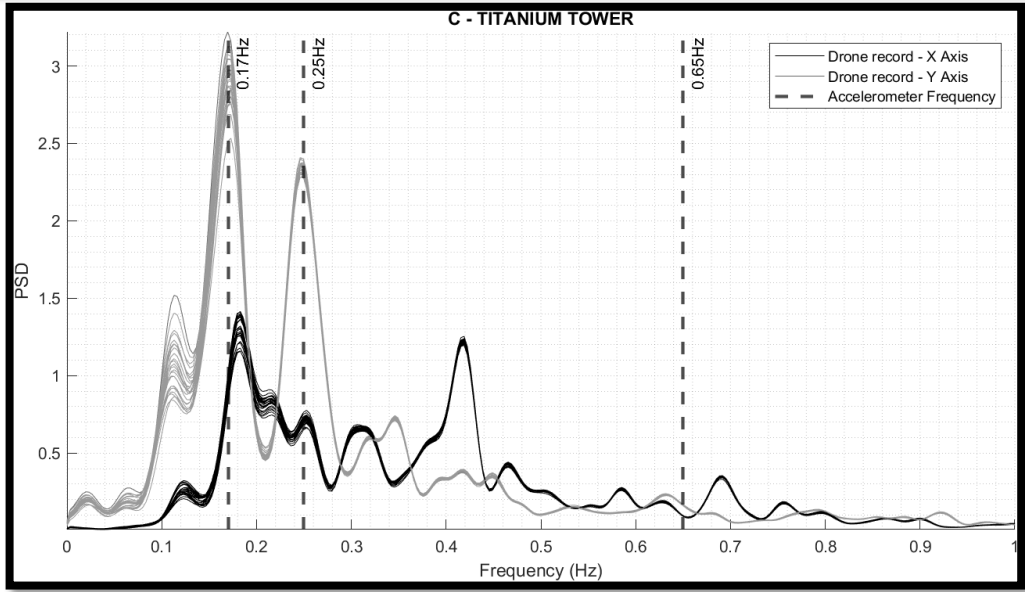
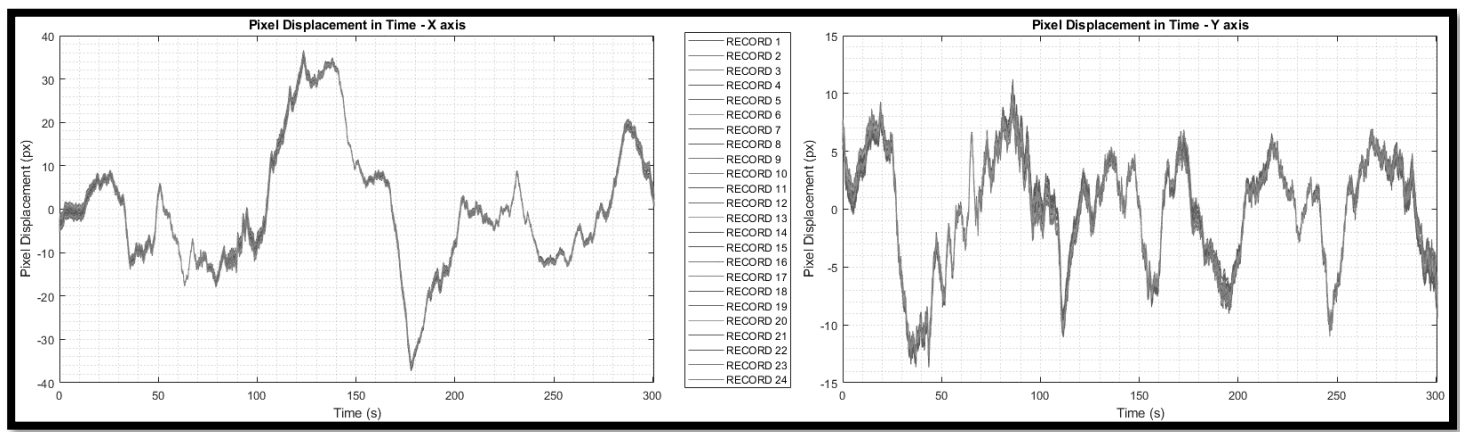


Video: EFE Ing. Oscar Muñoz



Student - Video M. A. Garreaud
Prof. R. Boroschek



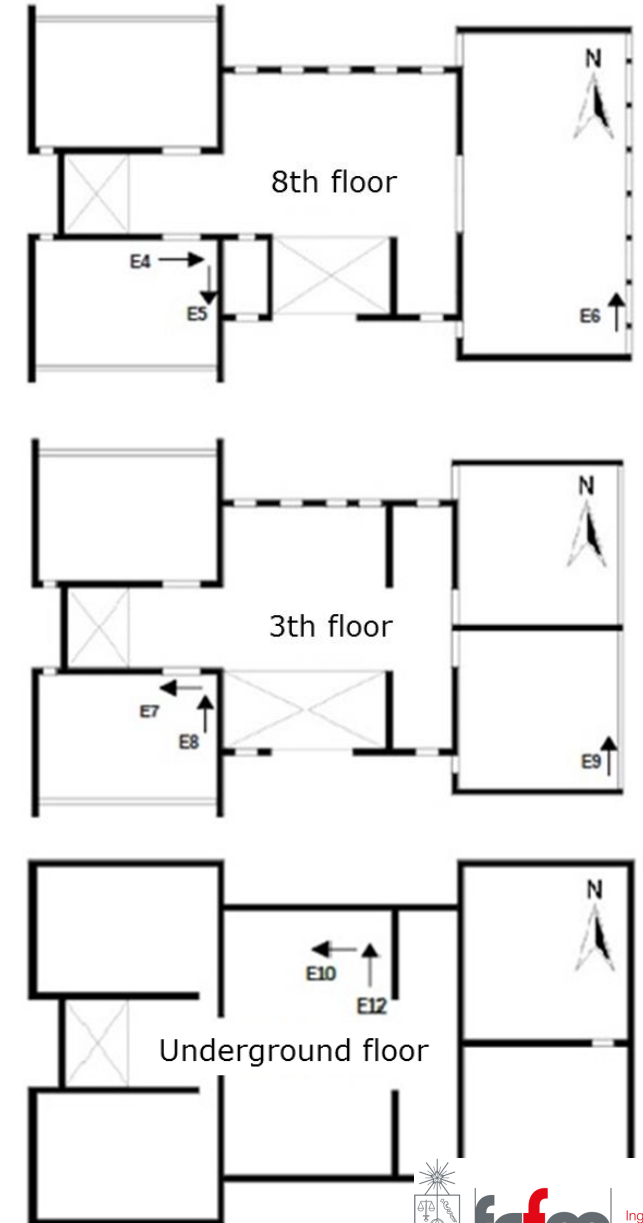
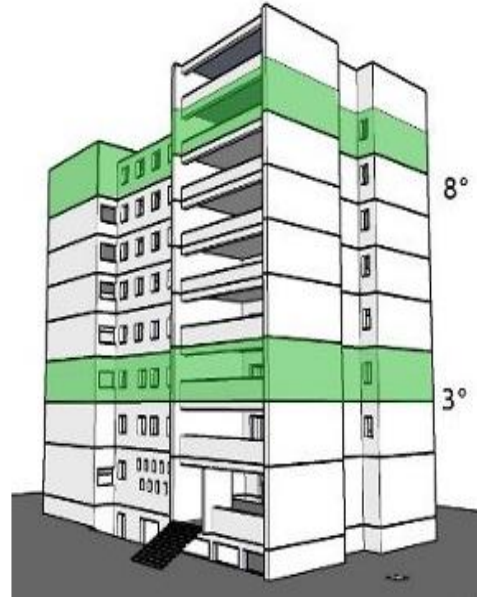


Alarcon, Felipe. Boroschek, Ruben. Dynamic response of structures under operational vibrations using drone video footage without fiducial markers. IMAC-XLI Feb 2023



First SHM in CHILE 2009 University of Chile

- Structural Walls
- 9 Stories above ground (30.2 m).
- 2 Stories below ground (30x19 area).
- Wall thickness 35 cm.
- Slab thickness 25 cm.



Boroschek, R, Bilbao, J., Interpretation of Stabilization Diagrams Using Density-Based Clustering Algorithm. Engineering Structures Volume 178, 1 January 2019, Pages 245-257

Gonzalez, W.; Ferrada Lagos, A.; Boroschek, R; Lopez-Droguett, E "Characterization of the Modal Response Using Deep Recurrent Neural Networks" Engineer Structures, Volume 256, 1 April 2022, page 1-16.

W. González, RL. Boroschek, JA. Bilbao, Temperature Measurement Assisted Modal Tracking of an Instrumented Building, Engineering Structures, Volume 233, 15 April 2021.

Garrido, M; Boroschek, R; Alarcon, F; Gonzalez, W. Modal Parameter Changes as Function of Drift in Two Shear Wall Buildings. Engineering Structures 327 (2025).

AUTOMATIC IDENTIFICATION 2009/2014

Still running: 13 years data. Modal Parameters every 15 min.

Displacement in each strong shaking

EQ 2010 damage

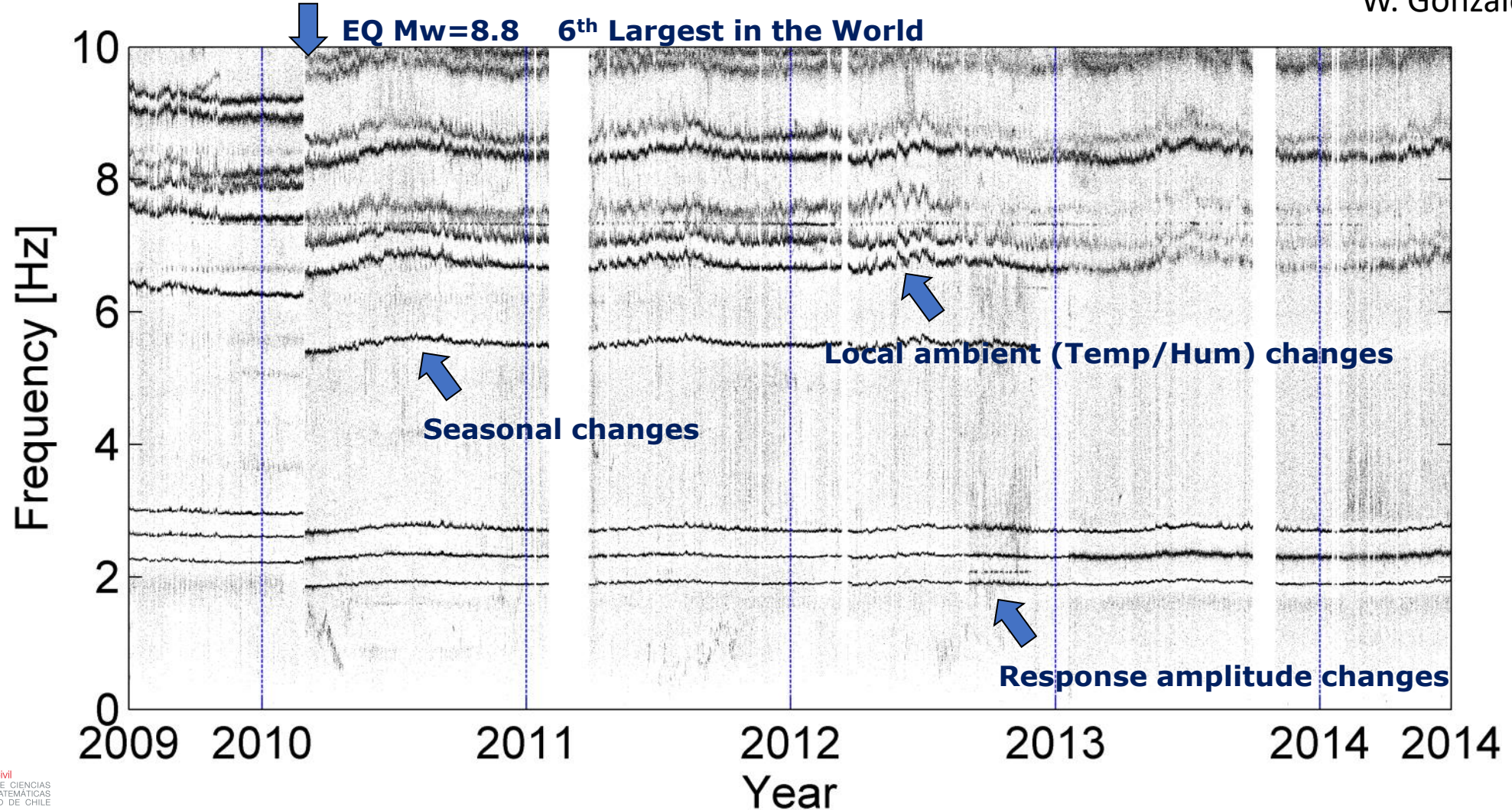
Effect:

EQ

DAILY and SEASONAL ambient variations

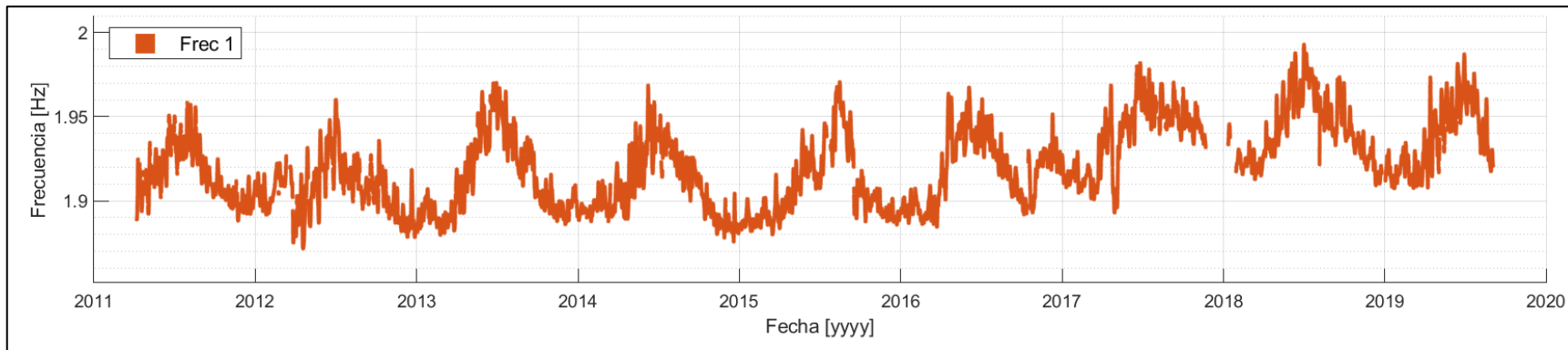
Students: J Bilbao

W. González



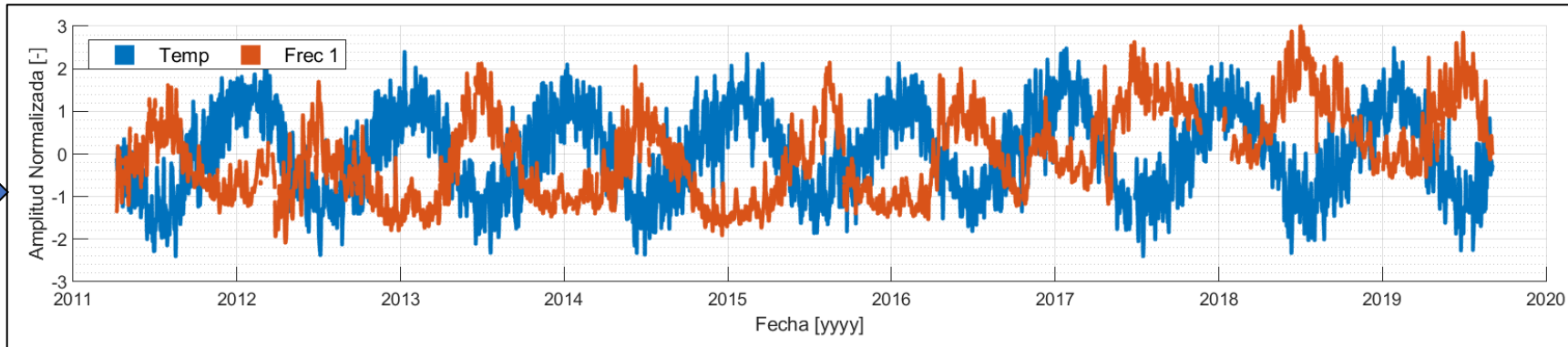
Frequency/Temperature: Seasonal

First Mode
Seasonal changes



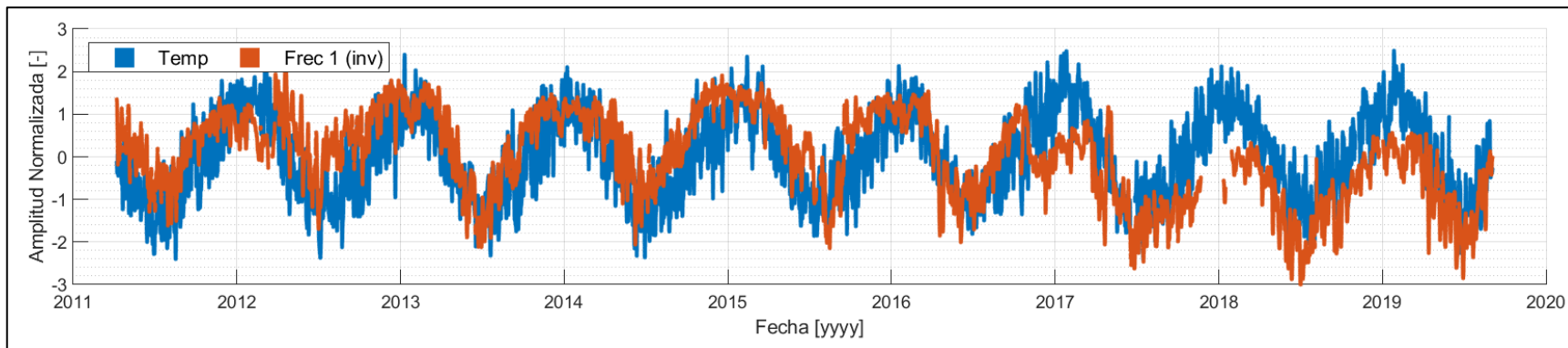
First Mode and
Temperature

Seasonal changes



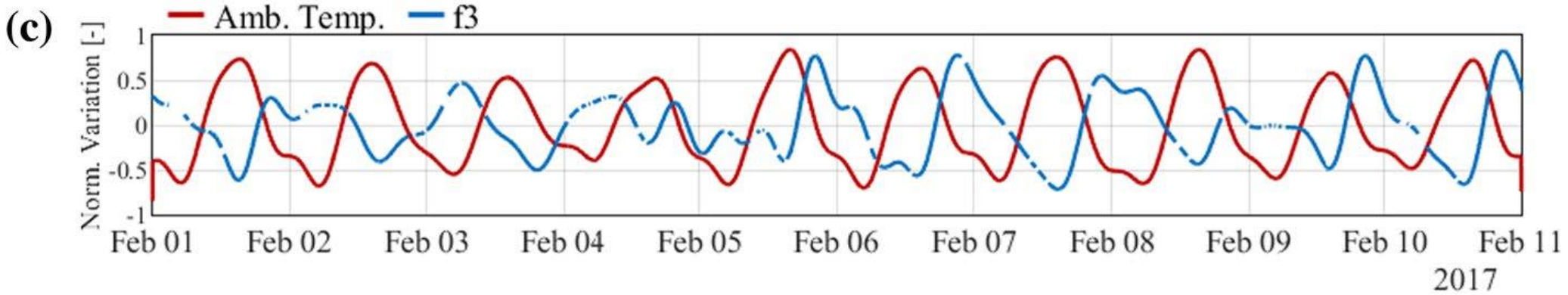
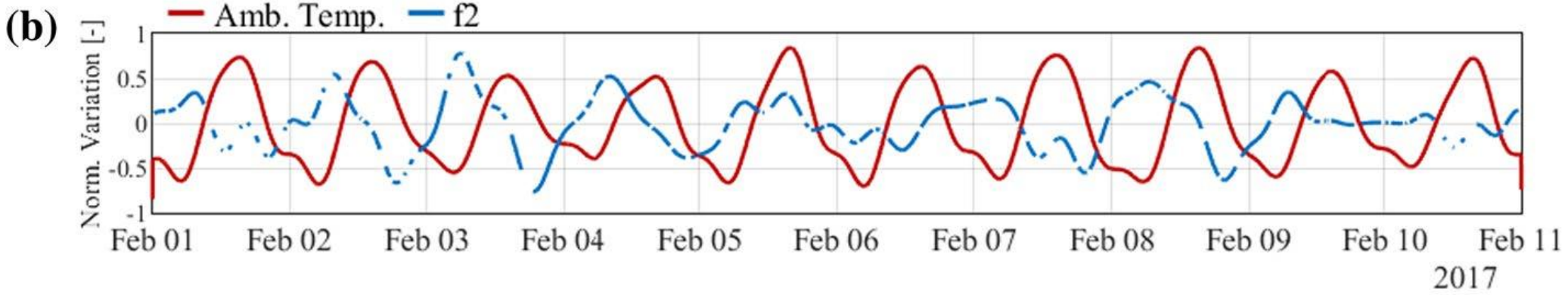
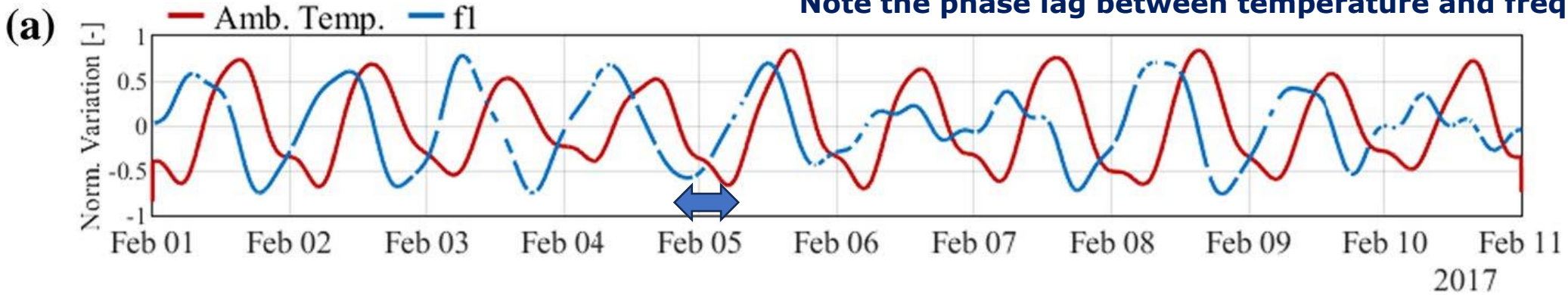
First Mode and
Temperature x (-1)

Seasonal changes



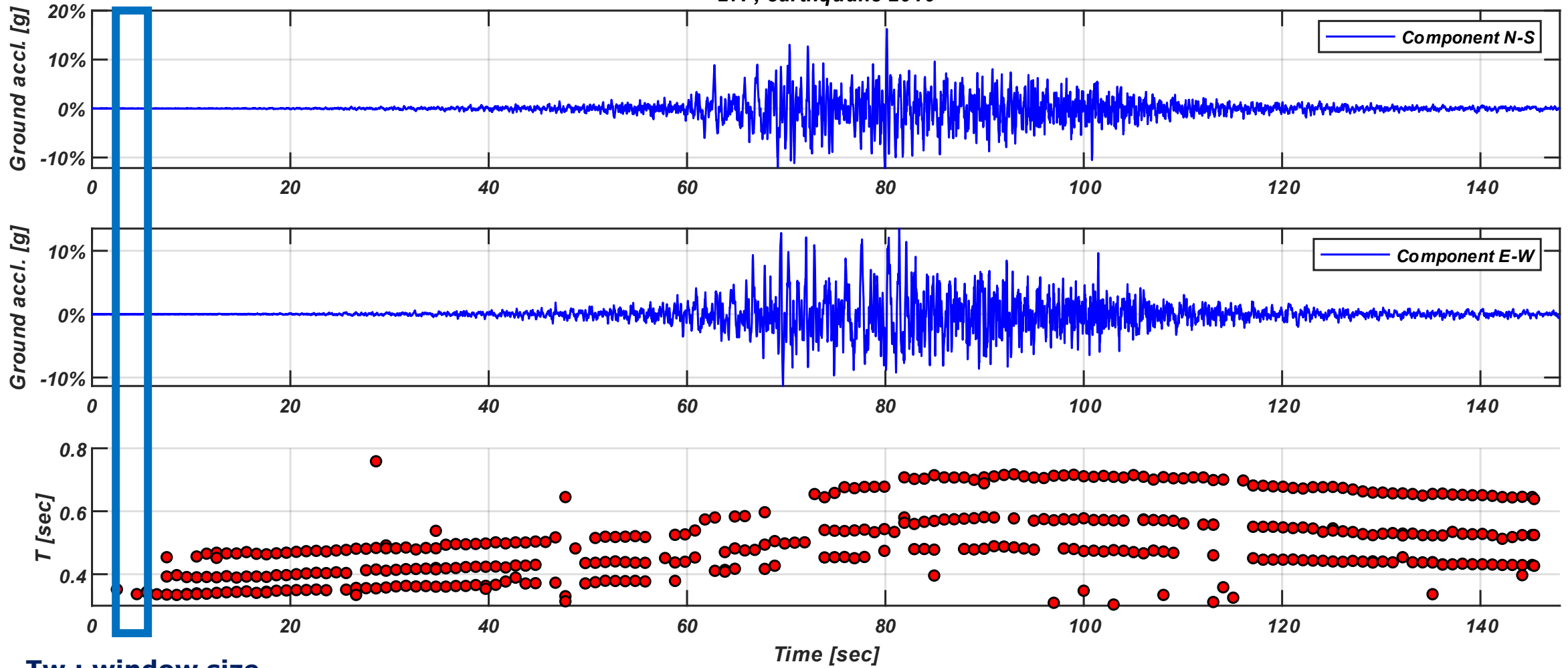
Frequency/Temperature: DAYLY

Note the phase lag between temperature and frequency



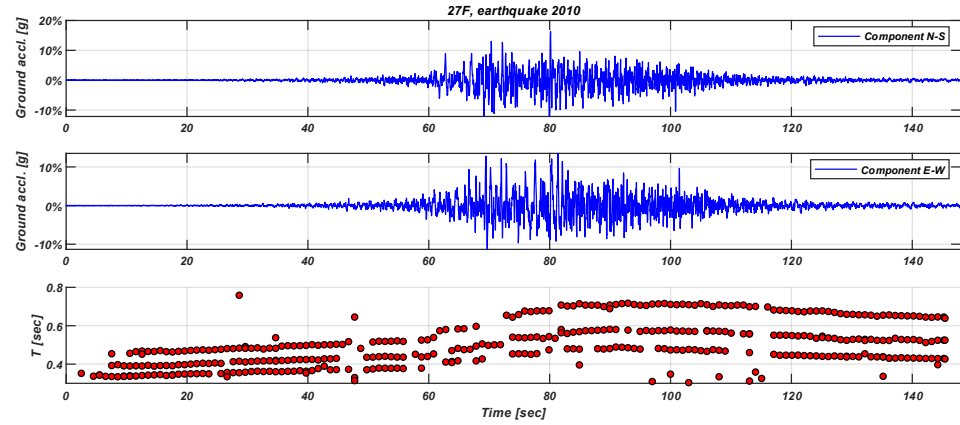
Frequency Variations Earthquakes

27F, earthquake 2010



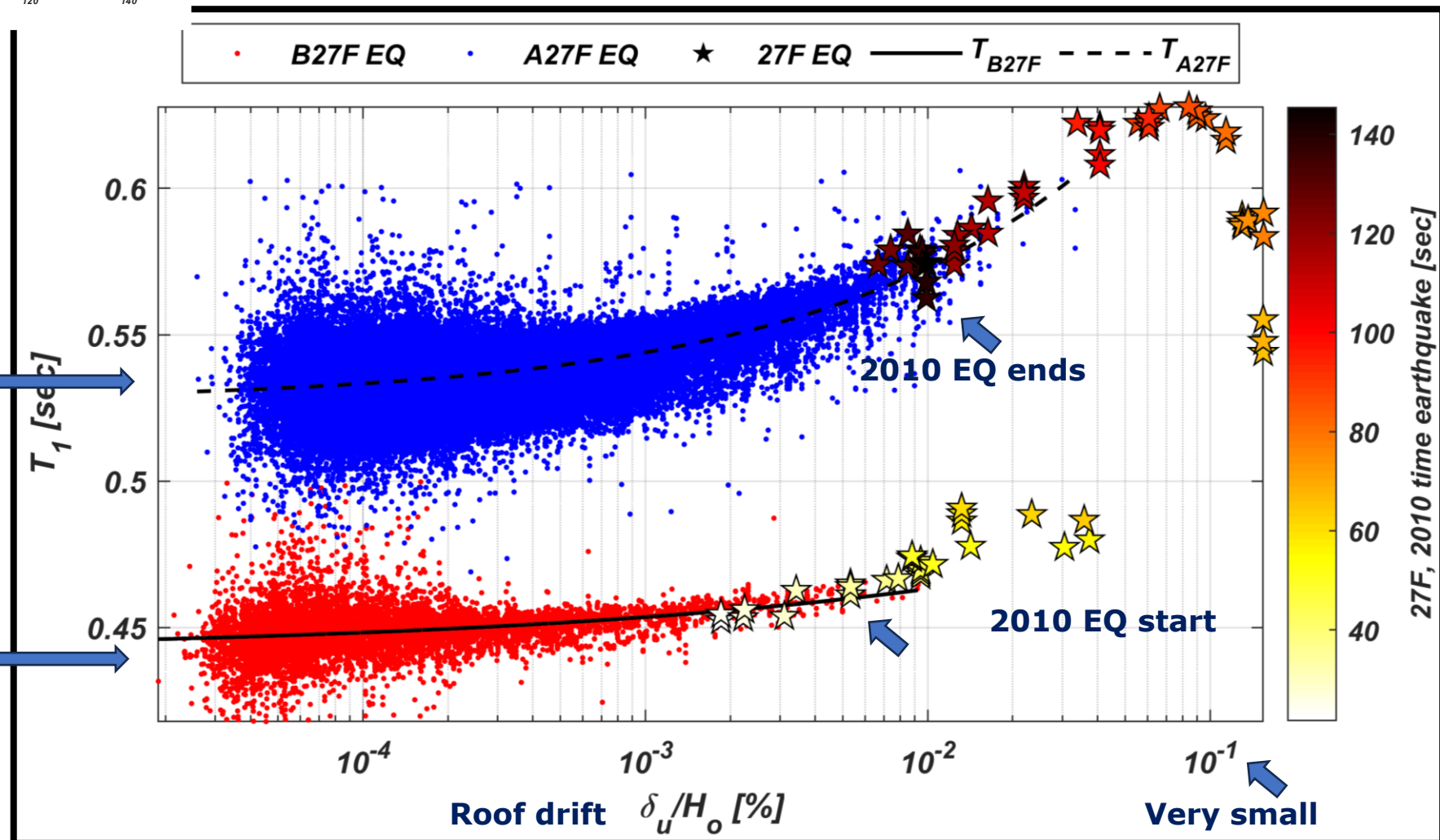
Tw : window size

Frequency Variations Earthquakes

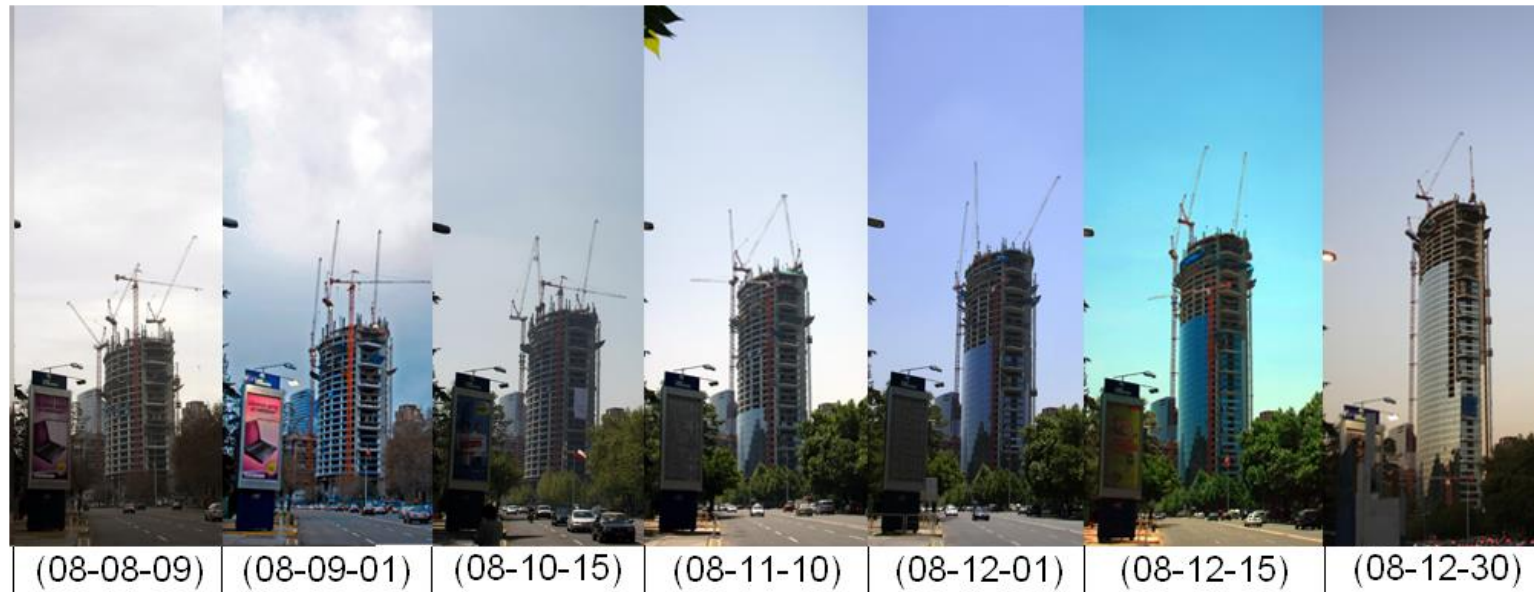
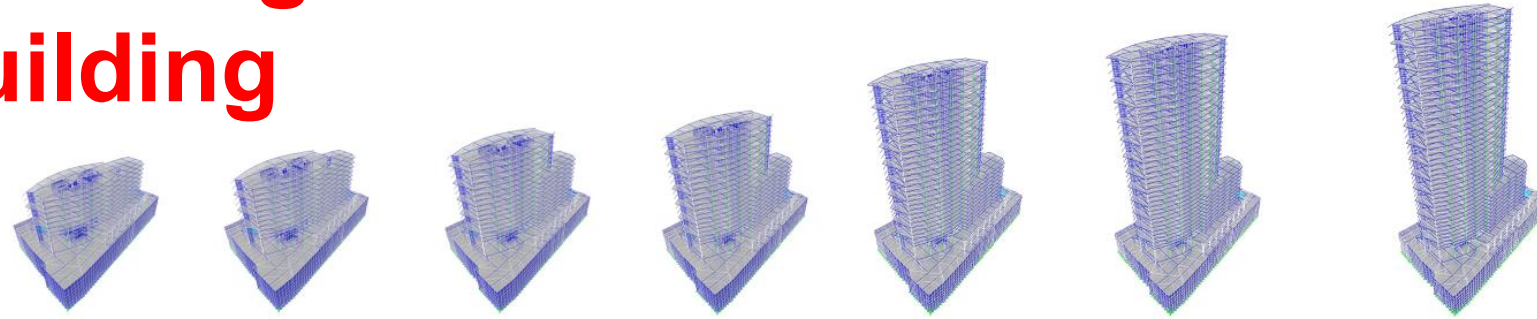


After de 2010 EQ

Before de 2010 EQ



CHILE: Monitoring Under Construction Titanium Building

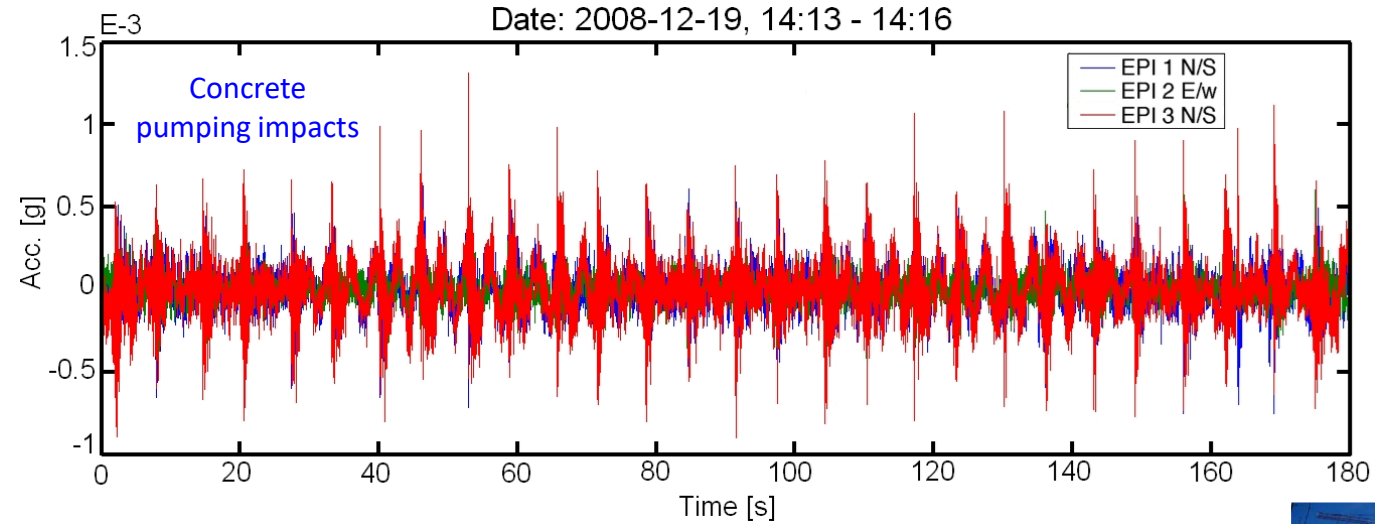


2 studies:

- (a) 5 month continuous under construction monitoring
- (b) Records every 2 or 3 stories during 5 construction stages

Construction Process: Monitoring Difficulties

- High transient vibration due to impact.
- Continuous and permanent variations of mass and stiffness.
- Operation of small and large machinery like cranes, concrete pumping and others.



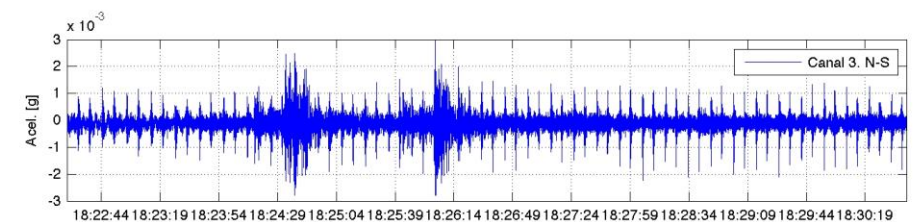
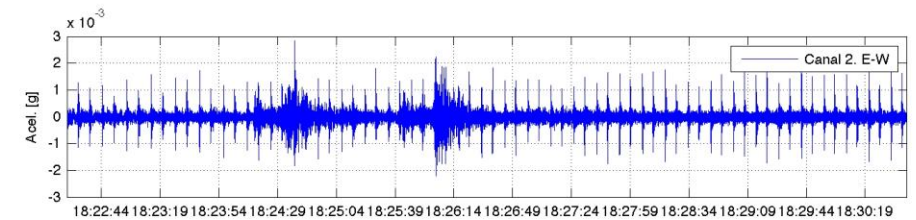
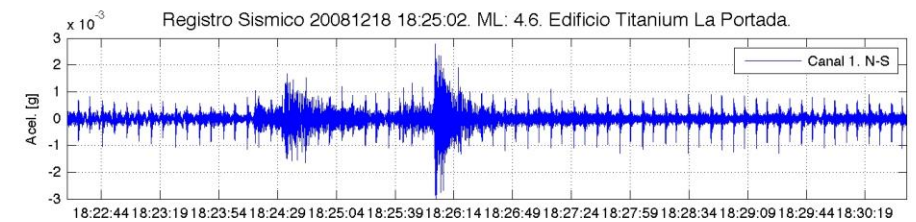
All this activities affects the system identification processes producing nonstationary signals



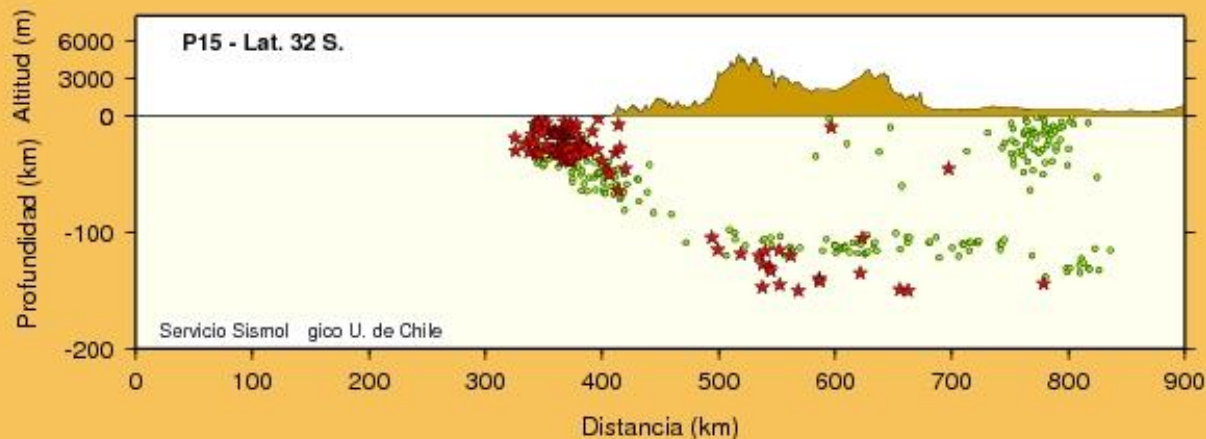
Earthquakes During Monitoring



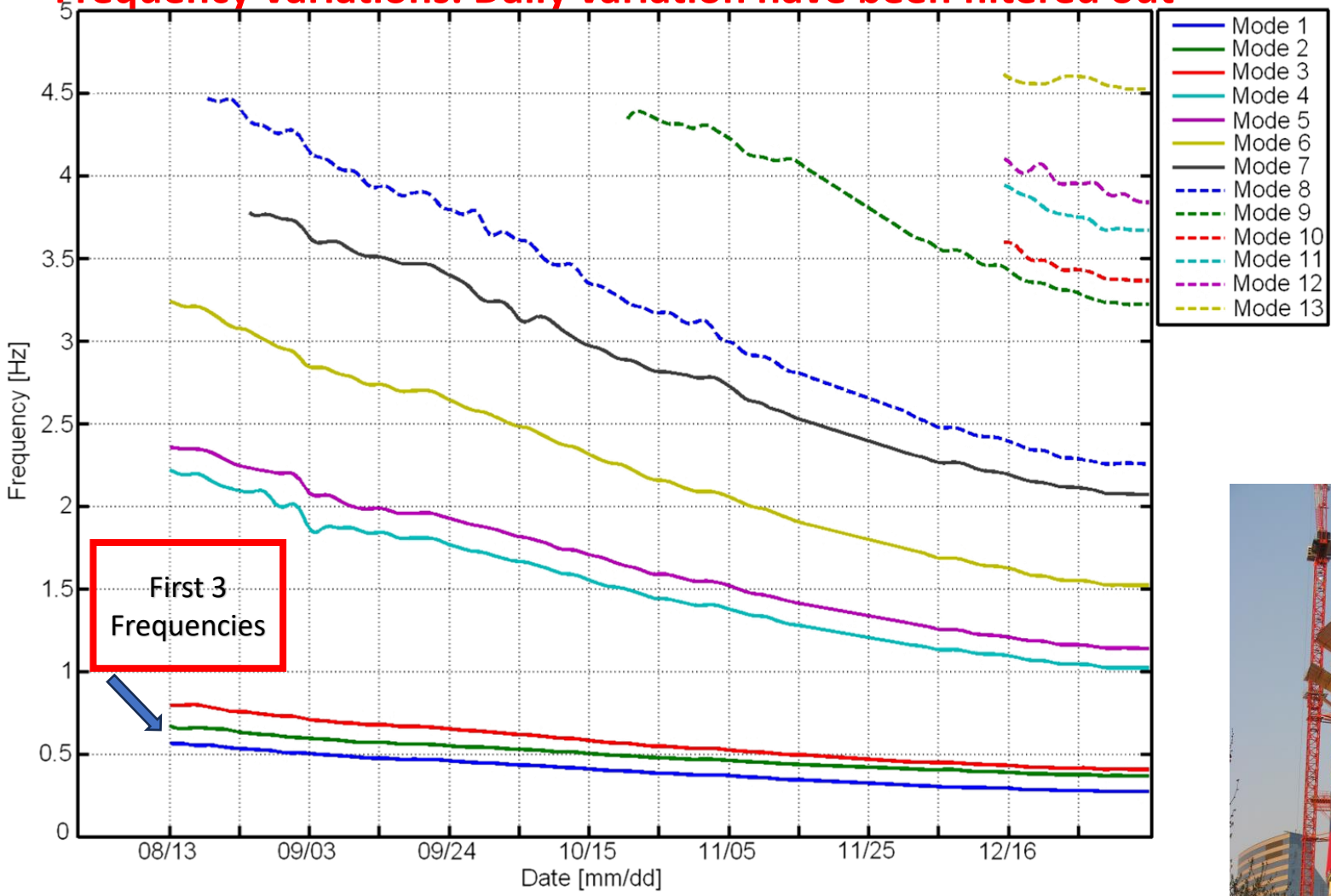
	Date	Time	Lat	Long	Depth	Mag
1	18-12-2008	18:19:28	-32 28' 33"	-71 54' 00"	24.0	5.9
2	18-12-2008	18:25:02	-32 29' 24"	-71 52' 37"	37.7	4.6
3	18-12-2008	18:50:28	-32 28' 44"	-72 04' 15"	25.1	5.5
4	19-12-2008	0:04:16	-32 29' 27"	-71 54' 50"	26.7	4.5
5	19-12-2008	4:30:06	-32 32' 20"	-72 01' 19"	12.0	5.1
6	19-12-2008	6:36:04	-32 27' 28"	-71 56' 56"	32.2	5.8
7	19-12-2008	10:57:30	-32 35' 02"	-71 51' 07"	13.8	5.1
8	19-12-2008	13:48:49	-32 35' 41"	-72 00' 21"	6.0	4.9
9	19-12-2008	14:43:26	-32 36' 43"	-71 49' 47"	29.5	4.2
10	19-12-2008	16:25:54	-32 34' 30"	-71 48' 21"	14.1	4.9
11	19-12-2008	18:33:10	-32 33' 07"	-71 57' 25"	32.0	4.4



Perfil de Profundidad

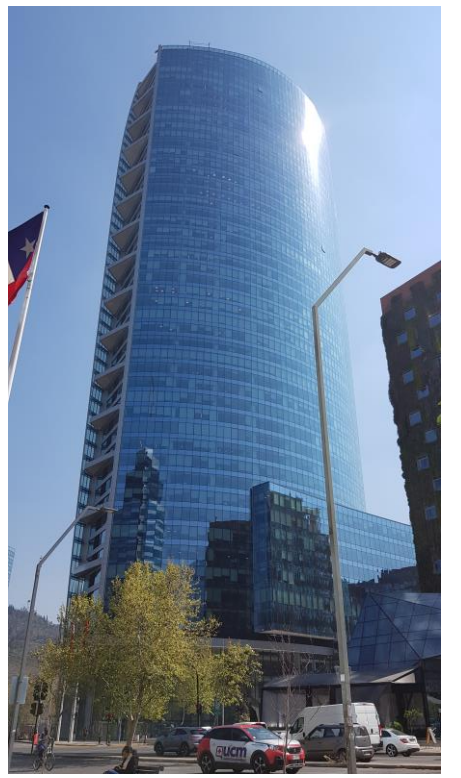
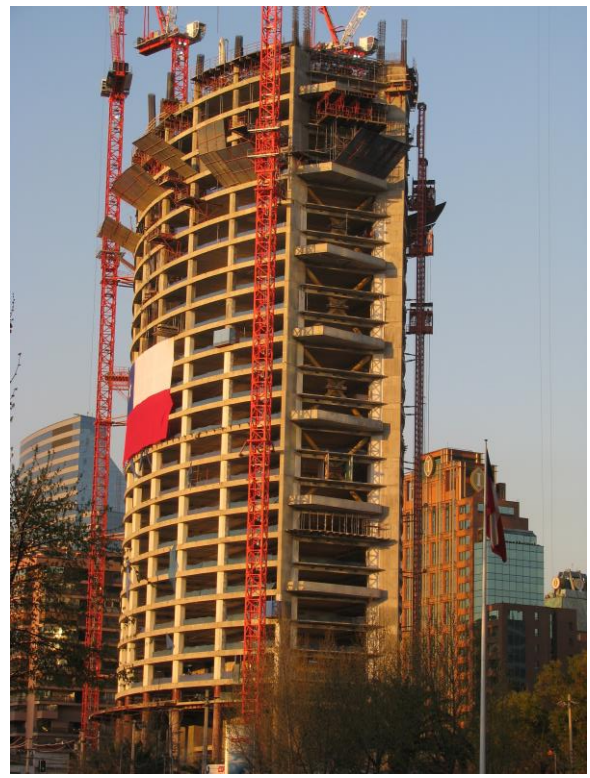


Frequency Variations. Daily variation have been filtered out

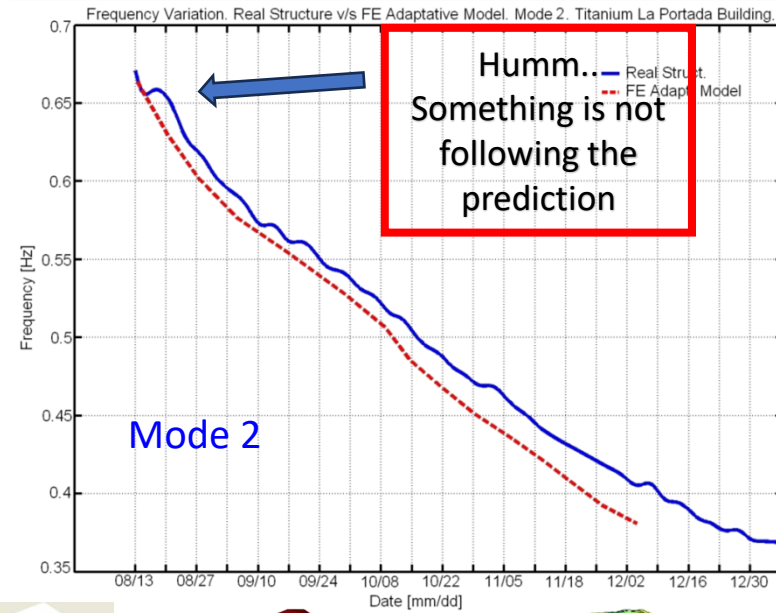
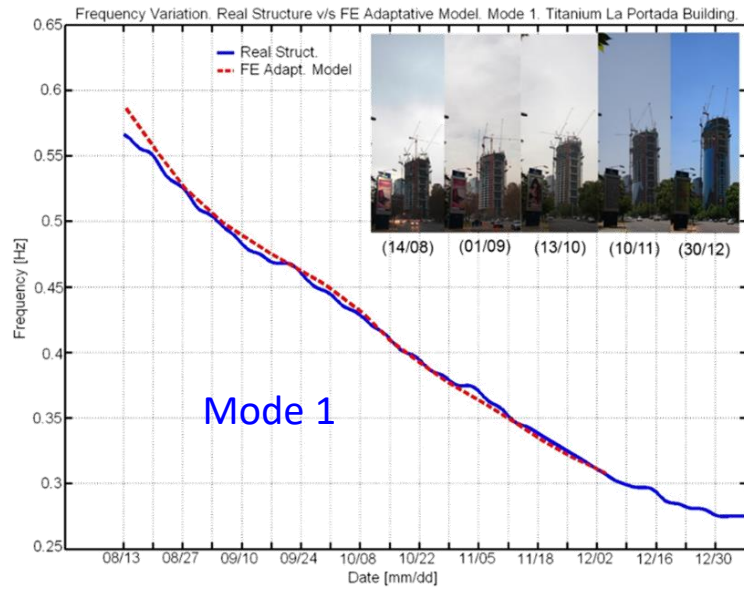


Weekly pattern (construction of 1 story)

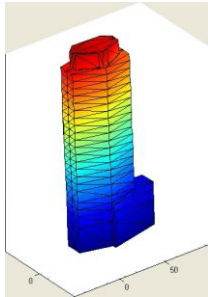
Weekly Variations Range: [1.5 - 5.5]%
(respect to the frequency at the beginning of each week)



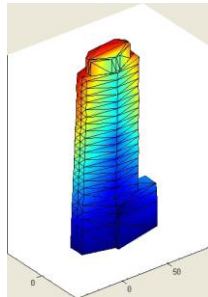
Comparison Finite Element Design Model - Adaptive Models.



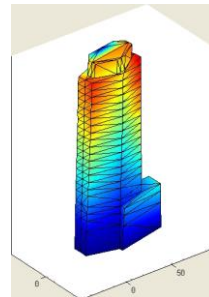
Source: MACEC 3.0



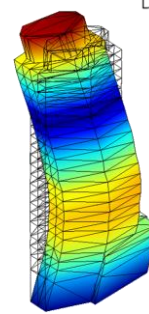
f1 = 0.187 [Hz]



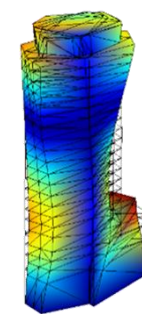
f2 = 0.256 [Hz]



f3 = 0.297 [Hz]

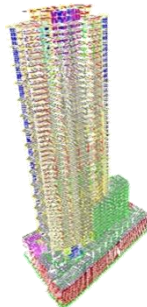


f4 = 0.713 [Hz]

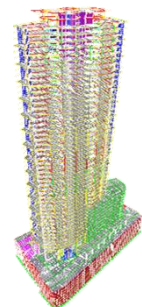


f5 = 0.864 [Hz]

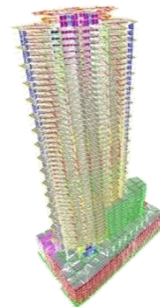
Source: ETABS



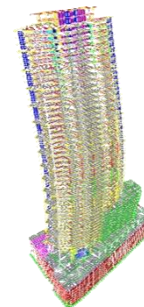
f1 = 0.187 [Hz]



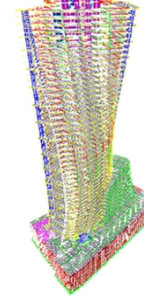
f2 = 0.250 [Hz]



f3 = 0.288 [Hz]



f4 = 0.700 [Hz]

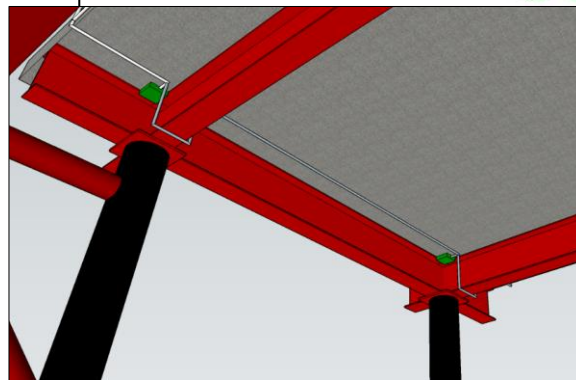
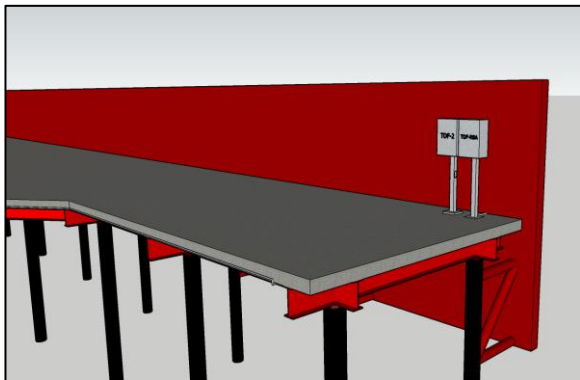
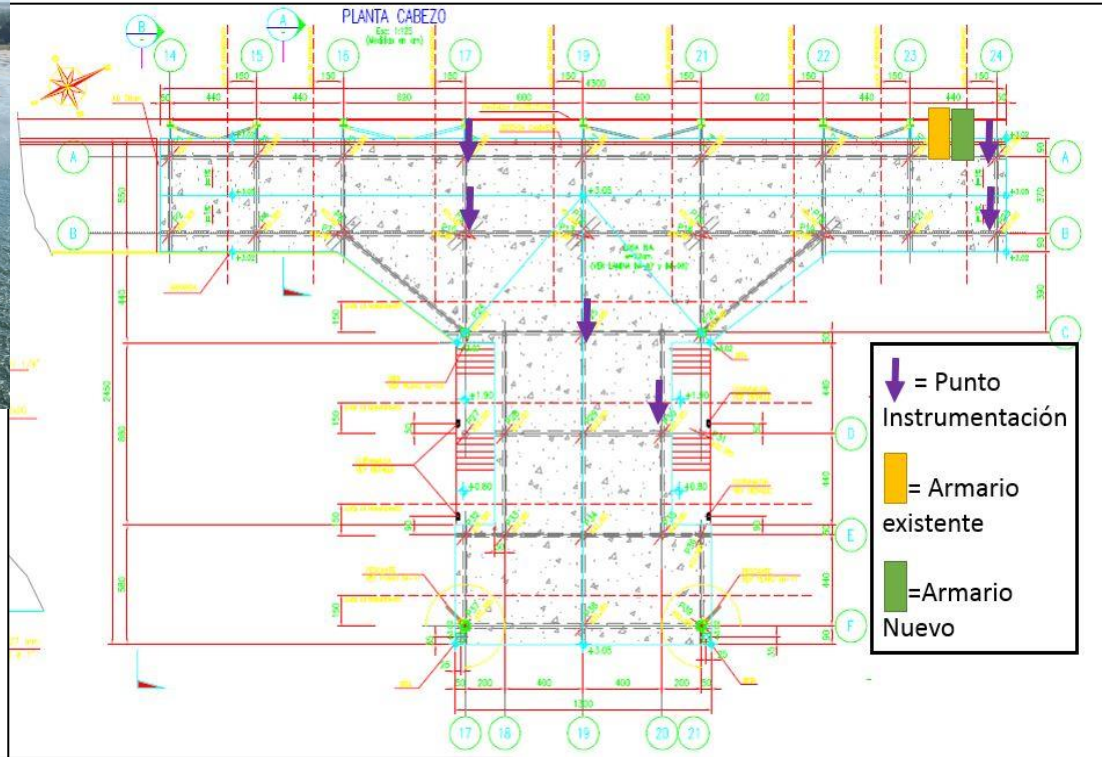


f5 = 0.811 [Hz]

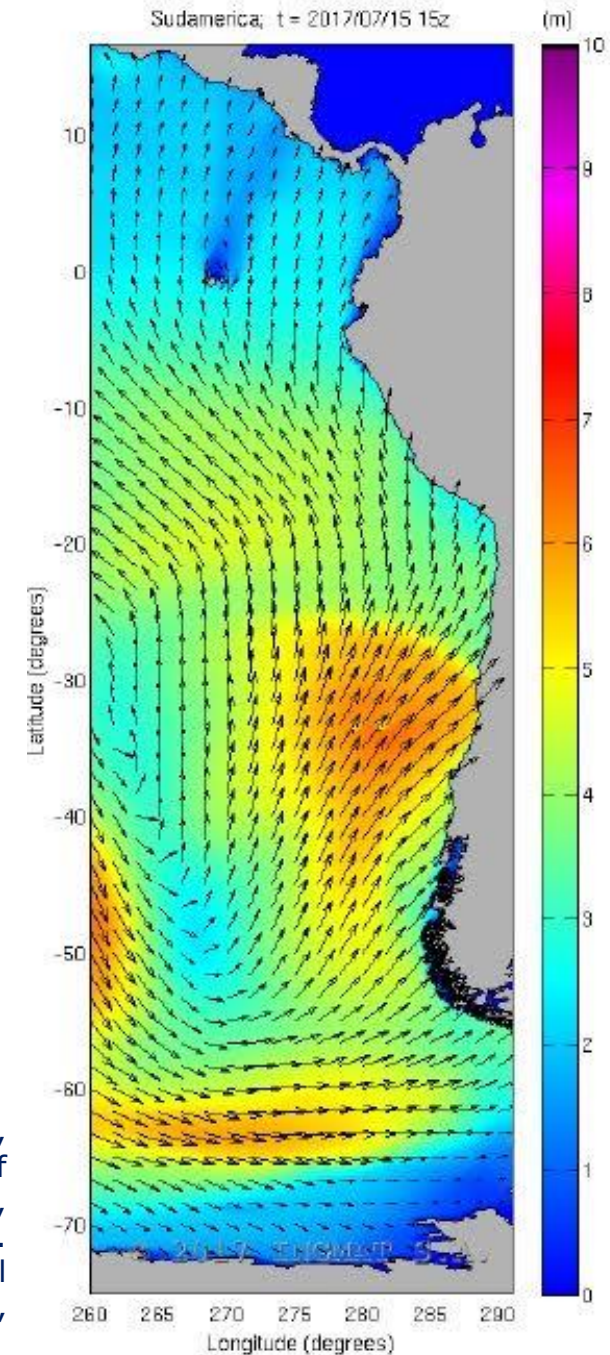
ArchDaily



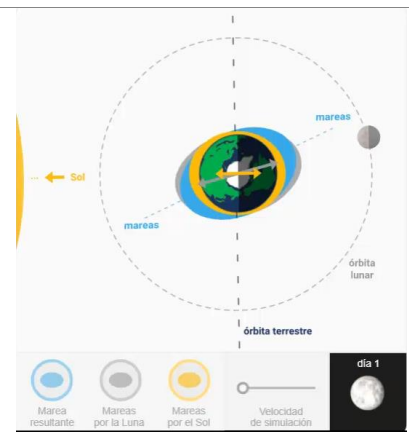
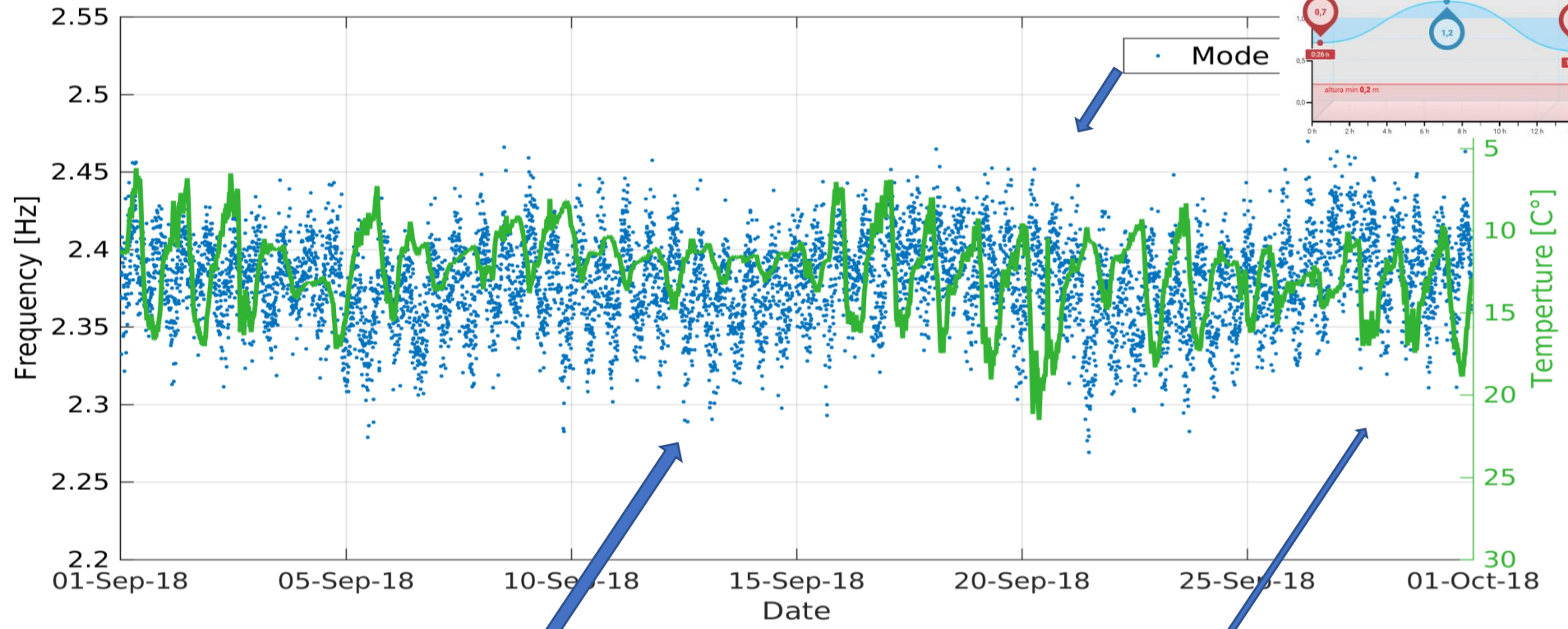
MODAL TRACKING OF TWO WHARF STRUCTURES UNDER ENVIRONMENTAL, OPERATIONAL AND EARTHQUAKE LOADS



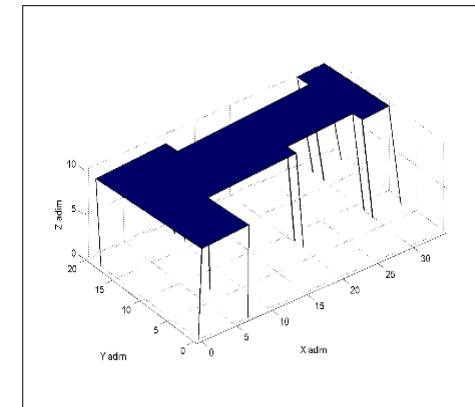
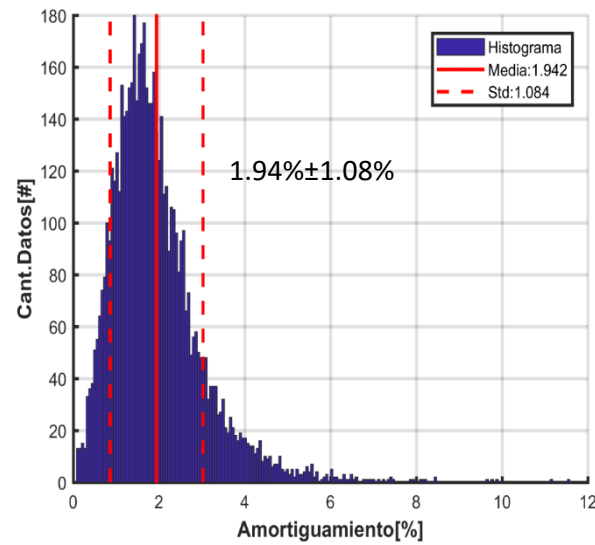
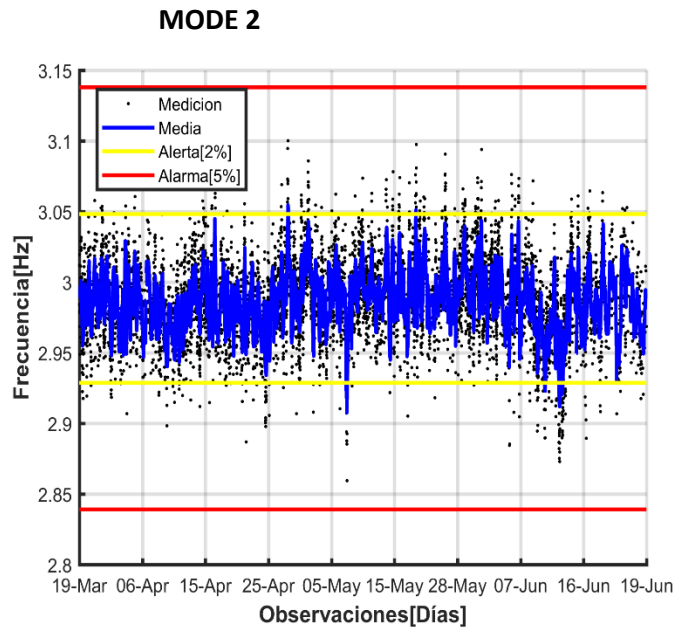
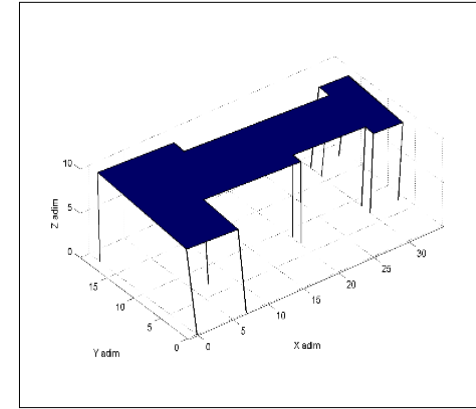
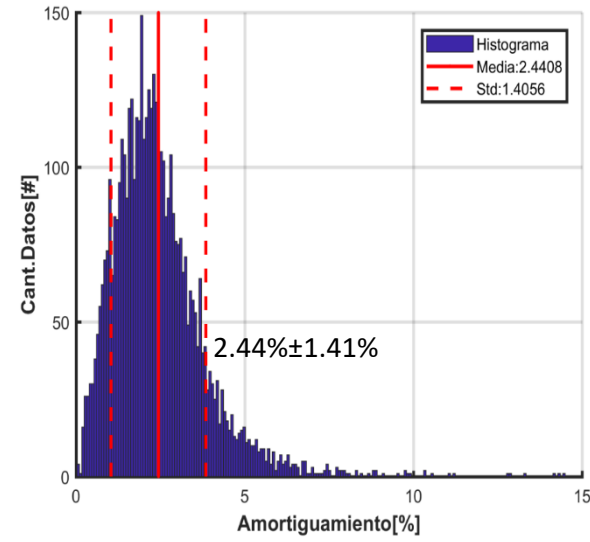
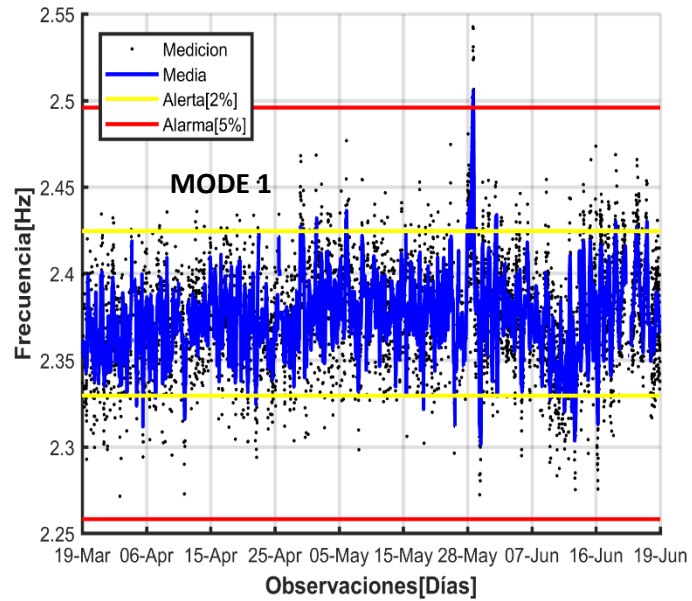
R. Boroschek, E. Pena, P. Villalpando, N. Novoa. Modal Tracking of two wharf structures under environmental, operations and earthquake loads. IOMAC International Operational Modal Analysis Conference, Copenhagen, Denmark 13-15 May 2019.



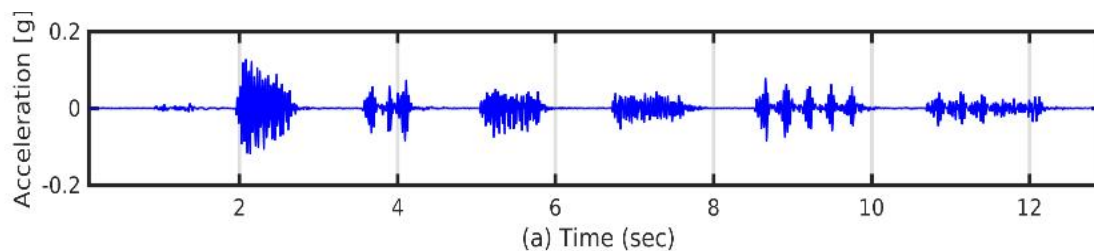
ENVIRONMENT EFFECTS ON FIRST PREDOMINANT FREQUENCY – CALETA HORNOS



CONTINUOUS MEASUREMENT – TRACKING AND ANALYSIS– CALETA HORNOS



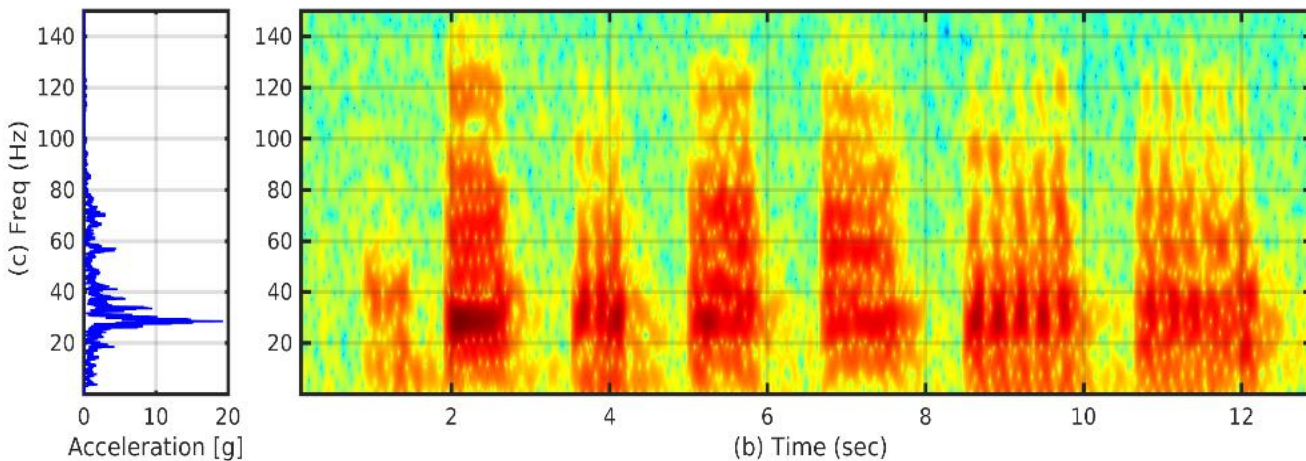
CHILE: OPERATION – EARTHQUAKE - BLAST



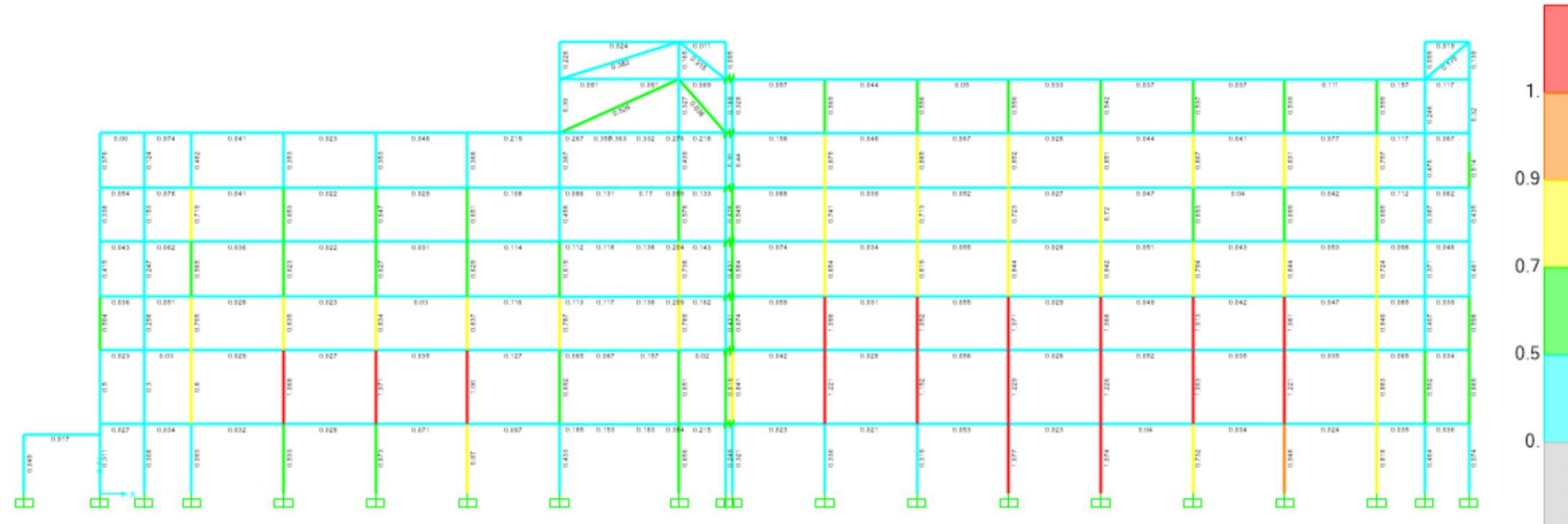
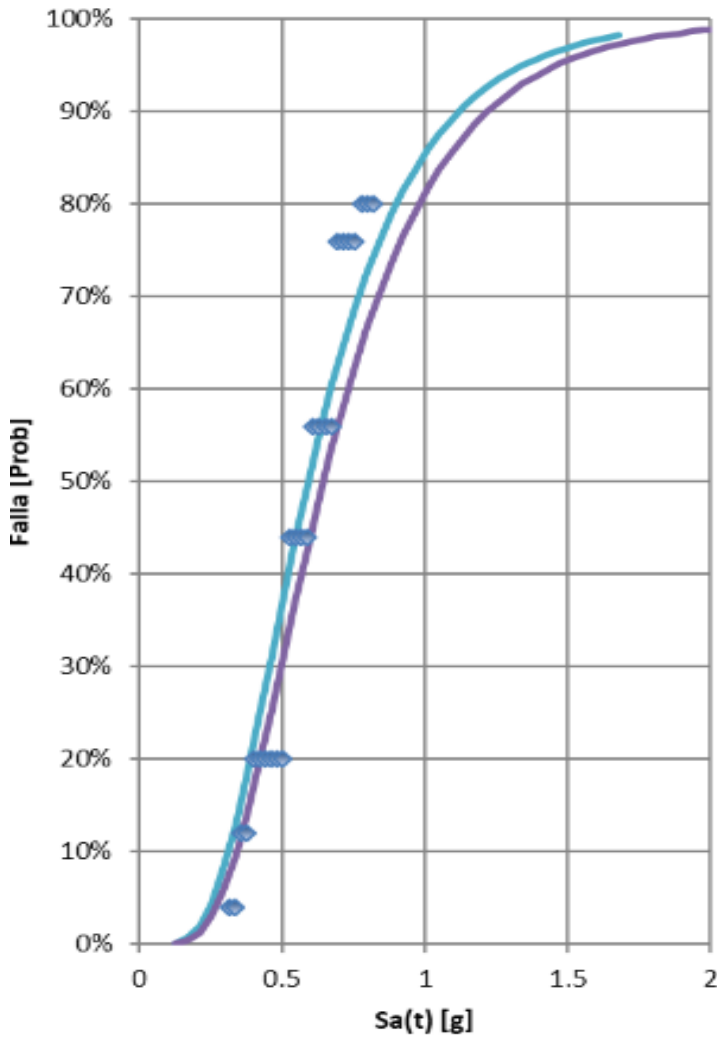
Blast Distance: 25–1500m
Charge: 16 – 850 kTon

Best Industrial Project of the Year
Structural Engineers Association Chile 2019 - AICE

Boroschek R., Villalpando P., Peña E. (2019) Building Structural Health Monitoring Under Earthquake and Blasting Loading: The Chilean Experience. In: Limongelli M., Çelebi M. (eds) Seismic Structural Health Monitoring. Springer Tracts in Civil Engineering. Springer, Cham. pp 361-383.

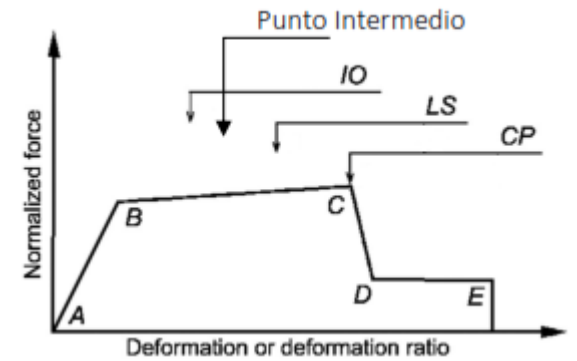


ESTABLISHING SAFETY LEVELS

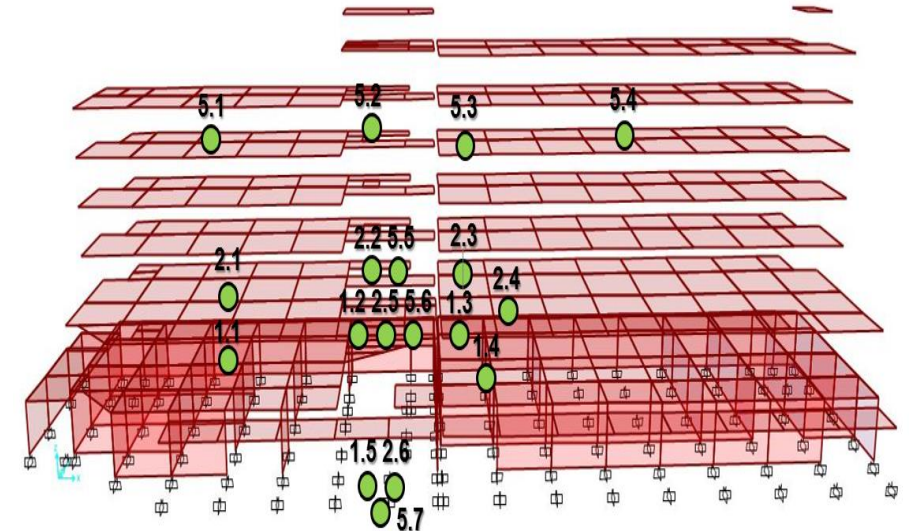
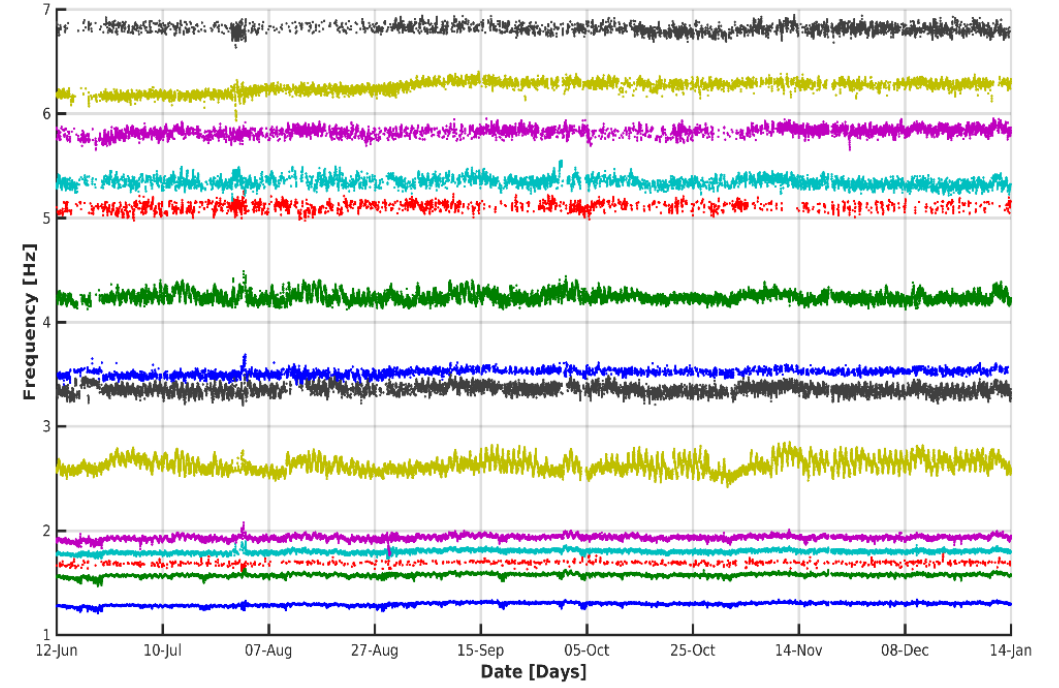


Element Type Immediate Mid Performance Life Safety

Tipo de Elemento	Ocupación Inmediata (IO)	Punto Intermedio	Seguridad de Vida (LS)
Vigas	1.25	1.6	2.0
Diagonales	1.25	2.0	4.0
Columnas	1.25	1.25	1.25



MODEL – UPDATED (?) - VARIATIONS



TRONADURA: 2017.07.04 15.47.19

**SERVICIO RBA-SMA
REPORTE PRELIMINAR 003**

RESULTADO DE LA EVALUACIÓN:

**NO SE SUPERAN LOS LIMITES PREVIAMENTE
DEFINIDOS**



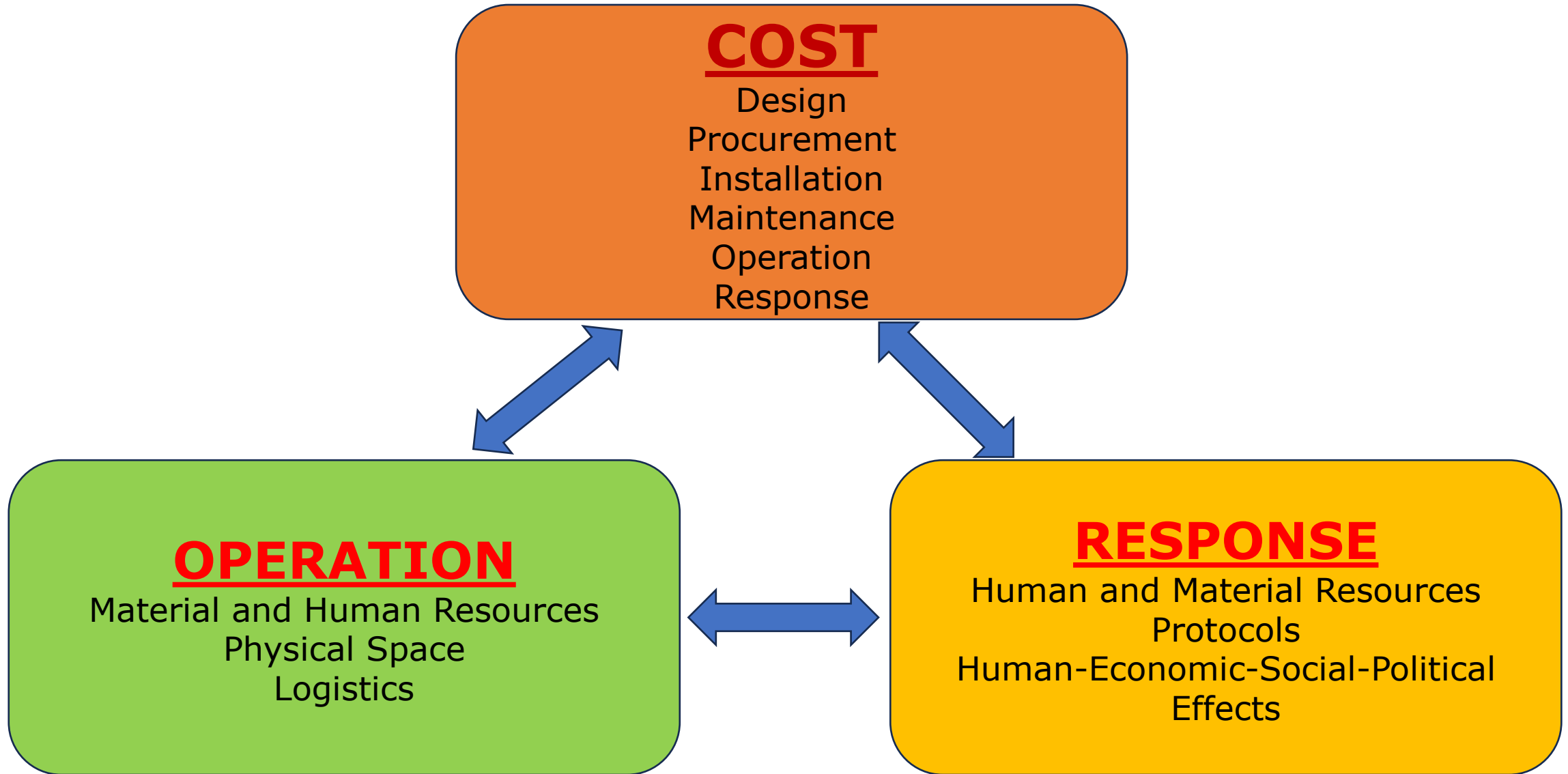
PROYECTO: Efecto de Tronadura
FECHA: 2017-07-04
HORA: 15:47:19
VERSION: 0.1

	Elemento	Seccion	FU(COMB0)	FU(COMB1)	Estado	% de Aumento
1	568	XL20x15.1	0.82	0.91		11.01
2	1275	XL20x15.1	0.75	0.78		4.13
3	566	XL20x15.1	0.73	0.75		3.65
4	565	XL20x15.1	0.72	0.74		3.61
5	1318	HN30x128	0.72	0.74		1.86
6	538	Ca150x5	0.7	0.74		4.65
7	1302	HN30x128	0.72	0.74		1.87
8	1326	HN30x128	0.72	0.74		1.88
9	1342	HN30x128	0.72	0.73		1.68
10	2647	IE25x21.1	0.72	0.73		2.34
11	532	Ca150x5	0.69	0.72		5.01
12	1277	XL20x15.1	0.69	0.72		4.07
13	539	Ca150x5	0.7	0.72		2.9
14	2022	Canal15x5.66	0.68	0.71		3.66
15	2672	IE25x21.1	0.68	0.71		4.1
16	1462	HN25x87.4	0.7	0.71		1.83
17	537	Ca150x5	0.69	0.71		2.3
18	2696	IE25x21.1	0.68	0.71		4.37
19	1502	HN25x87.4	0.69	0.7		1.92
20	1283	XL20x15.1	0.67	0.7		4.43



Video: FLESAV

But do not forget





fcfm

Ingeniería Civil
FACULTAD DE CIENCIAS
FÍSICAS Y MATEMÁTICAS
UNIVERSIDAD DE CHILE

Thank you

www.boroschek.com

