SEP 25, 2018 | CRL Summer School

RION - ANTIRION BRIDGE PROJECT

GENERAL INFORMATION | INSTRUMENTED & GEOMETRICAL MONITORING | CABLE VIBRATION & DECK VORTEX SHEDDING

BY GEFYRA SA TECHNICAL DEPT.

“BRIDGING THE GAP”

THE “RION –ANTIRION BRIDGE” PROJECT

The idea of bridging the gap in Rion Antirion strait was first envisaged by the Greek Prime Minister Charilaos Trikoupis back in late 19th century

Rion Antirion crossing time through ferries could exceed 45 min and significant traffic jams were experienced during:

- Peak season
- Bad weather conditions

Rion Antirion Bridge links the west motorway network of Greece connecting significant ports

Crossing time through Bridge dropped to less than 5 min regardless of weather conditions

Social and economic impact especially on local area

GEFYRA
RIO - ANTIRIO
CHARILAOS TRIKOUPIS

STRUCTURAL DESIGN:

ENVIRONMENTAL SITE CONDITIONS

- Weak Sea Bed up to 500m

  No bedrock encountered in first 100 m during soil investigations, while geological studies indicated similar conditions for up to 500 m

- Water depth up to 65 m

  Uniform sea bed at depth of 60 m with steep slopes near coast

- High Seismicity

  Active normal faults on both sides of Corinthian gulf, at the vicinity of Bridge

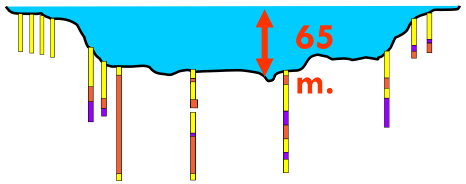
- Tectonic movements

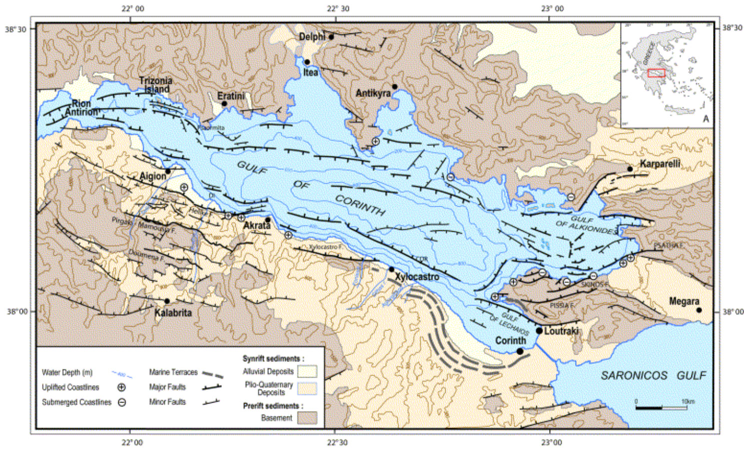
  Tectonic kinematic of area indicates separation of Peloponnese from mainland Greece with rate of ~20 mm/year

- Strong Wind area

- Navigation channel

  Significant marine traffic through Rion - Antirion strait

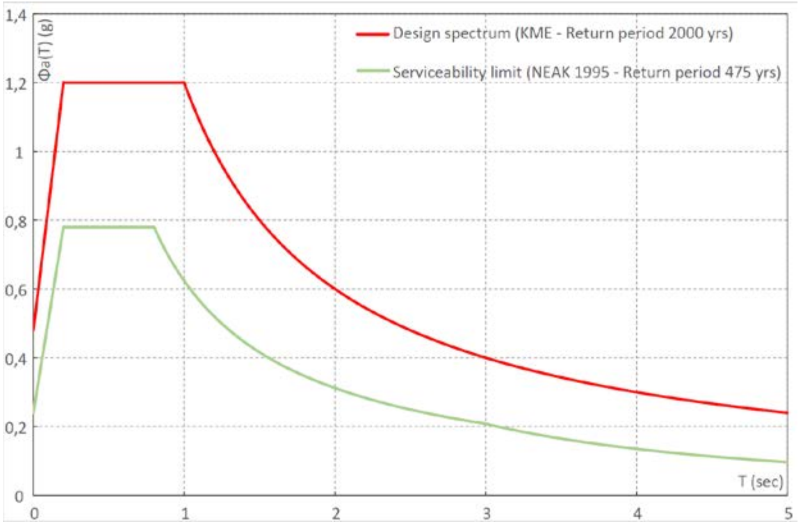


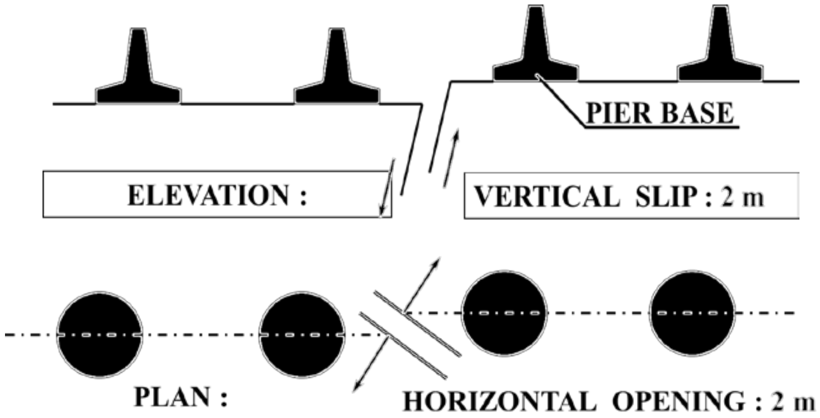


STRUCTURAL DESIGN:

MAIN DESIGN LOADS

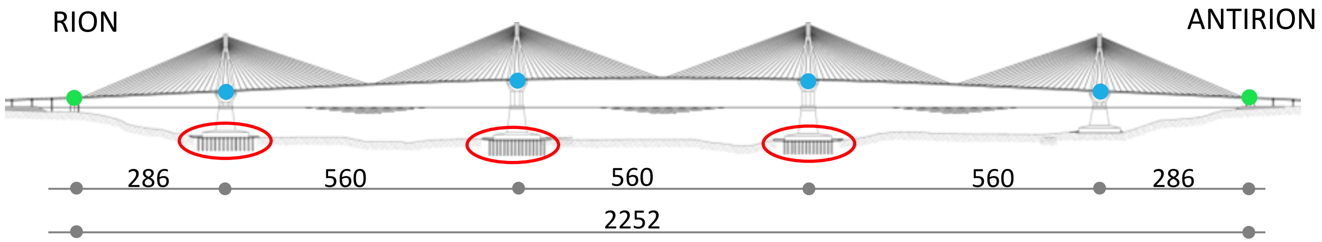
- Seismic load (Spectrum: pga 0,48 g, max Sa 1,20 g for T=0,2 up to 1,0 sec) - EQ of 2000 years Return Period
- Tectonic movements up to 2m (between adjacent piers)
- Design Wind speed 50m/sec at deck height
- Aerodynamic stability up to 74m/sec
- Ship collision:
  - 85000 dwt bulk carrier (full laden) at 16 knots
  - 180000 dwt tanker (on ballast) at 16 knots





STRUCTURAL DESIGN:

MAIN CHARACTERISTICS OF STRUCTURE

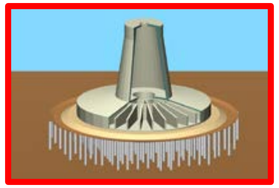


4 DAMPERS ON EACH MAIN PIER & 2 ON EACH TRANSITION PIER (TP)

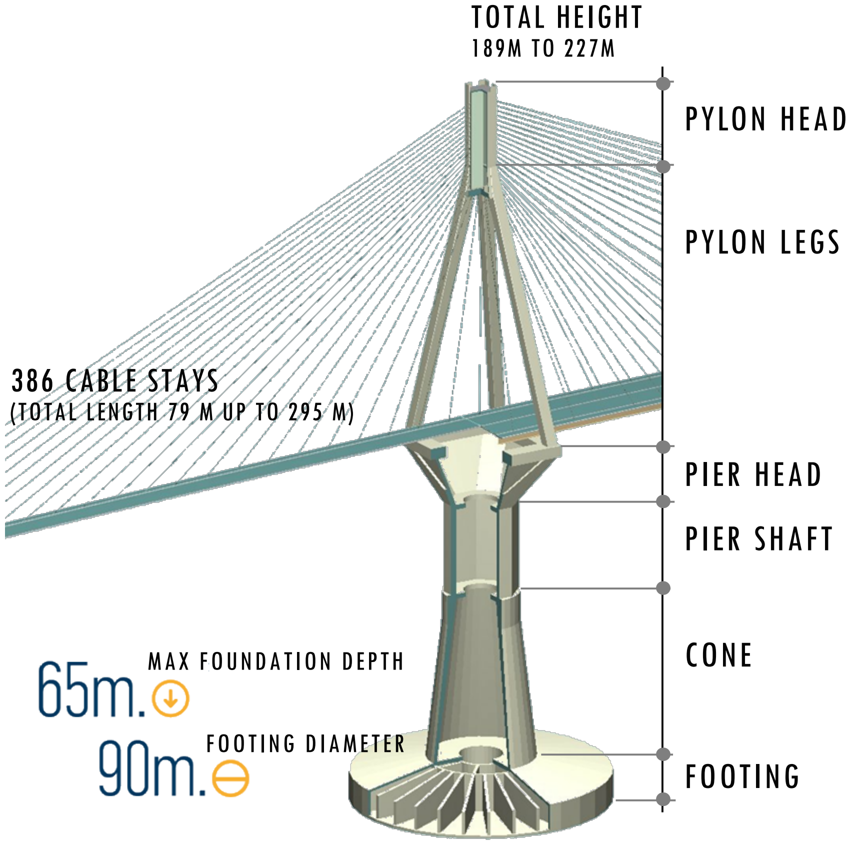
- In service: The deck is laterally supported by means of a restrainer (nominal load: ±10,5MN for main piers / ± 3,5MN for TP)
- In ultimate conditions: It fuses allowing the dissipation system to absorb the induced energy (dampers stroke: 3,5 m for main piers / 5,2 m for TP)

2 EXPANSION JOINTS:

+1,26/-1,15 m longitudinal expansion in service
(max longitudinal expansion +2,81/-2,20 m)

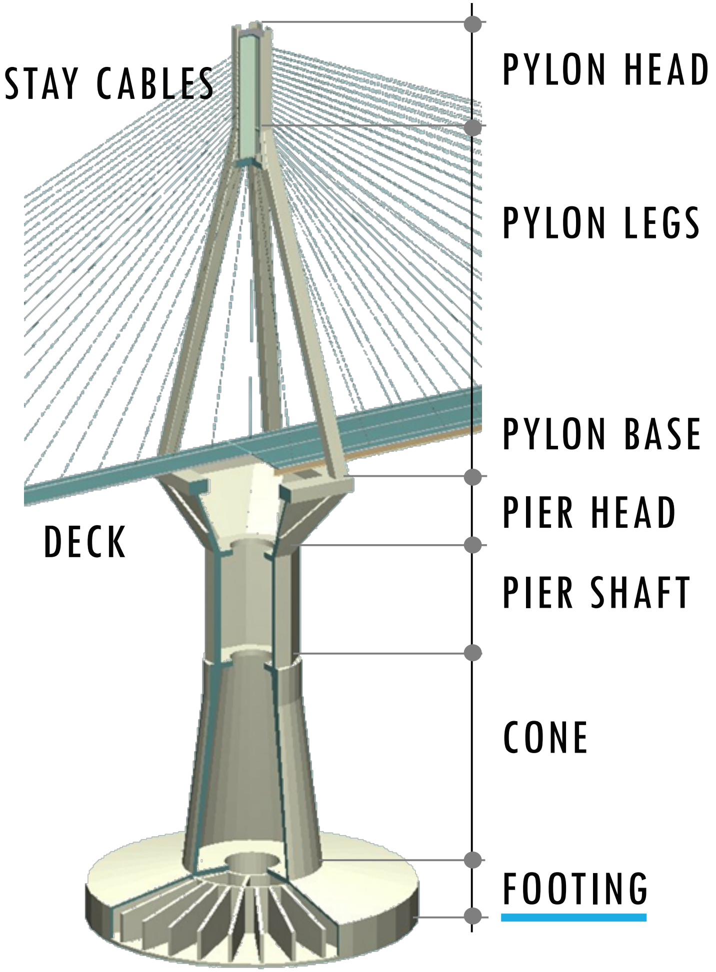


SHALLOW FOUNDATION ON REINFORCED SOIL



STRUCTURAL ELEMENTS AND DESIGN

SOIL & FOUNDATION (FOOTING)



Weak soil was reinforced with steel inclusions (steel pipes 2m diameter)

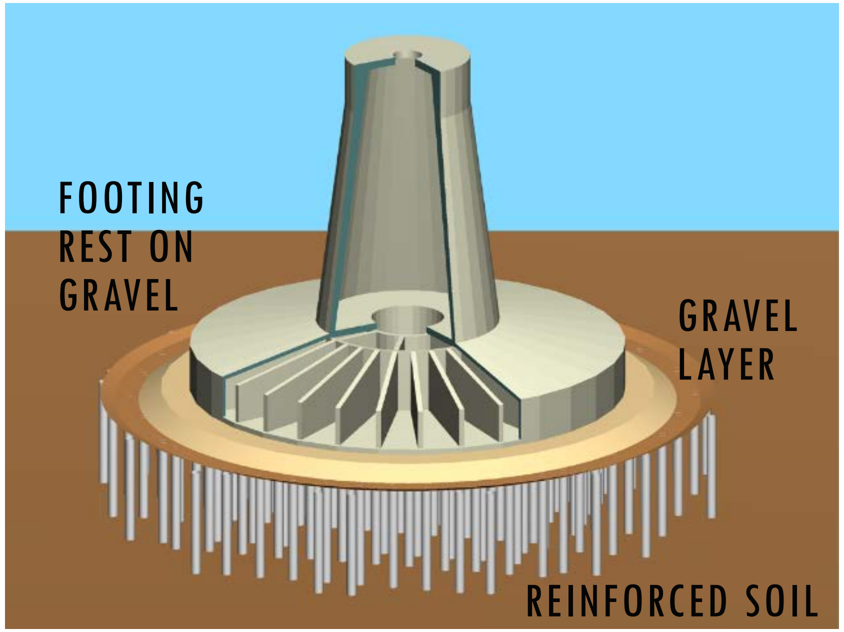
M1	M2	M3	M4
112	194	156	-

Crushed gravel was laid on top to achieve required friction coefficient

Footing was floated and rested on top gravel layer – no connection with inclusions

Enlarged footing diameter to enhance stability and minimize soil stress (80/90m diameter M4/M1-M3)

Preloading of soil to accumulate settlements during construction

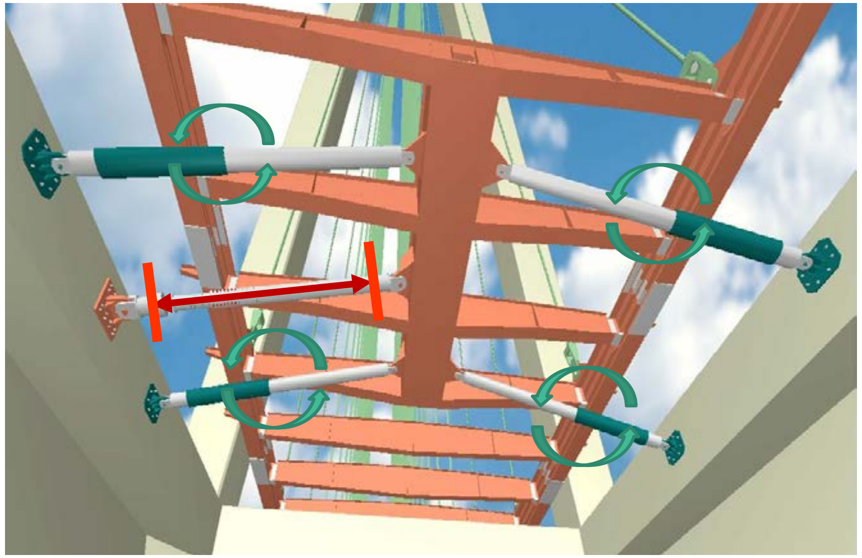


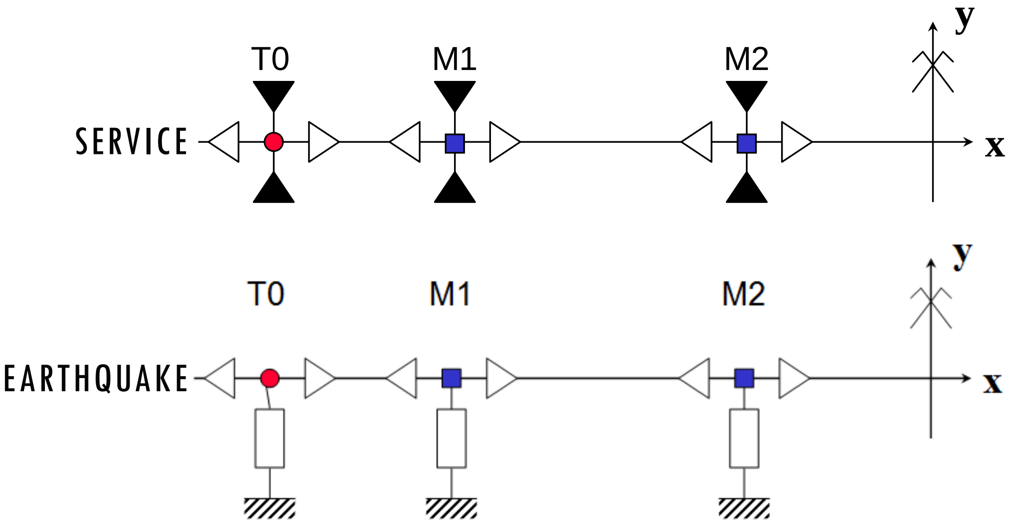
STRUCTURAL ELEMENTS AND DESIGN

STRUCTURAL EQUIPMENT: DISSIPATION SYSTEM AT MAIN PIERS

Dissipation system: absorbs earthquake energy, reducing the lateral movement during strong earthquakes

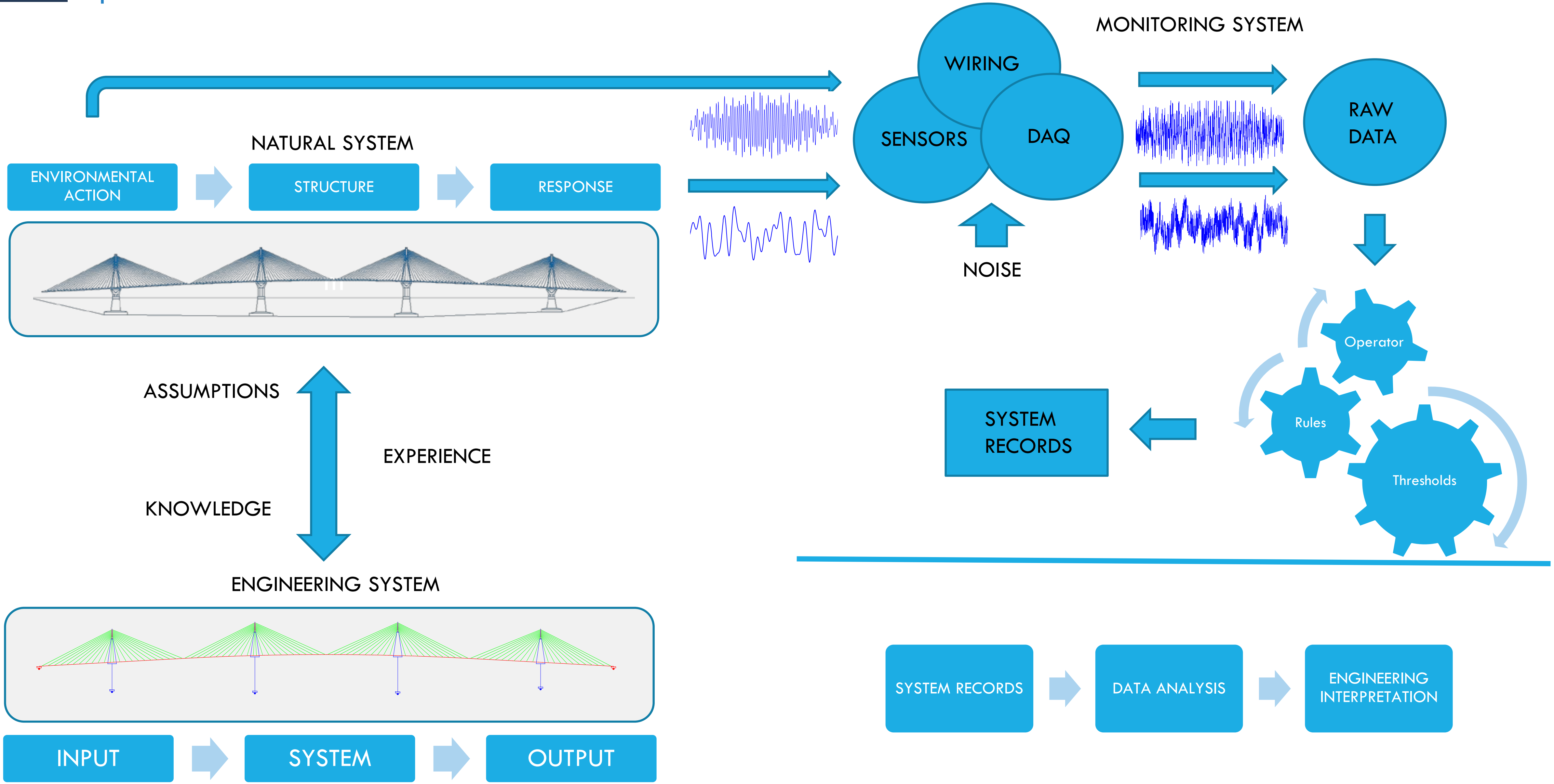
- To avoid transverse movements during normal operation conditions or small earthquakes, the deck is attached to the pylons (and rotating frames) through the fuses
- Fuses on pylons are devices that release the deck when the force exceeds 10500kN in both directions,
- Fuses can be replaced after a strong earthquake easily by replacing the sacrificial thread
- Dampers can absorb lateral deck motions up to ±1,65 m and loads up to 3500kN





INSTRUMENTED MONITORING

STRUCTURAL HEALTH MONITORING (PERMANENT SYSTEM)



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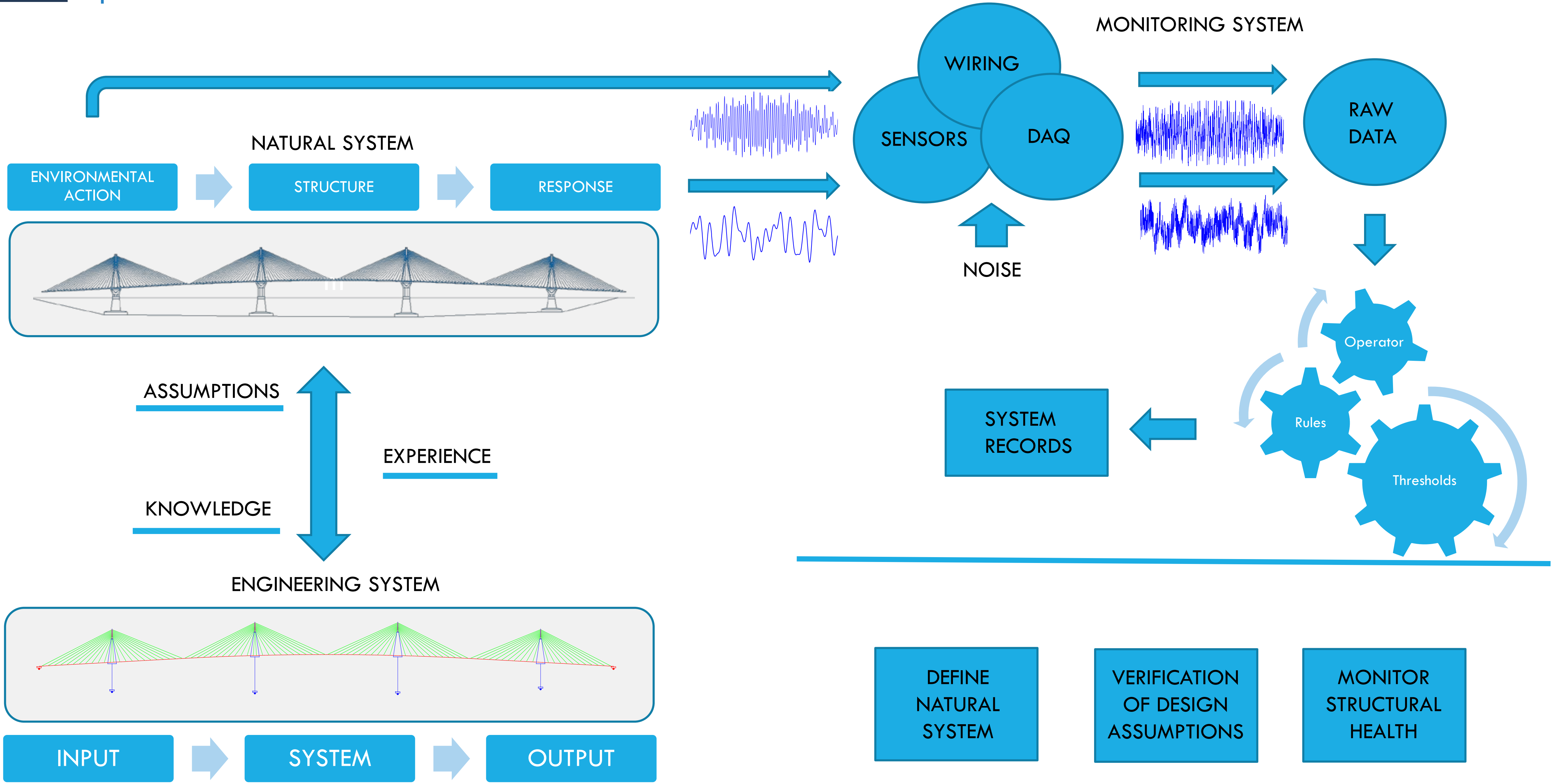
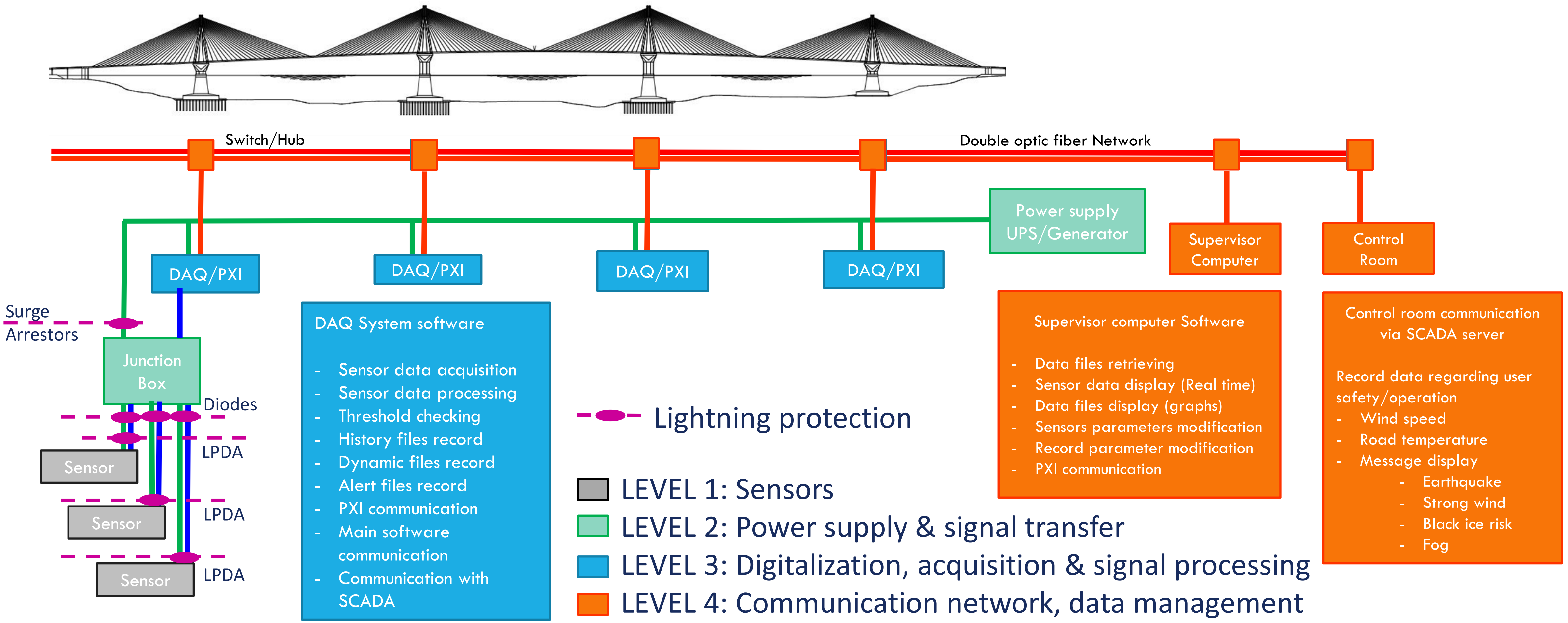


INSTRUMENTED MONITORING:
STRUCTURAL HEALTH MONITORING ARCHITECTURE



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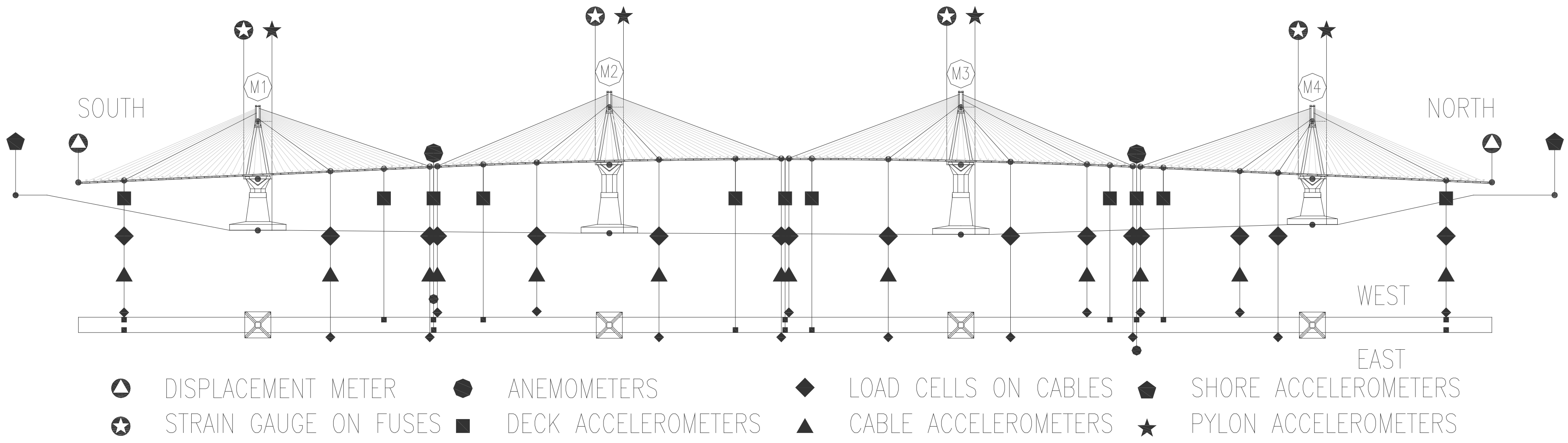


Sensor	Quantity	Expected range	Sensor range	Monitored phenomenon
3D anemometers	2	0-50 m/sec	0-60 m/sec	Wind intensity
Temperature and Humidity sensor	2	50º C/0-100%RH	-50ºC, up to 50ºC/ 0- 100% RH	Thermal loading
3D Pylon accelerometers	12	±1.9g (top) ±1.0g(base)	±20g(top) ±3g(base)	Pylon vibration (Earthquake/wind)
1D/3D Deck accelerometers	3/12	±2.7g	±3g	Deck vibration (Earthquake/wind)
3D Ground accelerometers	2	±0.48g	±3g	Earthquake
3D Cable accelerometers	13	-	±3g	Cable vibration Wind
Monostrand load of cables	16	0 up to 75% F_{GUTS} (199 kN)	0-320 kN	Cable load variation (Wind/Earthquake/Balance)
Magnetic distance meter	2	+1260/-1150 mm	3 m	Expansion joint opening (Earthquake/Balance/Thermal)
Strain gauges (full bridge)	4	±10500 kN	±1500$\mu\varepsilon$ ±17000 kN	Wind induced lateral load
Road temperature sensors	4	-	-50ºC, up to 50ºC	User safety (black ice risk)
Deck temperature sensors	5	-	-10ºC, up to 80ºC	Thermal loading

Lightning protection

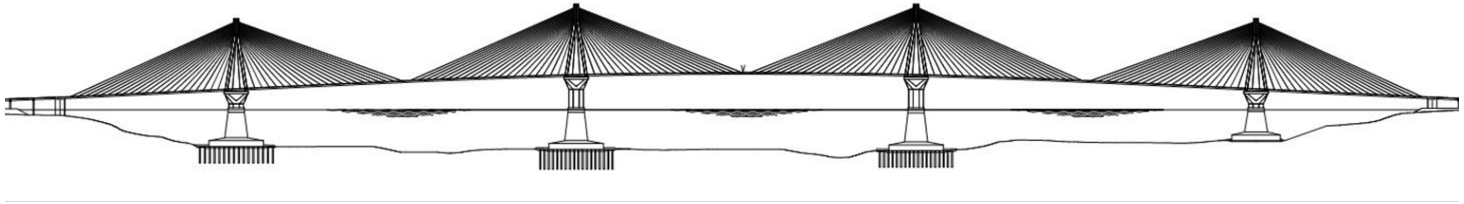
LEVEL 1: Sensors

LEVEL 2: Power supply & signal transfer

LEVEL 3: Digitalization, acquisition & signal processing

LEVEL 4: Communication network, data management

INSTRUMENTED MONITORING:
STRUCTURAL HEALTH MONITORING ARCHITECTURE



LEVEL 2: Power supply & signal transfer

- Sensors more than 400 m away from DAQ unit
- AC/DC convertors (~230 V to 24 VDC)
- Signal conditioning (Amplifiers)

LEVEL 3: Digitalization, acquisition & signal processing

- 4 acquisition points (one per pylon)
- Low pass filtering at 10 kHz
- Digitalization at 500 Hz
- Signal conversion to engineering unit
- Alert checking and file creation & Real time data transmission
- Synchronization (SNTP)

LEVEL 4: Communication network, data management

- Optic fiber network in ring configuration for redundancy
- Communication with Supervisor Server (SE) for permanent file storage/visualization/parameter management

Lightning protection

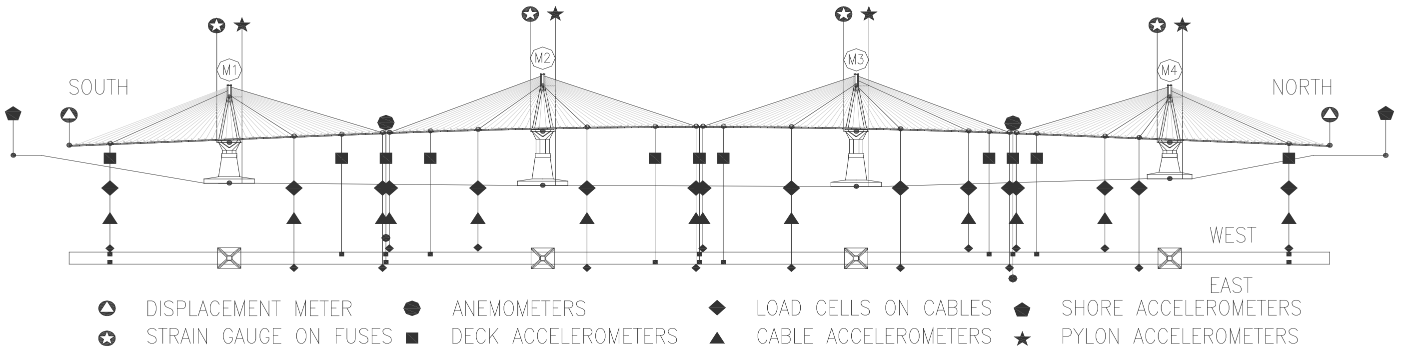
LEVEL 1: Sensors
LEVEL 2: Power supply & signal transfer
LEVEL 3: Digitalization, acquisition & signal processing
LEVEL 4: Communication network, data management

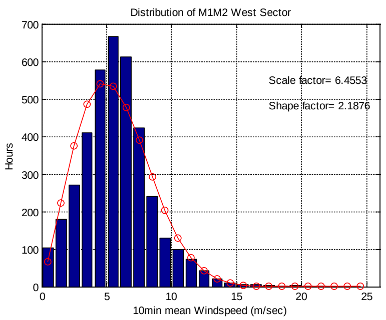
INSTRUMENTED MONITORING

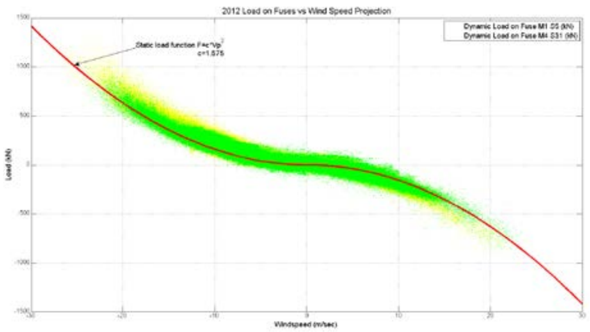
Structural Health Monitoring (permanent system)

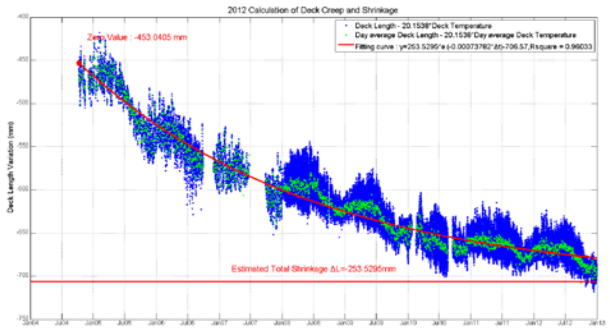
MONITORING SYSTEM OPERATION PROVIDES:

1. Dynamic characteristics of actual structure
2. Characterization of real actions
3. Design verification and feedback
4. Structural health status determination
5. Supports Operation



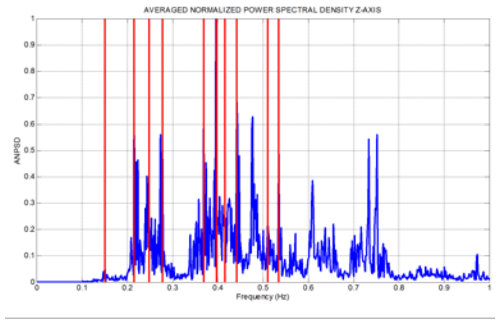


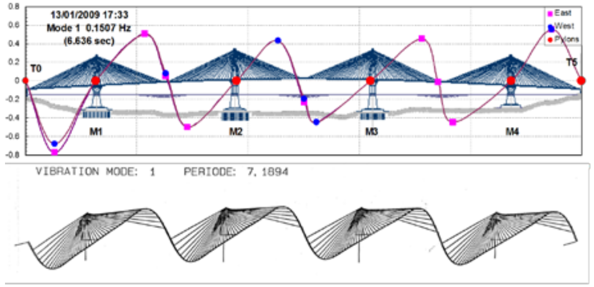


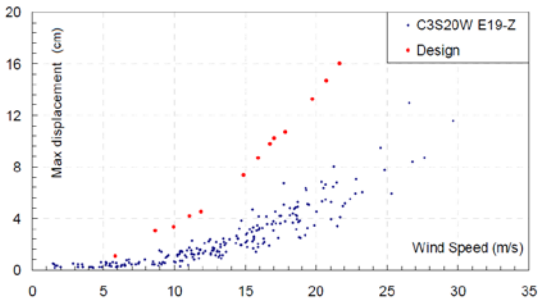


History Files analysis: Slow varying processes/statistical parameters of structural response

History files: 1 value every 30 sec







Dynamic Files analysis: Dynamic process/actual measurements of structural response

Dynamic files: High frequency (100hz) records of limited duration

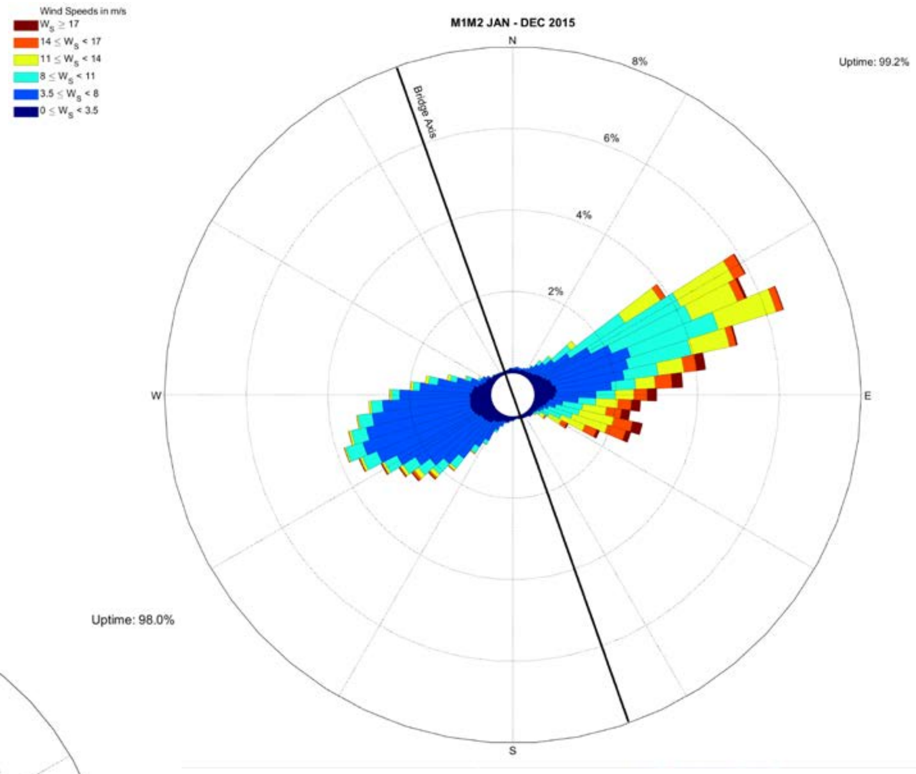
AMBIENT CONDITIONS DATA ANALYSIS

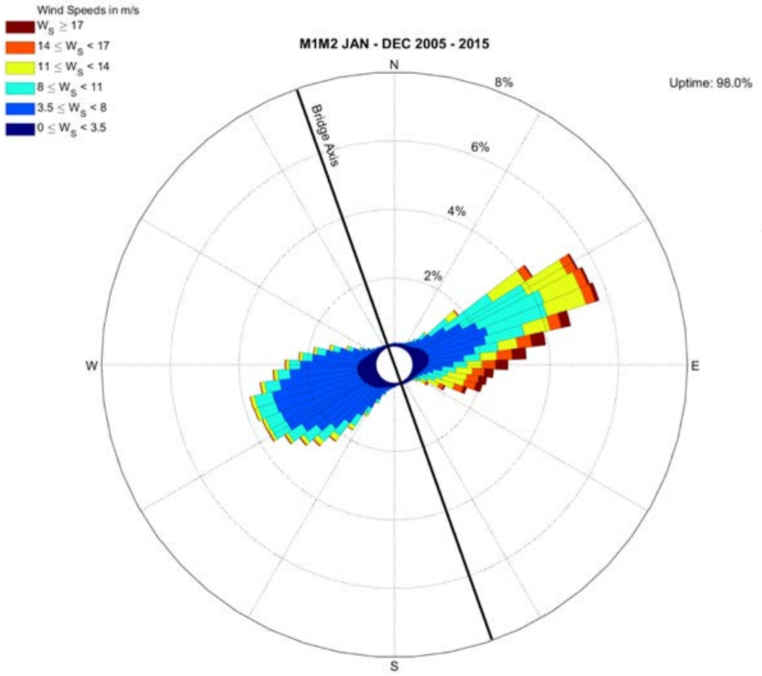
DATA: History

Analysis output

Wind speed & direction

- Data exclusion algorithm on selected data
- Addition of Meteo Year data to global Meteo database
- Statistical properties calculation per month
- Distribution per wind direction
- Graphic representation



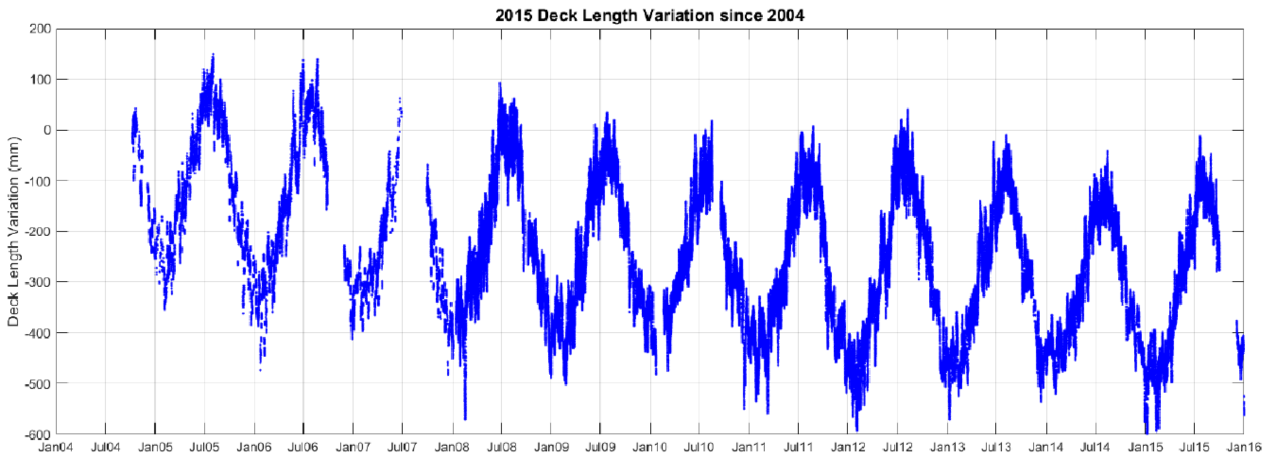


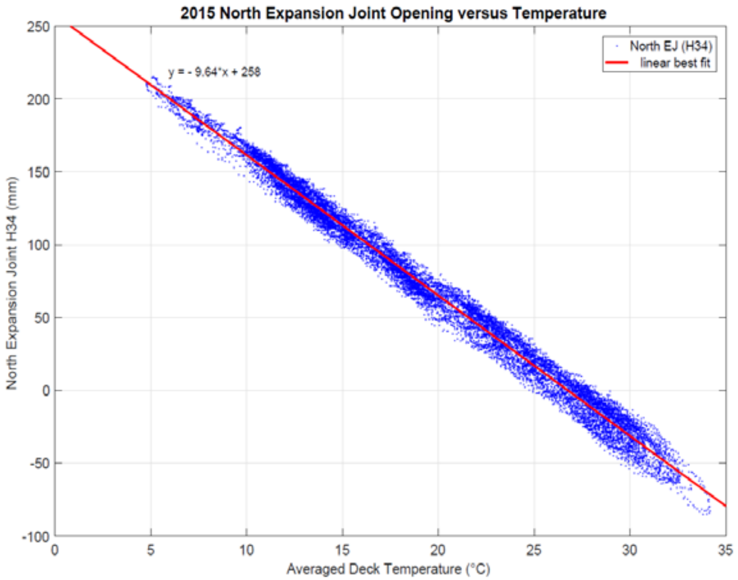
EXPANSION JOINT DATA ANALYSIS

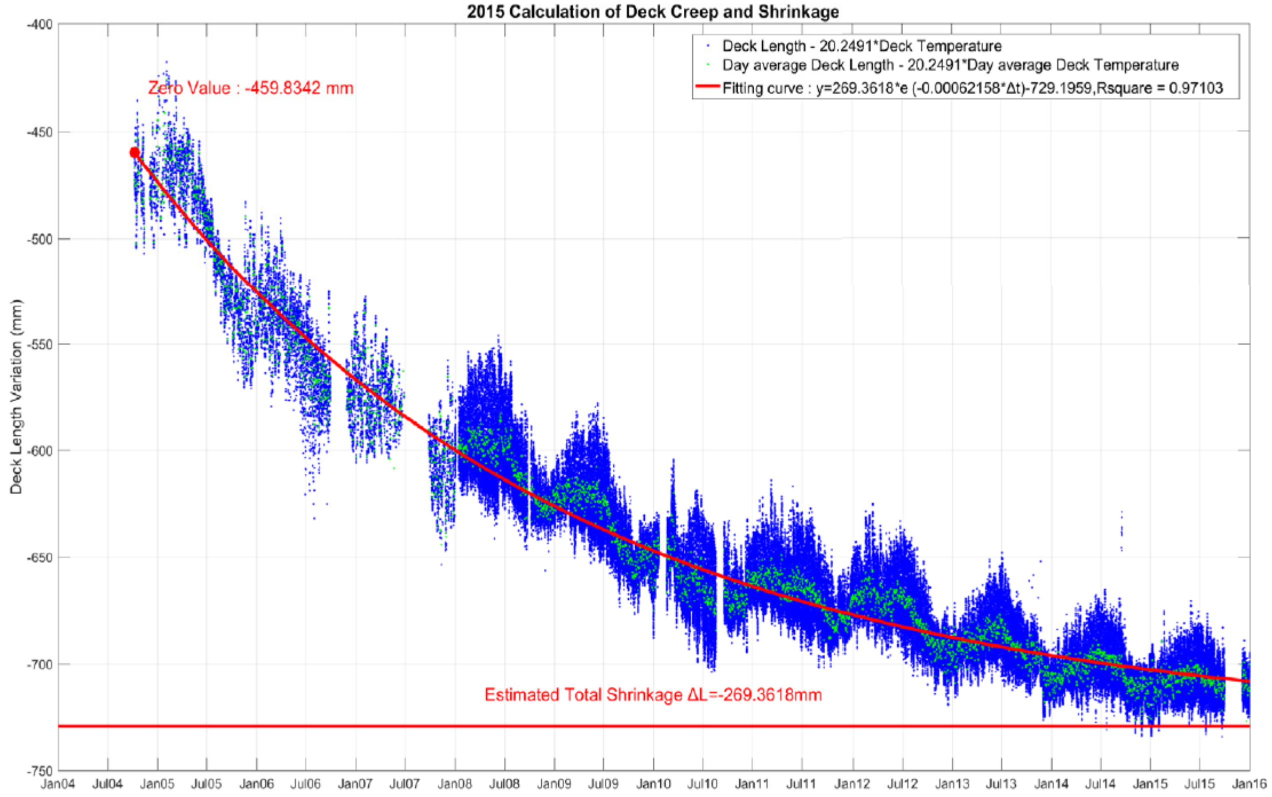
DATA: History

Analysis output

- Data exclusion algorithm on selected data
- Dependence on Deck temperature
- Deck length calculation
- Estimation of creep & shrinkage
- Addition of EJ Year data to global EJ database





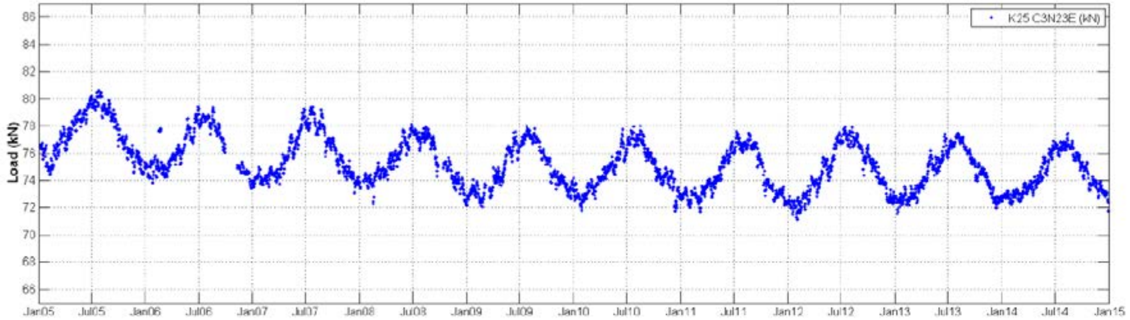


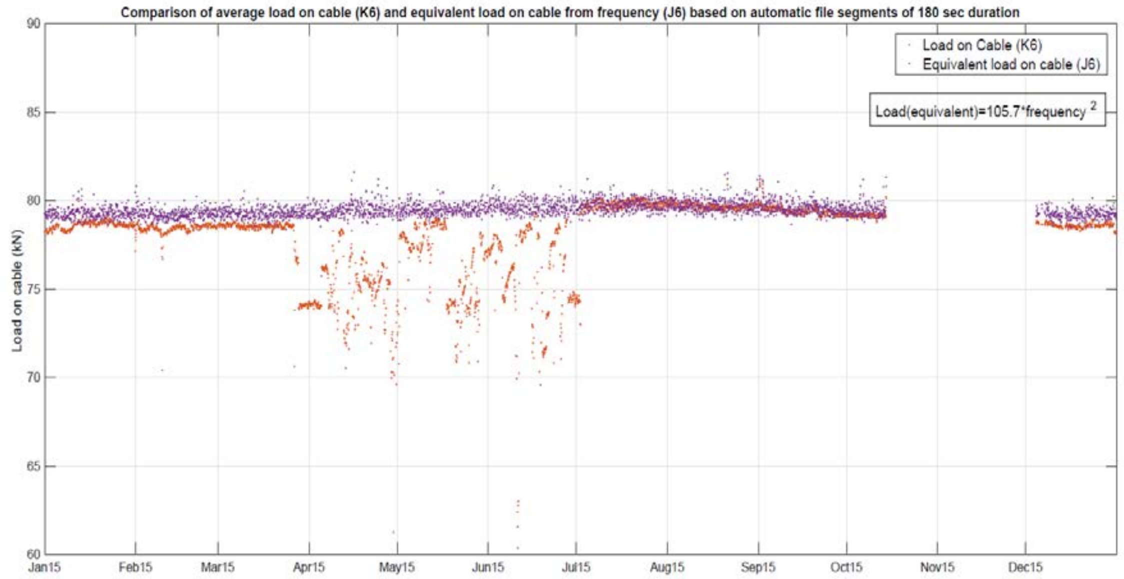
LOAD ON CABLE DATA ANALYSIS

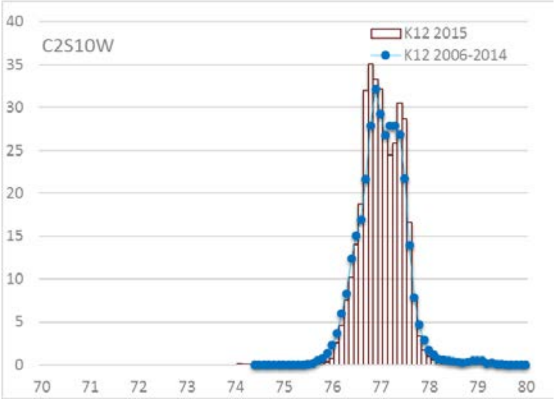
DATA: History & Dynamic

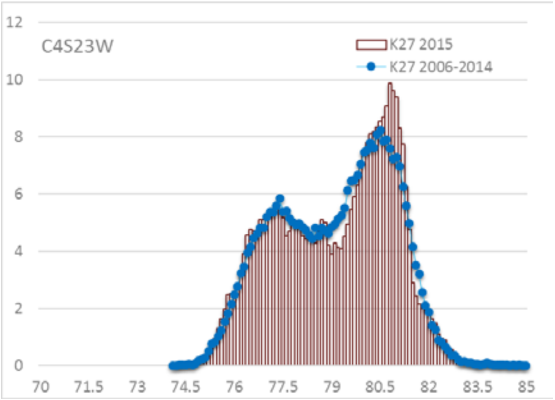
Analysis output

- Data exclusion algorithm on selected data
- Statistical properties
- Distribution
- Addition of LoC Year data to global LoC database
- Comparison with equivalent LoC (frequency calculation)







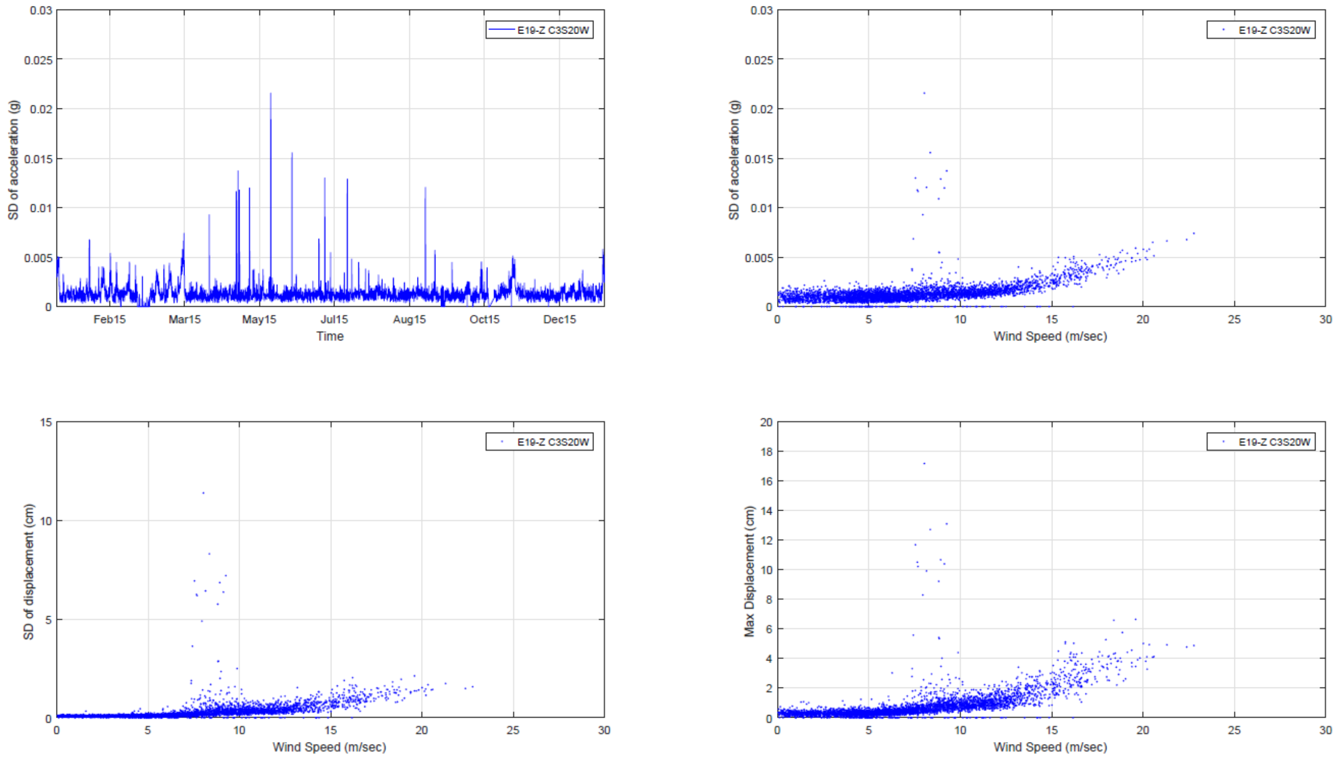


DECK VIBRATION

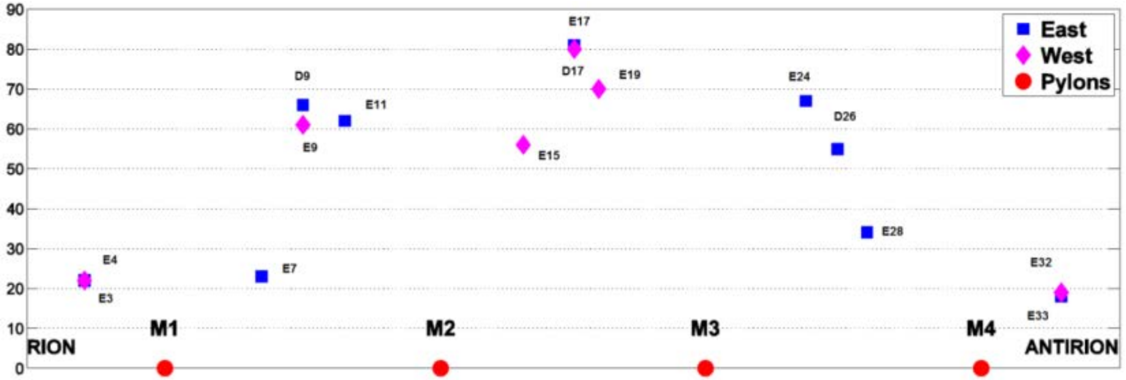
DATA: Dynamic

Analysis output

- Data exclusion algorithm on selected data
- Calculation of vibration indexes
- Statistical properties calculation
- Dependence on Wind speed
- Identification of single mode vibration cases
- Modal identification



Date Time	WS M1-M2 (m/s)	WD M1-M2 (º)	WS M3-M4 (m/s)	WD M3-M4 (º)	M1S18E E3-Z	M1S18W E4-Z	M1N17E E7-Z	M1M2W E9W-Z	M1M2E D9E-Z	M2S17E E11-Z	M2N17W E15-Z	M2M3E E17E-Z	M2M3W D17W-Z	M3S20W E19-Z	M3N20E E24-Z	M3M4E D26E-Z	M4S20E E28-Z	M4N18W E32-Z	M4N18E E33-Z
1/2/14 18:00	24.5	108	22.4	108	6.9	6.5	5.2	7.1	7.4	7.0	6.8	7.5	7.6	6.8	6.8	6.7	5.6	5.2	5.5
1/2/14 20:00	25.2	109	21.8	100	6.3	6.0	7.0	7.6	7.8	7.5	7.4	8.0	7.9	7.9	8.5	8.0	6.9	5.0	5.4
2/2/14 0:00	24.2	113	24.6	110	5.5	5.5	5.6	7.9	8.1	7.4	8.6	10.7	10.6	10.8	9.9	9.5	8.2	6.6	6.9
9/5/14 14:00	8.8	93	8.7	94				10.4	10.8	12.4	12.9	18.2	18.1	16.3	14.1	10.6	6.1		



DECK VIBRATION

DATA: Dynamic

Analysis output

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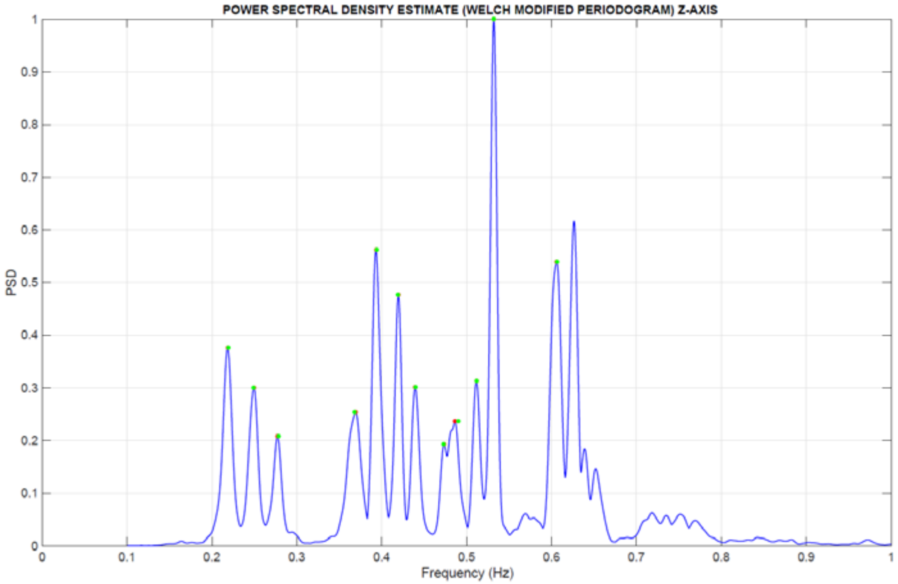
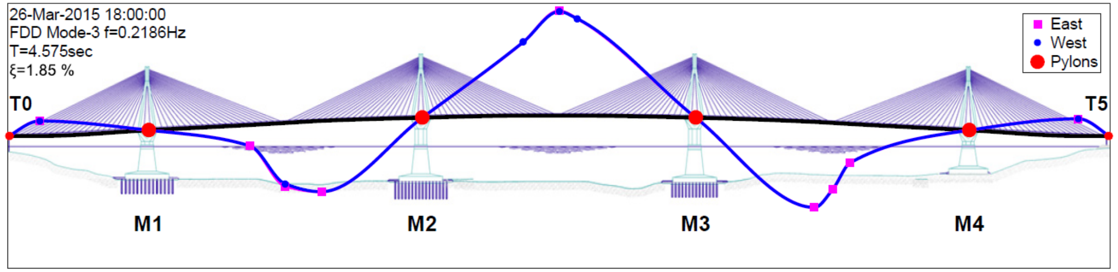
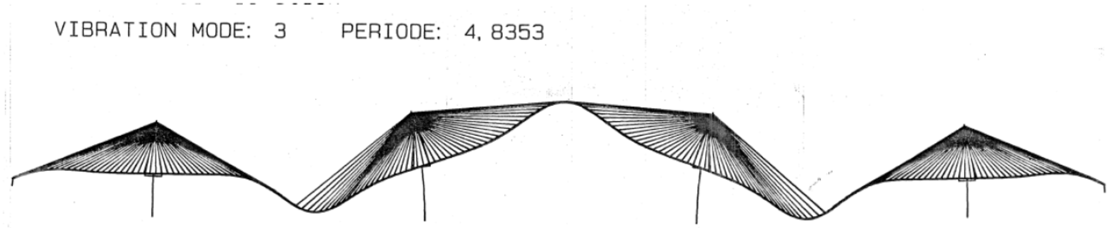
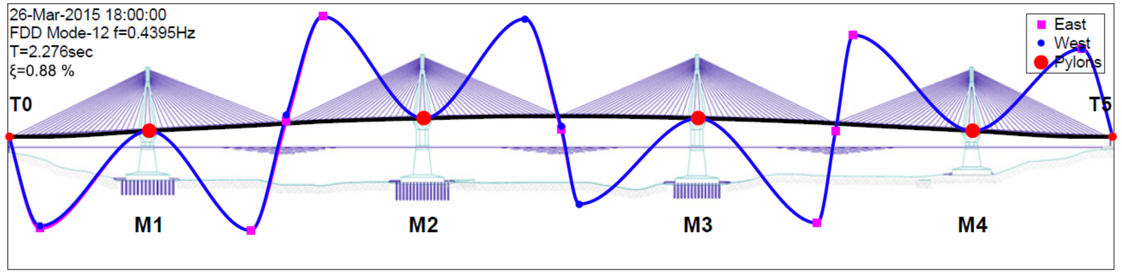
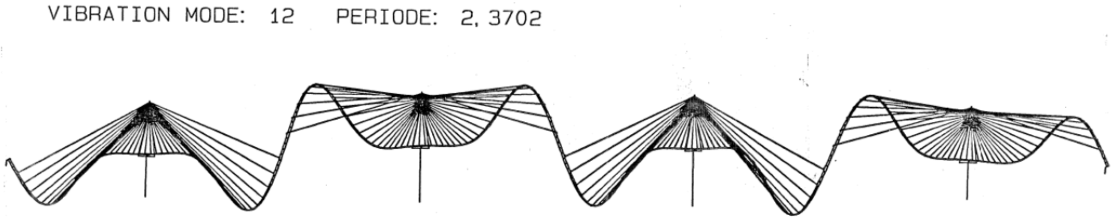
- Dependence on Wind speed
- Identification of single mode vibration cases
- Modal identification*











*Synchronization algorithm is necessary

CABLE STAY VIBRATION

Cable stays are characterized by low intrinsic damping and are prone to large amplitude vibrations.

- Damping ratio to critical $\xi s=-6x10^{-4}xL+0.24$ (L in m)

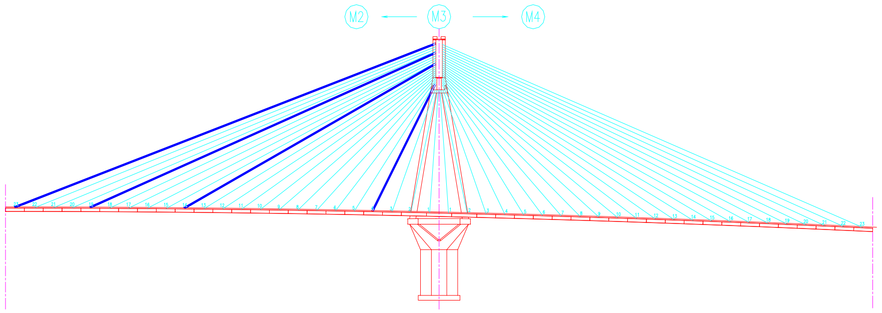
Rion - Antirion cable system critical phenomenon for vibration is excitation due to deck combined with buffeting.

- Cable modal frequencies are within the range of torsional deck frequencies
- For moderate winds (16 m/sec) vibration amplitude of up to 800mm can occur for longer cables (L>200m)

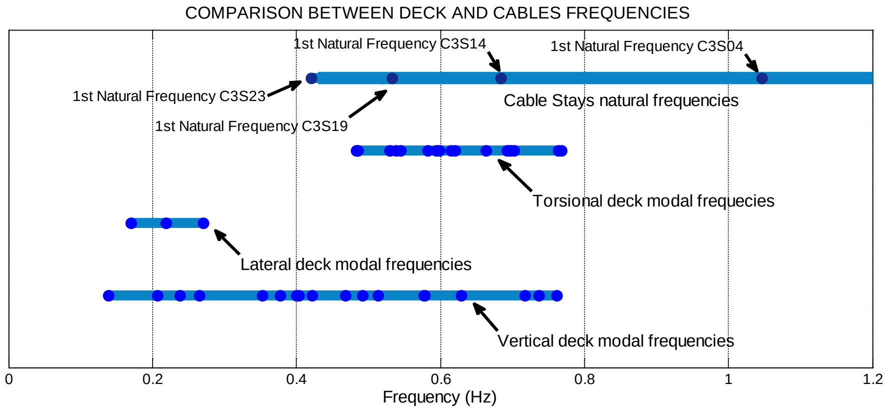
Proper provisions were available in order to implement various mitigation measures.

- Cross ties installation at pre-installed steel collars on L/3 & 2L/3 of cable
- Installation of External Hydraulic Dampers (EHD) on longer cables and Internal Hydraulic Dampers (IHD) on shorter ones (#1 to #10)

Selection of optimum mitigation measures required actual structural data from SHM system



Cable	No of Strands	Length (m)	Area (cm^2)	Mass (kg/m)	Tension (kN)	Inclination (deg)	1st Frequency (Hz)
C3S23	70	286.2	105.0	97.1	6023	20.5	0.435
C3S19	59	239.4	88.5	81.4	5316	23.0	0.533
C3S14	47	182.5	70.5	65.2	4063	28.5	0.684
C3S04	43	87.0	64.5	59.8	1980	70.0	1.046



CABLE STAY VIBRATION

Event Characteristics

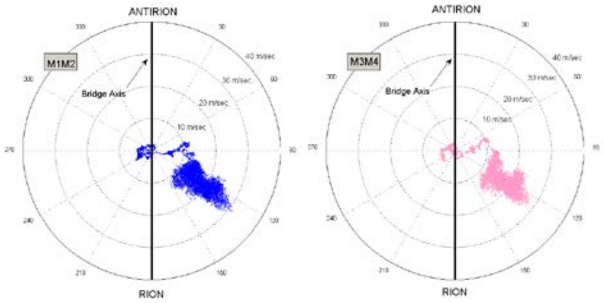
- Eastern winds ~120 ° from deck axis
- Maximum wind speed (2' average) 31.2 m/sec M1M2 28.3 m/sec M3M4
- Lower temperature 1.2 °C (ice formation on cables)

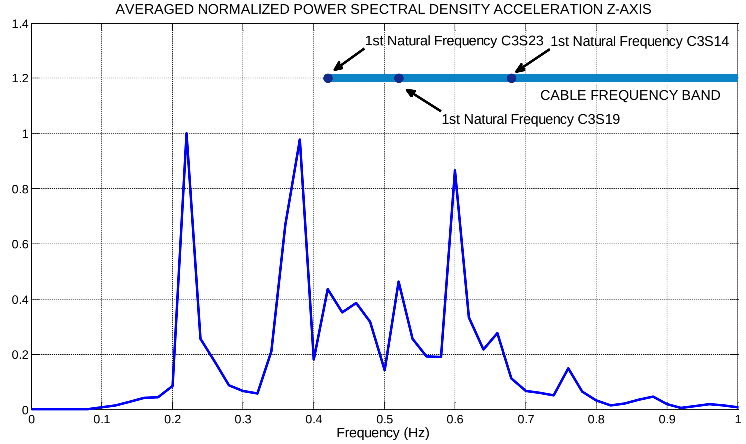
Deck Response

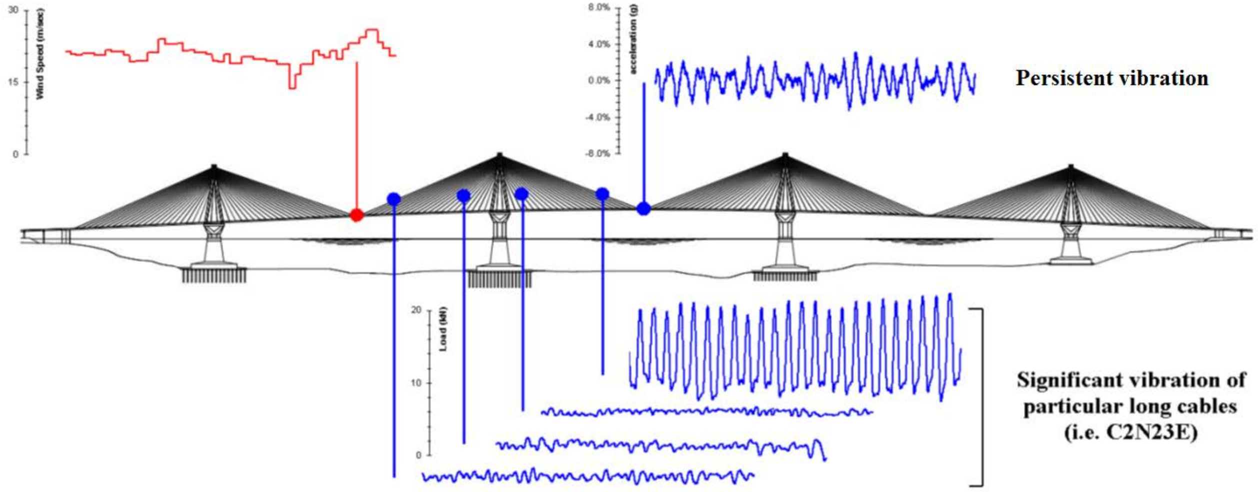
- Maximum deck vertical amplitude ±16 cm
- Frequency bandwidth 0.2 to 0.7 Hz

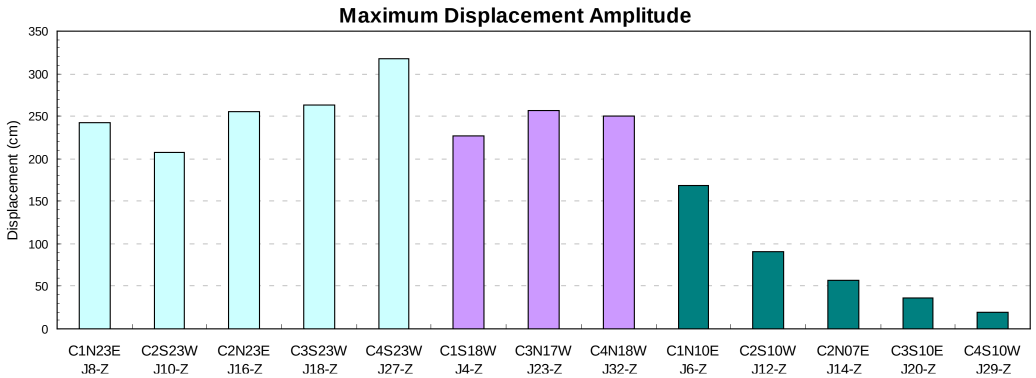
Cable Response

- Maximum vibration amplitude >2.0 m (cables L>200m)









CABLE STAY VIBRATION

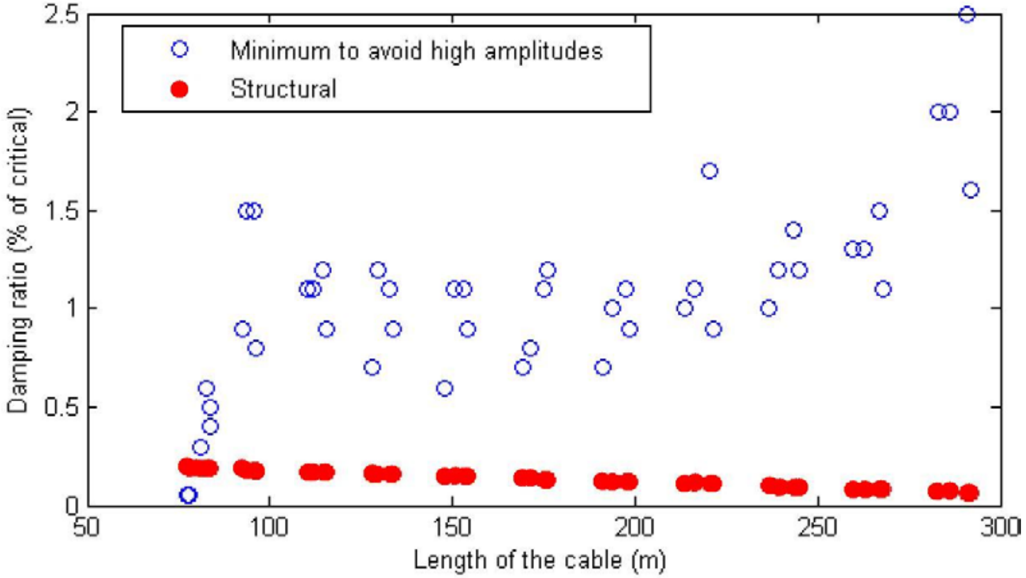
CSTB Analysis on recorded data

Based on data records an envelope of deck response was calculated

$V(f) = 1 + \frac{3}{f^2}$, f (frequency) in Hz, V (amplitude) in mm

The envelope was used as input for parametric excitation analysis and calculation of necessary damping for mitigation of cable vibration amplitude to one (1) cable diameter

- No additional damping for short cables L<100 m
- 1% damping ratio for intermediate cables L =100 – 250 m
- 1.5 % damping ratio for long cables L>250 m



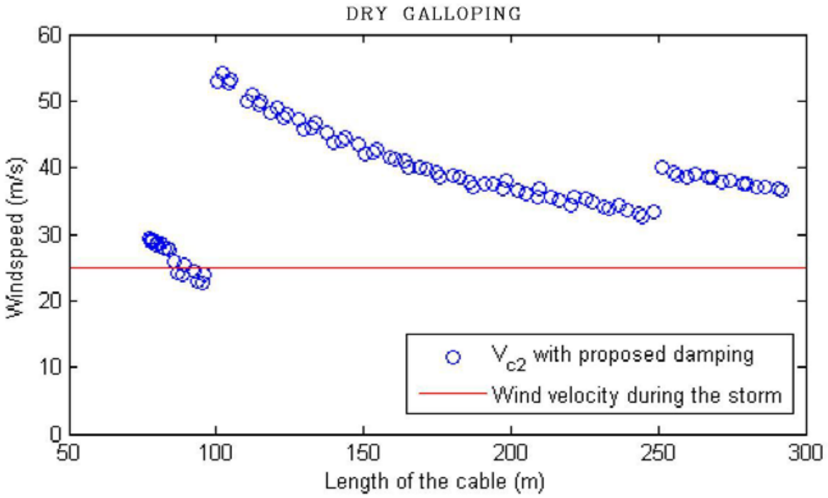
For above damping ratios, the cables were verified against ice and dry galloping

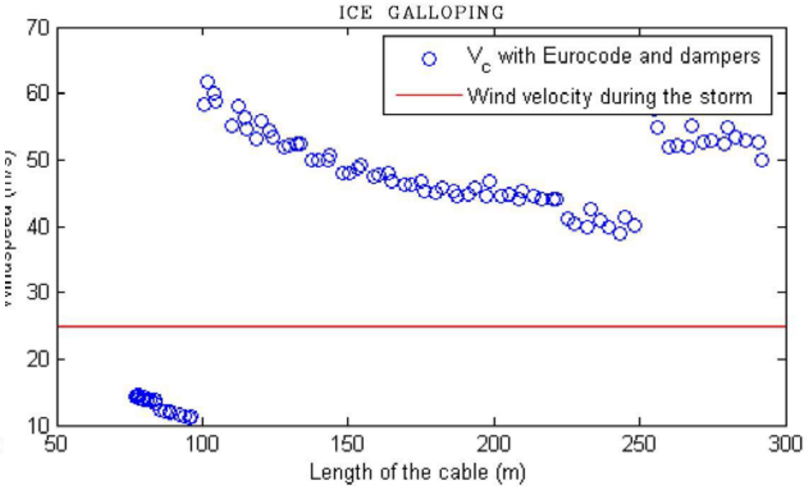
Mitigation measures by VCGP & FRE according to CSTB analysis

Solution adopted:

- No additional damping for short cables
- EHD on all intermediate and long cables #11 and above (with δ > 4%)

Commissioning tests verified EHDs efficiency





CABLE STAY VIBRATION

Event Characteristics

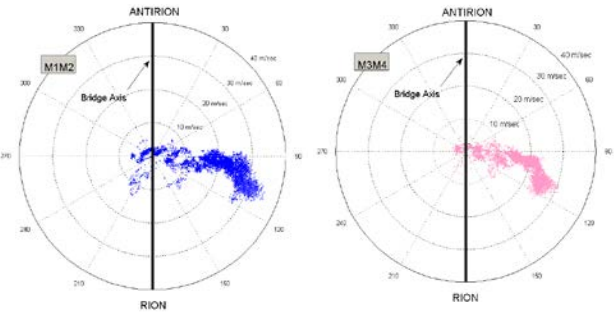
- Eastern winds ~100 ° from deck axis
- Maximum wind speed (10' average) 35.4 m/sec, M1M2 30.7 m/sec M3M4
- Lower temperature 6.5 °C

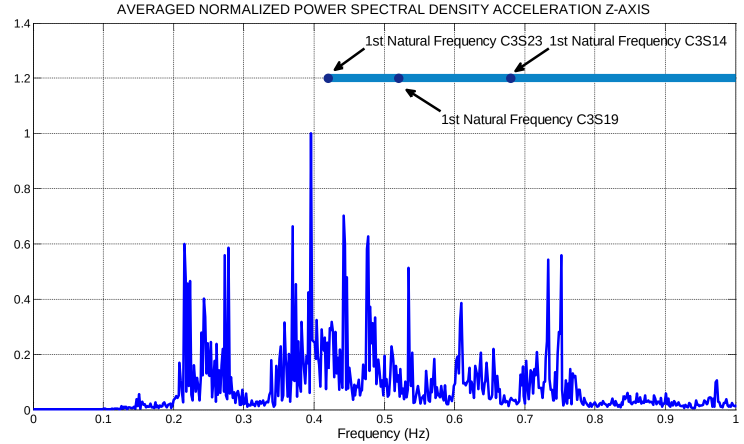
Deck Response

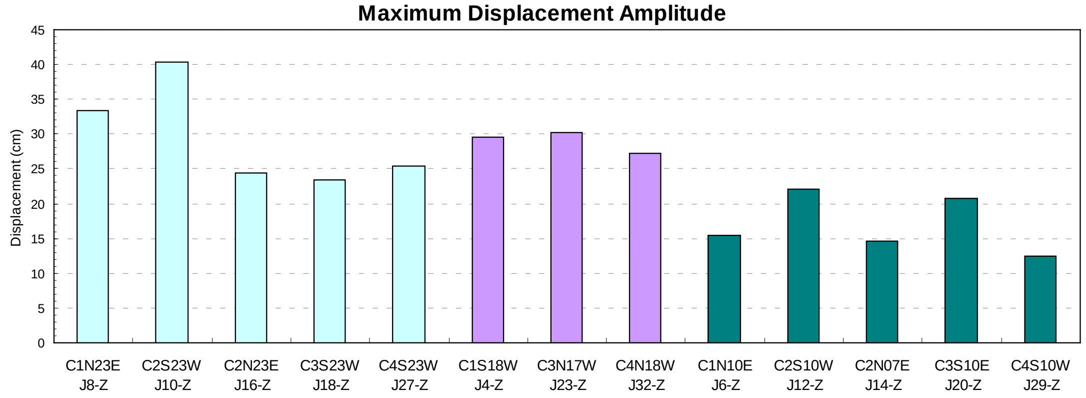
- Maximum deck vertical amplitude ±20 cm
- Frequency bandwidth 0.2 to 0.8 Hz

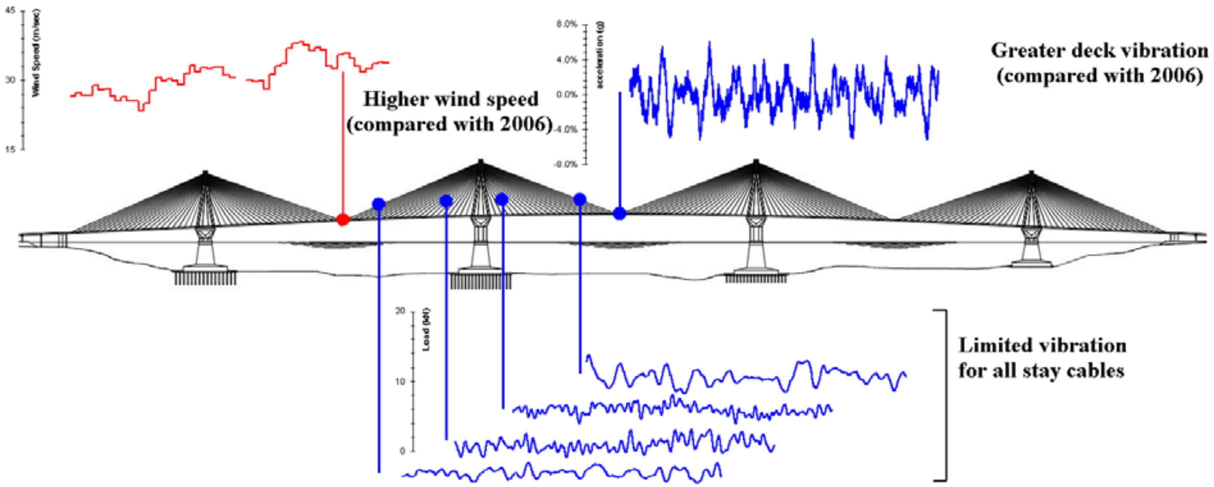
Cable Response

- Maximum vibration amplitude <0.5 m







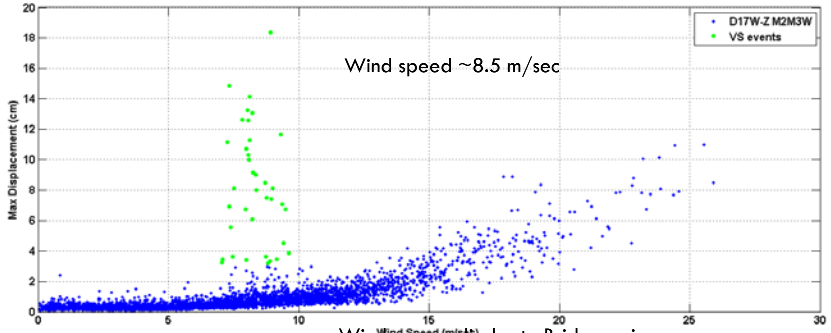


DECK VORTEX SHEDDING

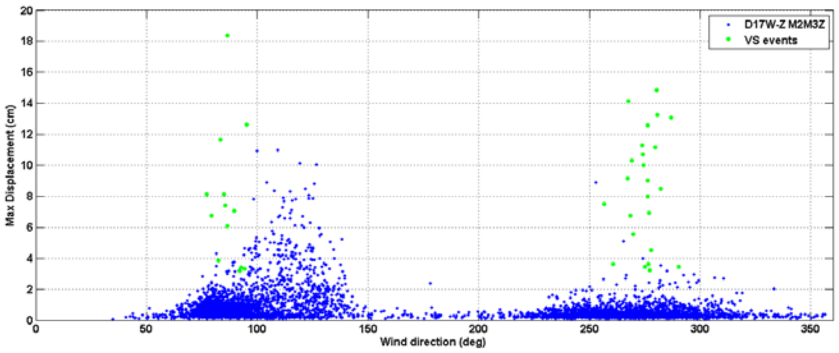
DECK VIBRATION EVENTS REPORTED ⇨ THRESHOLD PROCEDURES AND RULES FAILED TO DETECT ⇨ DYNAMIC FILES TARGETED ANALYSIS (automatic files)

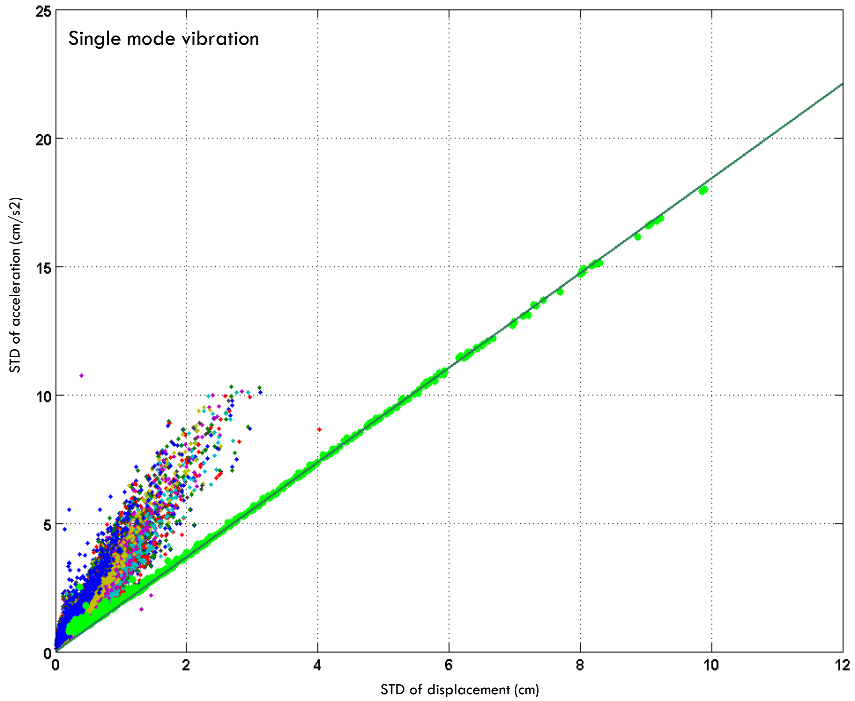
{ Low acceleration amplitudes (below thresholds) }

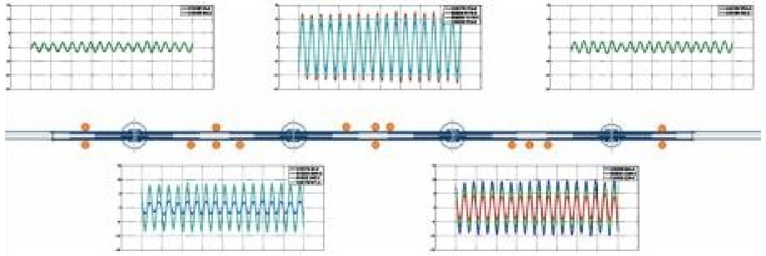
{ WS~8,5 m/sec
WD ⊥ Deck
DispAmp<20cm
3^{rd} mode excited
f=0,216 Hz }



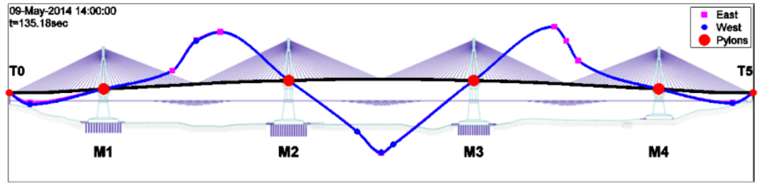
Wind perpendicular to Bridge axis







Maximum observed amplitude <20cm (in dynamic files)



Excited mode determination (3^{rd} Mode) f=0,216Hz (T=4,6 sec)

DECK VORTEX SHEDDING

INVESTIGATION IN COOPERATION

DECK VIBRATION EVENTS REPORTED ⇒ THRESHOLD PROCEDURES AND RULES FAILED TO DETECT ⇒ DYNAMIC FILES TARGETED ANALYSIS (automatic files)

THRESHOLD PROCEDURES AND RULES FAILED TO DETECT: Low acceleration amplitudes (below thresholds)

DYNAMIC FILES TARGETED ANALYSIS (automatic files):
WS~8,5 m/sec
WD ⊥ Deck
DispAmp<20cm
3rd mode excited
f=0,216 Hz

WHAT ARE THE CONSEQUENCES OF THE EVENTS?

ARE MITIGATION MEASURES NECESSARY?

IF SO, COST?

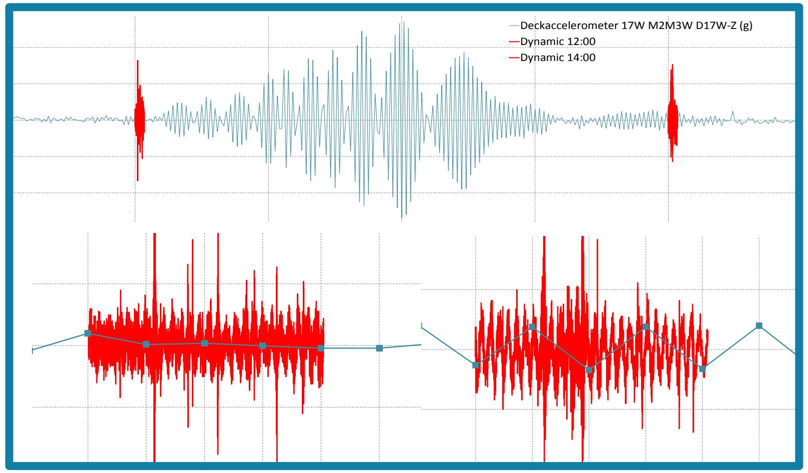
More information is necessary:

1. Frequency of occurrence/Duration/Amplitude
2. Nature of phenomenon (evolution?)
3. Fatigue consequences on structural elements

GST (Data Processing) + CSTB (Wind phenomena) + VCGP (Fatigue)

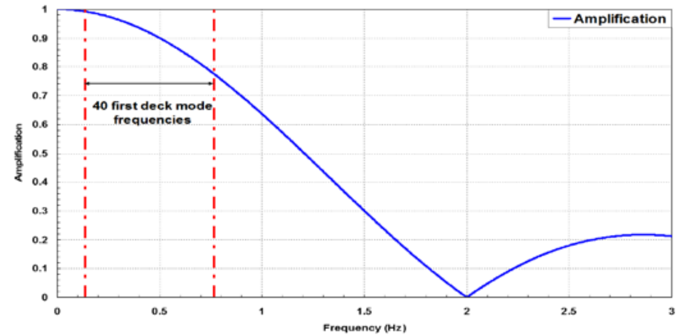
GST (Data Processing): Development of data analysis procedure for History files (1)

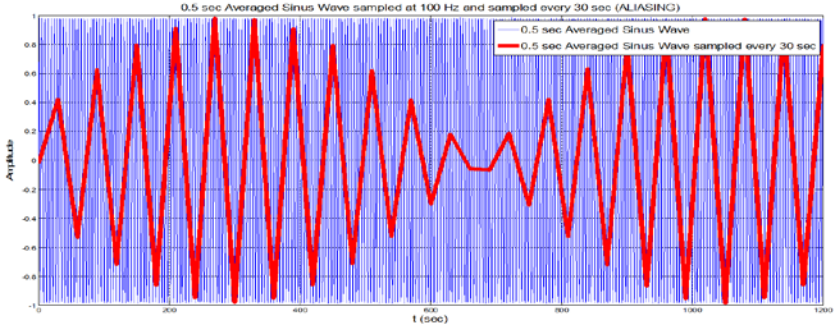
History files: 0,5sec averaged values every 30sec

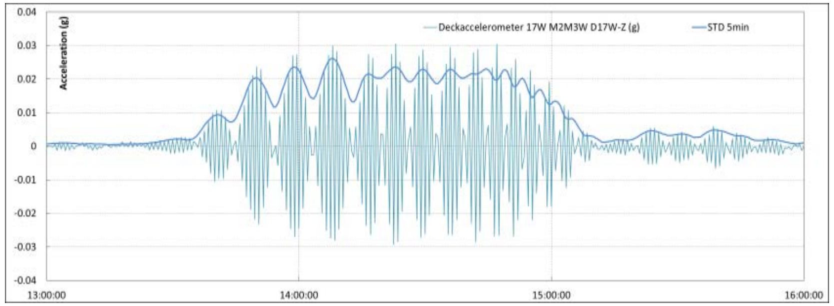


History files capture all events

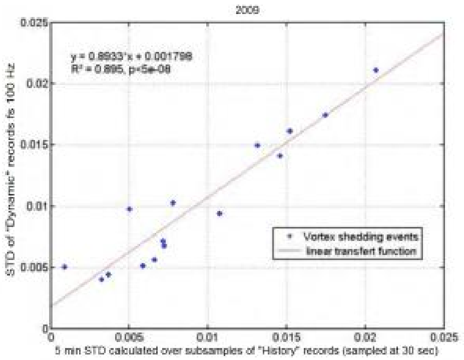
Study of averaging and aliasing properties







STD index correlated with Dynamic analysis results (STDh ~STDd)



DECK VORTEX SHEDDING

DECK VIBRATION EVENTS REPORTED ⇨ THRESHOLD PROCEDURES AND RULES FAILED TO DETECT ⇨ DYNAMIC FILES TARGETED ANALYSIS (automatic files)

THRESHOLD PROCEDURES AND RULES FAILED TO DETECT: Low acceleration amplitudes (below thresholds)

DYNAMIC FILES TARGETED ANALYSIS (automatic files): WS~8,5 m/sec; WD ⊥ Deck; DispAmp<20cm; 3rd mode excited; f=0,216 Hz

WHAT ARE THE CONSEQUENCES OF THE EVENTS?

ARE MITIGATION MEASURES NECESSARY?

IF SO, COST?

More information is necessary:

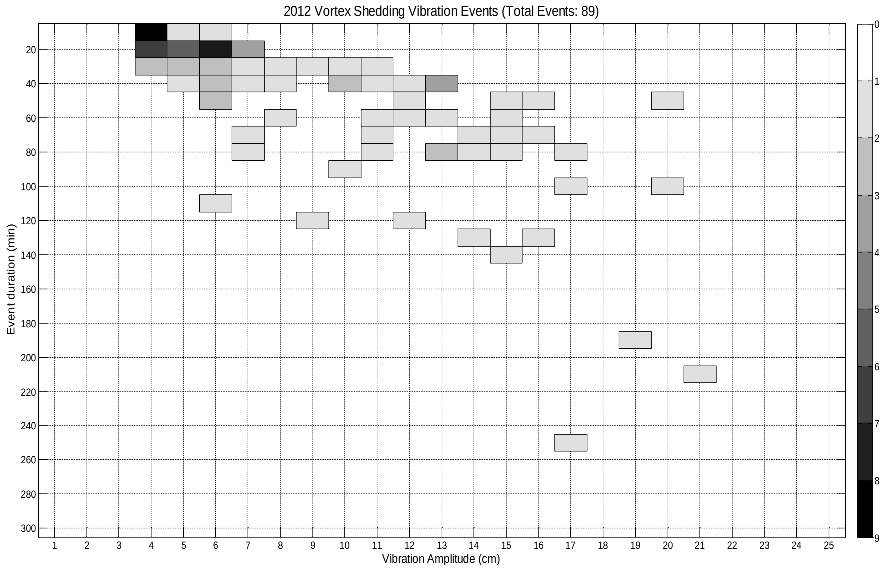
1. Frequency of occurrence/Duration/Amplitude
2. Nature of phenomenon (evolution?)
3. Fatigue consequences on structural elements

INVESTIGATION IN COOPERATION

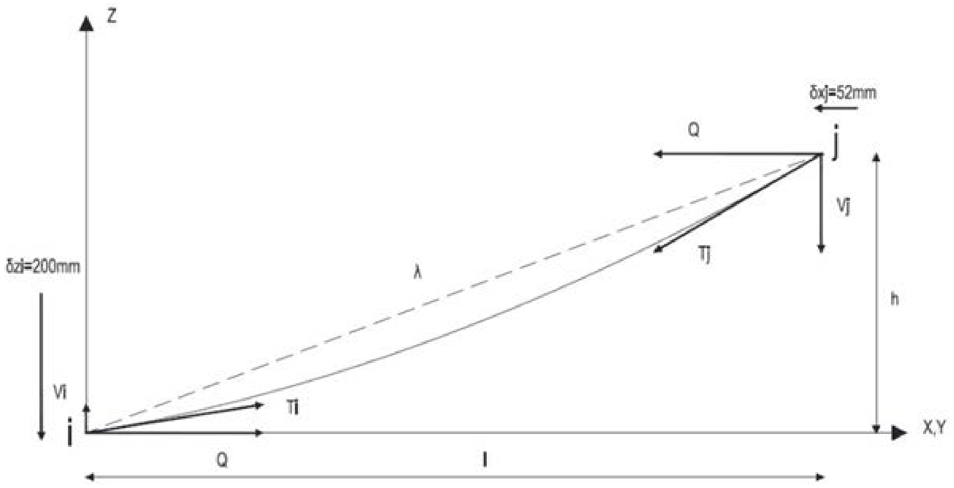
GST (Data Processing) + CSTB (Wind phenomena) + VCGP (Fatigue)

- GST: Development of data analysis procedure for History files (1)
- CSTB: Calculate load cycles & Identify phenomenon (Vortex shedding) **No Evolution** (2)
- VCGP: Calculate fatigue of structural elements (gussets) **No Risk** (3)

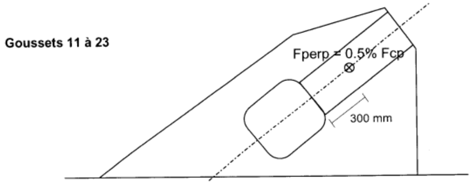
VS event duration/amplitude



Calculation of transverse loading of Gusset C3S23W for maximum VS vibration events



Maximum transverse loading due to VS events is <20 % of cut off limit 0,5% Fcp



VS vibration amplitude is less than specified limit for tolerable comfort according to BD49/01

Vibration amplitude < ymax=214 mm

$$K_D = f^2 * y_{max} \text{ , f in Hz}$$
$$K_D < 10\ cm/sec^2$$

INSTRUMENTED MONITORING

Geometrical Monitoring (non-permanent system)

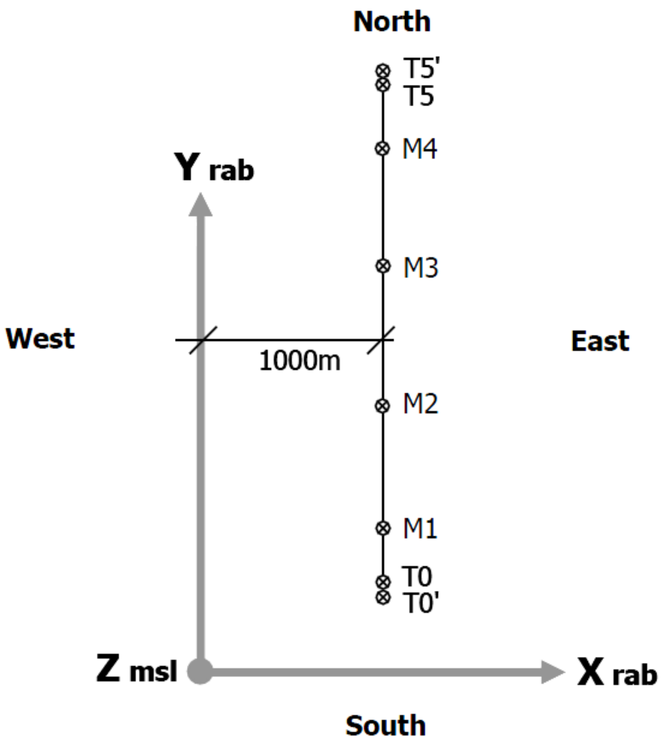
Measurements and evaluation of:

- tectonic movements
- Piers tilt & settlement
- Deck geometry
- TP settlement

The processed data are analyzed & compared with theoretical results

SECTION DETAILS

	SECTION	SUB SECTION	DESCRIPTION	SURVEY METHOD	TARGET ACCURACY
Global Network	**GN1**		PLANIMETRIC NETWORK Rion & Antirion	G: GPS STATIC	± 4mm
	GN2	**GN2.1**	LEVELING NETWORK Rion shore	A: GEOM. LEVEL.	± 3 mm
		GN2.2	LEVELING NETWORK Antirion shore	A: GEOM. LEVEL.	± 3 mm
		GN2.3	LEVELING NETWORK Traverse Rion – Antirion	B: STL	± 5 mm
Main Bridge	**MB1**	**MB1.1**	MAIN BRIDGE T0 & T5 Planimetry : MBT*WALL*	G: GPS STATIC	± 5 mm
		MB1.2	MAIN BRIDGE Pylon head top : MBM*PT	C: TERRESTRIAL	± 5 mm
		MB1.3	MAIN BRIDGE Pylon base : MBM*PB*	C: TERRESTRIAL	± 5 mm
	MB2	**MB2.1**	MAIN BRIDGE Deck cable stay points	C': TERRESTRIAL	± 10 mm
		MB2.2	MAIN BRIDGE Pylon head : MBM*PH	C: TERRESTRIAL	± 5 mm
	MB3	**MB3.1**	MAIN BRIDGE T0 & T5 Footing leveling	A: GEOM. LEVEL.	± 0.6 mm
		MB3.2	MAIN BRIDGE Pylon leveling : PB, HS, SS RS	A: GEOM. LEVEL.	± 0.6 mm
		MB3.3	MAIN BRIDGE Verticality Foot Slab – Shaft Slab	C: TERRESTRIAL	± 3 mm
Rion Viaduct	**RV1**		RION VIADUCT P7 Planimetry : RV*P7WALL*	G: GPS STATIC	± 5 mm
	RV2	**RV2.1**	RION VIADUCT Footing leveling link	A: GEOM. LEVEL.	± 3 mm
		RV2.2	RION VIADUCT Footing relative link	A: GEOM. LEVEL.	± 0.6 mm
	RV3		RION VIADUCT Deck leveling	A: GEOM. LEVEL.	± 4 mm
Antirion Viaduct	**AV1**		ANTIRION VIADUCT N16 Planimetry : AV*N16WALL*	G: GPS STATIC	± 5 mm
	AV2	**AV2.1**	ANTIRION VIADUCT Footing leveling link	A: GEOM. LEVEL.	± 3 mm
		AV2.2	ANTIRION VIADUCT Footing relative link	A: GEOM. LEVEL.	± 0.6 mm
	AV3		ANTIRION VIADUCT Deck leveling	A: GEOM. LEVEL.	± 4 mm
Toll Plaza	**TP1**	**TP1**	TOLL PLAZA Leveling	A: GEOM. LEVEL.	± 3 mm
		TP1new	TOLL PLAZA Leveling on buildings	A: GEOM. LEVEL.	± 0.6 mm

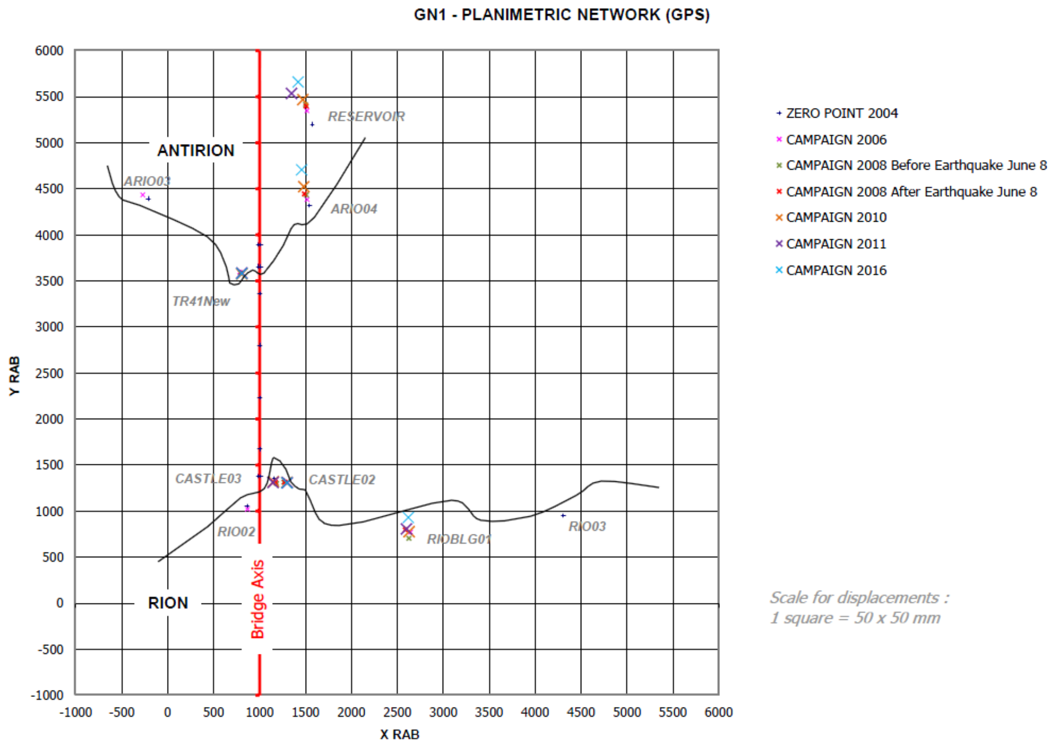


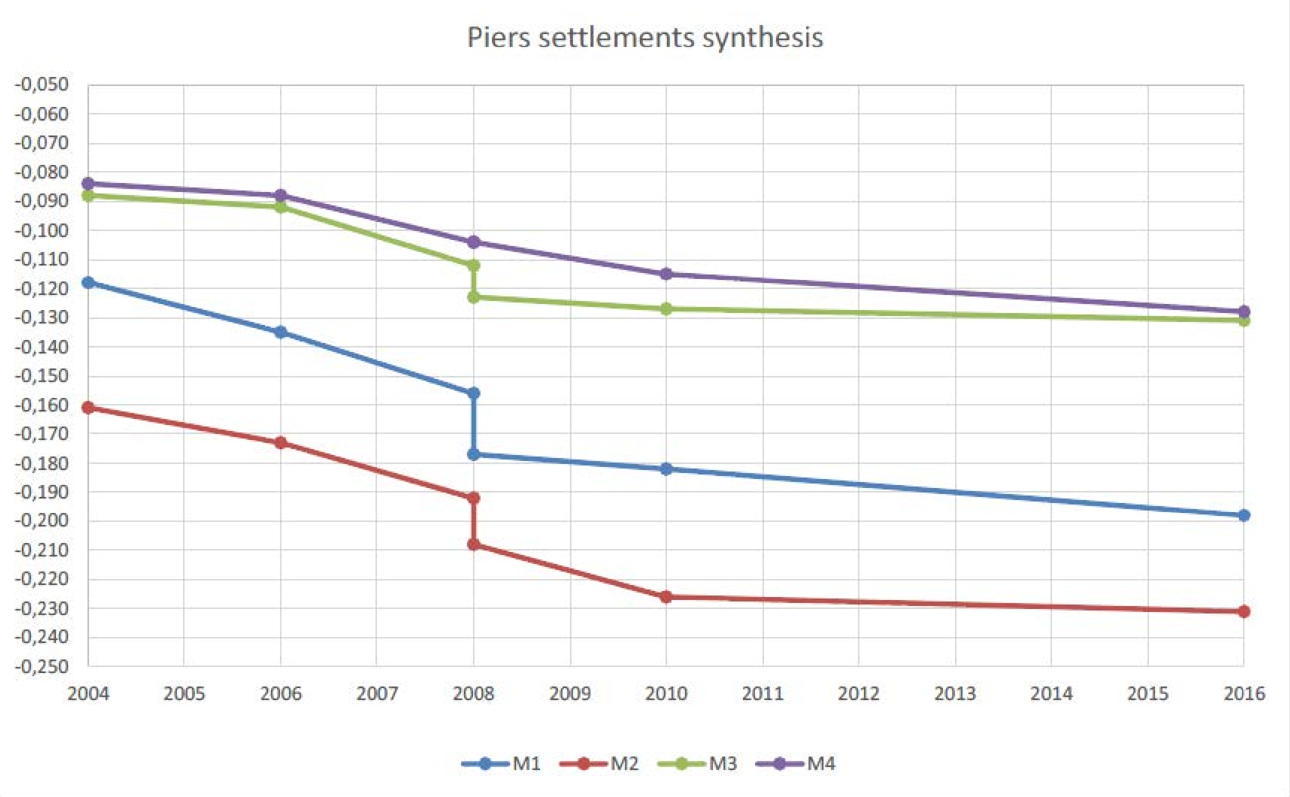
INSTRUMENTED MONITORING

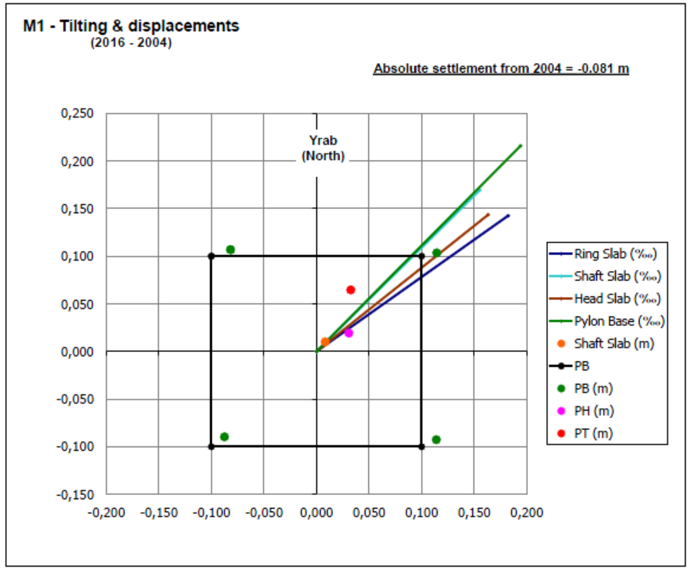
Geometrical Monitoring (non-permanent system)

Measurements and evaluation of:

- **tectonic movements (T0-T5 opening rate ~2.2 mm/year)**
- **Piers tilt & settlement (max settlement <8 cm since 2004)**
- Deck geometry
- TP settlement





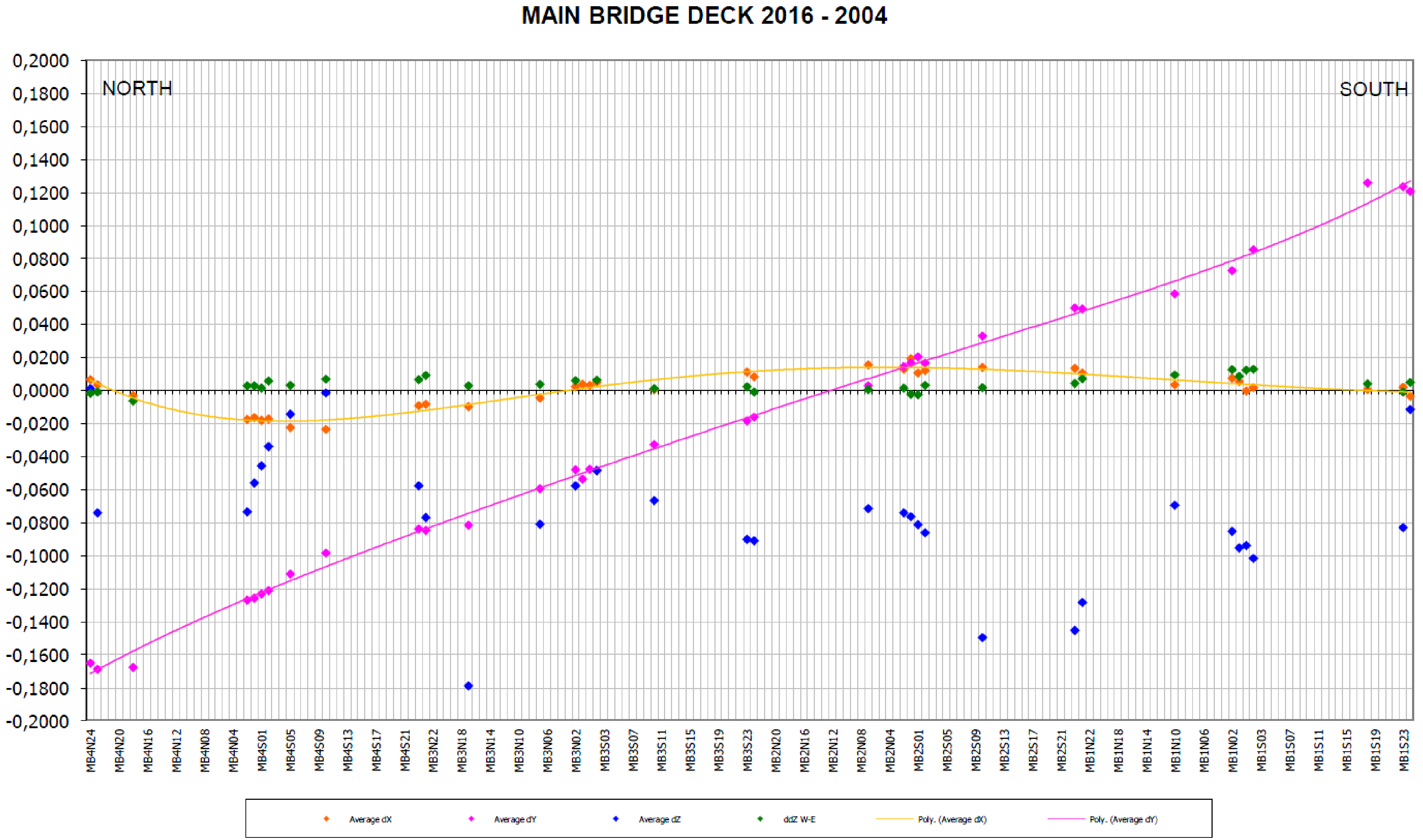


INSTRUMENTED MONITORING

Geometrical Monitoring (non-permanent system)

Measurements and evaluation

- tectonic movements
- Piers tilt & settlement
- **Deck geometry**
- TP settlement

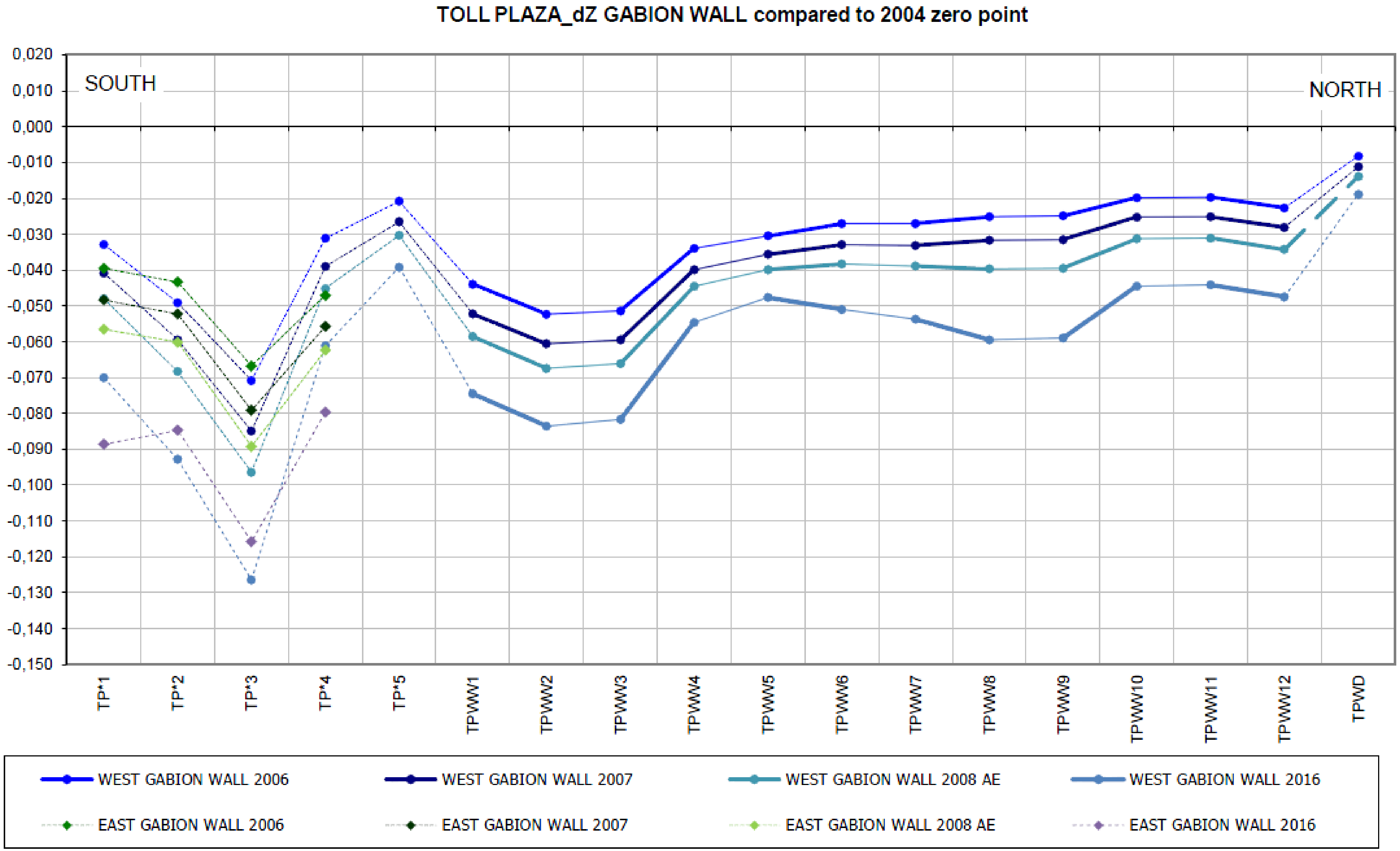


INSTRUMENTED MONITORING

Geometrical Monitoring (non-permanent system)

Measurements and evaluation of:

- tectonic movements
- Piers tilt & settlement
- Deck geometry
- **TP settlement (~13cm since 2004)**



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Thank you for your attention