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BRIDGING THE RIFT

EARTHQUAKE DESIGN OF RION-ANTIRRION BRIDGE

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2019 Geosciences Information for Teachers (GIFT) Workshop, 8-10 APR 2019 VIENNA
Plate tectonics and Earth’s structure – yesterday, today, tomorrow

RION ANTIRRION BRIDGE "CHARILAOS TRIKOUPIS"

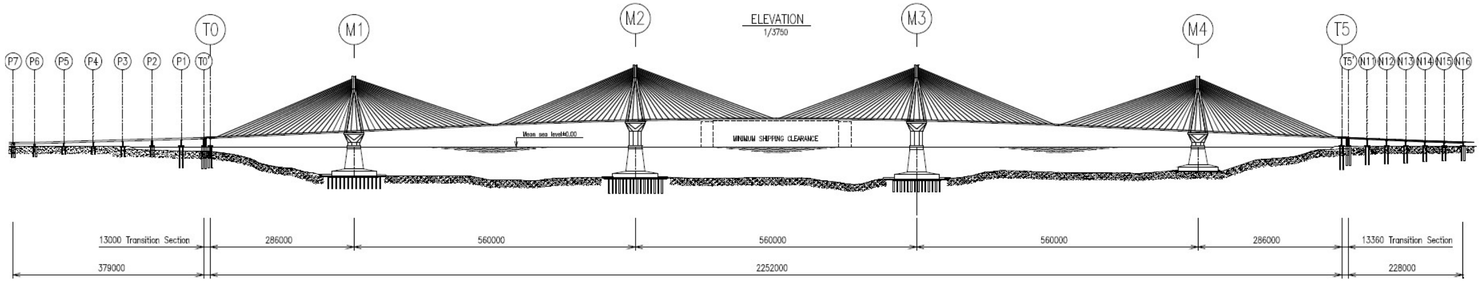
LOCATION

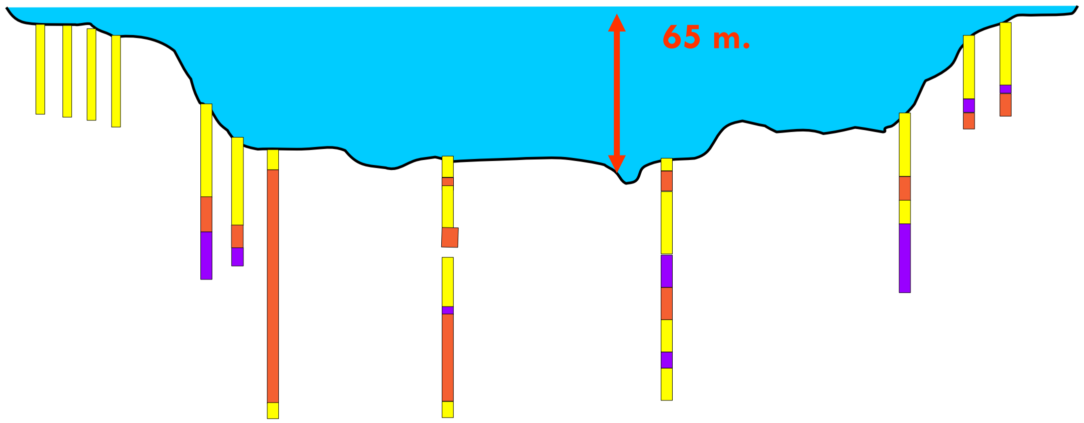
The idea of bridging the gap in Rion Antirion strait was first envisaged by the Greek Prime Minister Charilaos Trikoupis back in late 19^{th} century

Rion Antirion Strait, is the entrance of Gulf of Corinth and is separating Peloponnese from mainland Greece

There was significant traffic through the strait since it provides a link of West Greece with Peloponnese and eventually Athens

RION ANTIRRION BRIDGE “CHARILAOS TRICOUPIS”

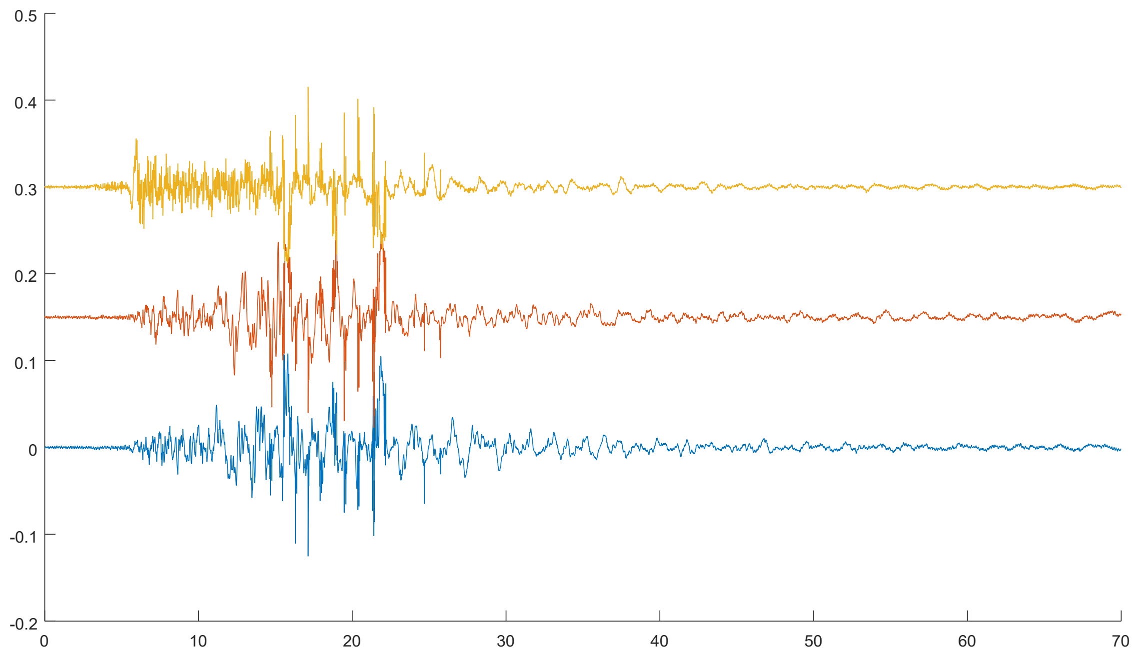




ENVIRONMENT

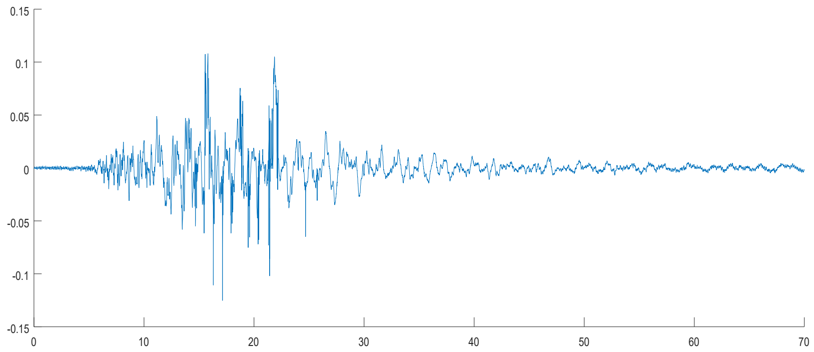
- **Weak Sea Bed up to 500m**
  No bedrock encountered in first 100 m during soil investigations, while geological studies indicated similar conditions for up to 500 m
- **Water depth up to 65 m**
  Uniform sea bed at depth of 60 m with steep slopes near coast
- **High Seismicity**
  Active normal faults 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**
  Design Wind speed 50 m/sec , aerodynamic stability 74 m/sec
- **Navigation channel**
  Significant marine traffic through Rion - Antirion strait

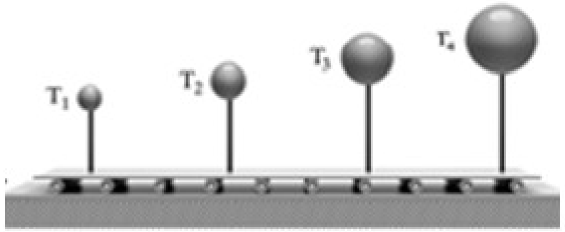
GROUND MOTION



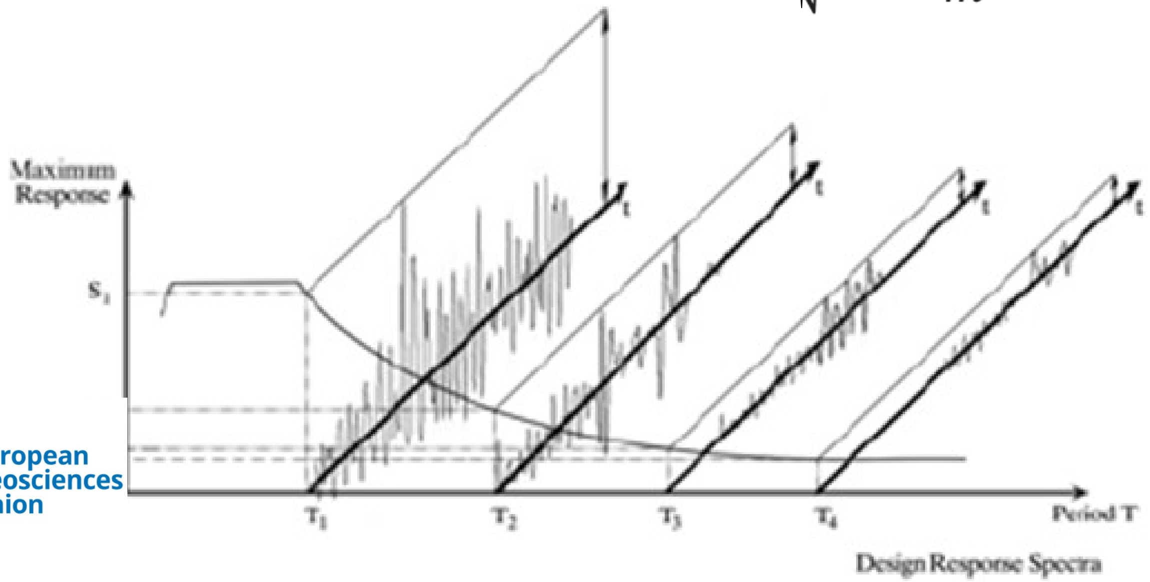
- During an EQ event the structures are experience vibration induced though their foundation
- The Forces induced in a building are mainly inertial forces and are directly related to the acceleration asserted on structural masses
- The ground motion is described through acceleration time histories (3 axes)
- Acceleration capture the motion characteristics in a wider frequency range than displacement and is easily recorded with “ordinary” instruments
- The acceleration time history is proportional to the inertial forces applied on a rigidly connected mass to the ground F=mA

RESPONSE SPECTRUM & DESIGN

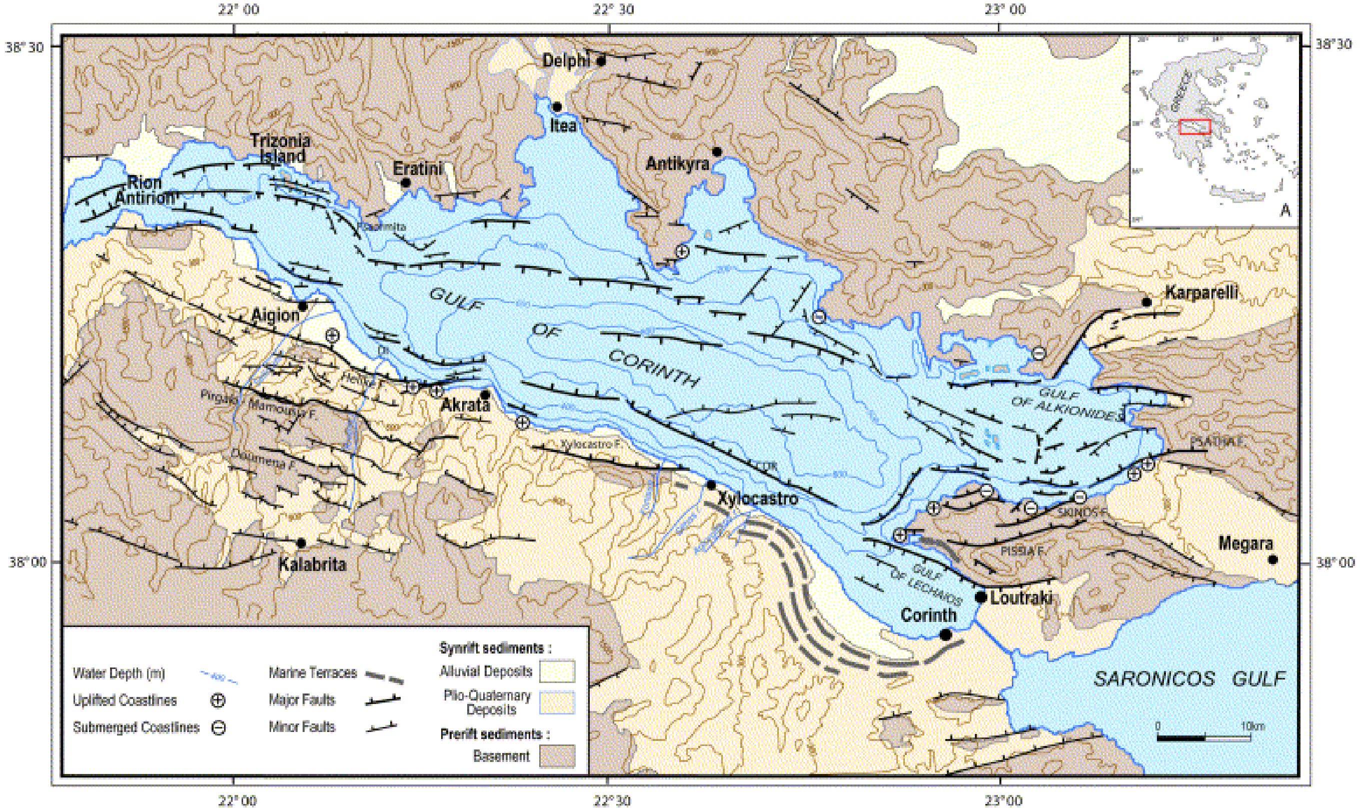


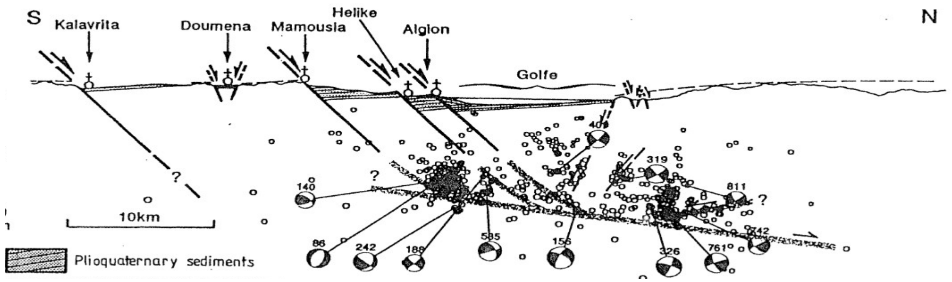


$$T(sec) = \sqrt{\frac{M\left(\frac{N sec^2}{m}\right)}{K\left(\frac{N}{m}\right)}}$$



- The impact of an acceleration time history (EQ event) on various structures can be assessed by Response Spectrum
- Structures fundamental dynamic characteristics are MASS and STIFFENESS
- The square root of the ratio MASS over STIFFNESS is called Eigen-Period (and the inverse ration is eigen-frequency)
- All structures can be described and classified based on eigen-period T (sec)
- The maximum response (acc) of a structure with eigen-period T when subjected to an acceleration time history, produce the Spectral Acceleration SA(T) function
- Combination of various normalized time histories can yield to Design Spectra, a lovely curve for engineers

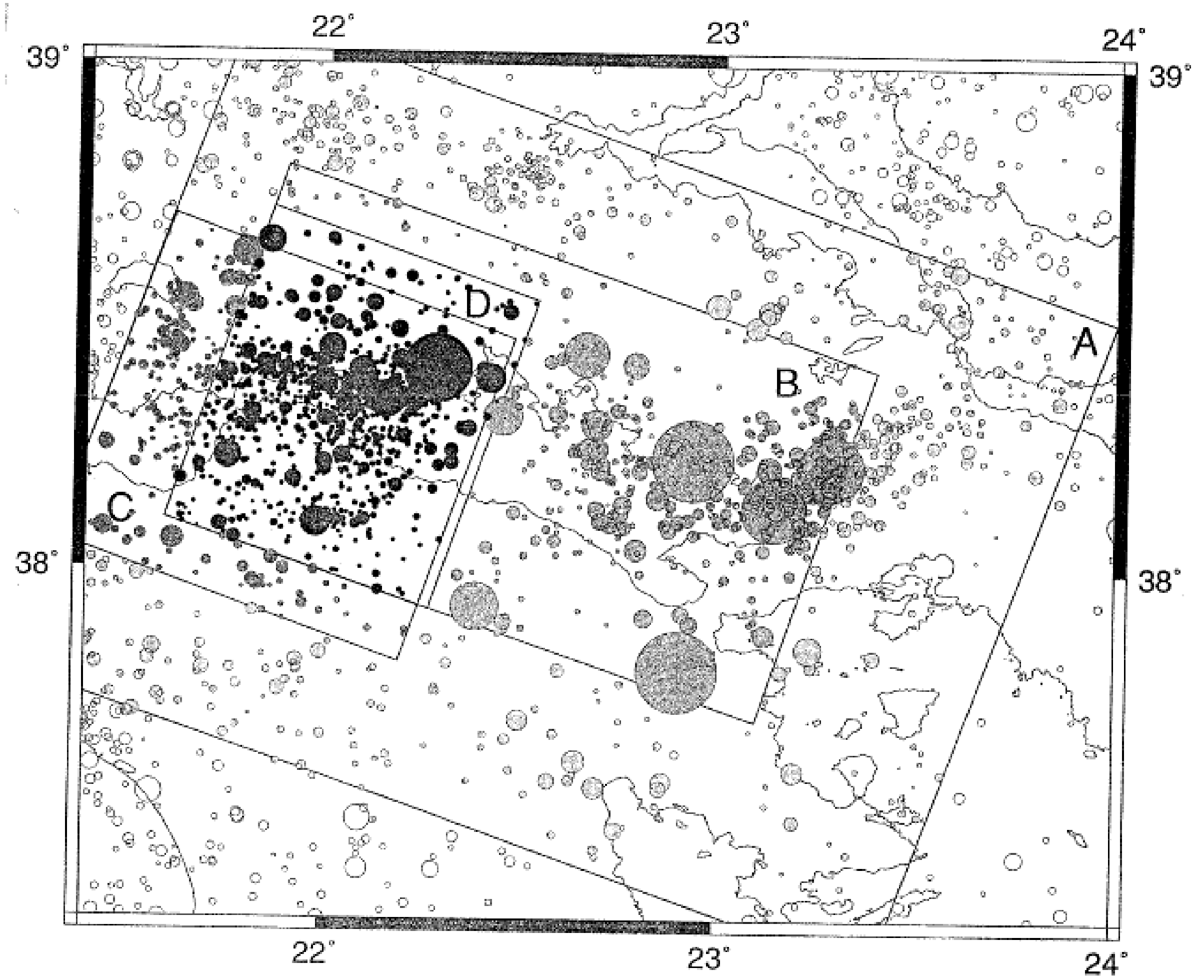




SEISMIC HAZARD ANALYSIS OF RA BRIDGE

- Due to size and importance of Rion Antirrion Bridge, the Design Spectrum is calculated based on a more precise Seismic Hazard analysis, particular of the site (Corinth Rift)
- First Step is the identification of seismic sources
    - Location
    - Size

Please Check Corinth Rift Laboratory Site: http://crlab.eu/ to get great Geoscience information of the Area



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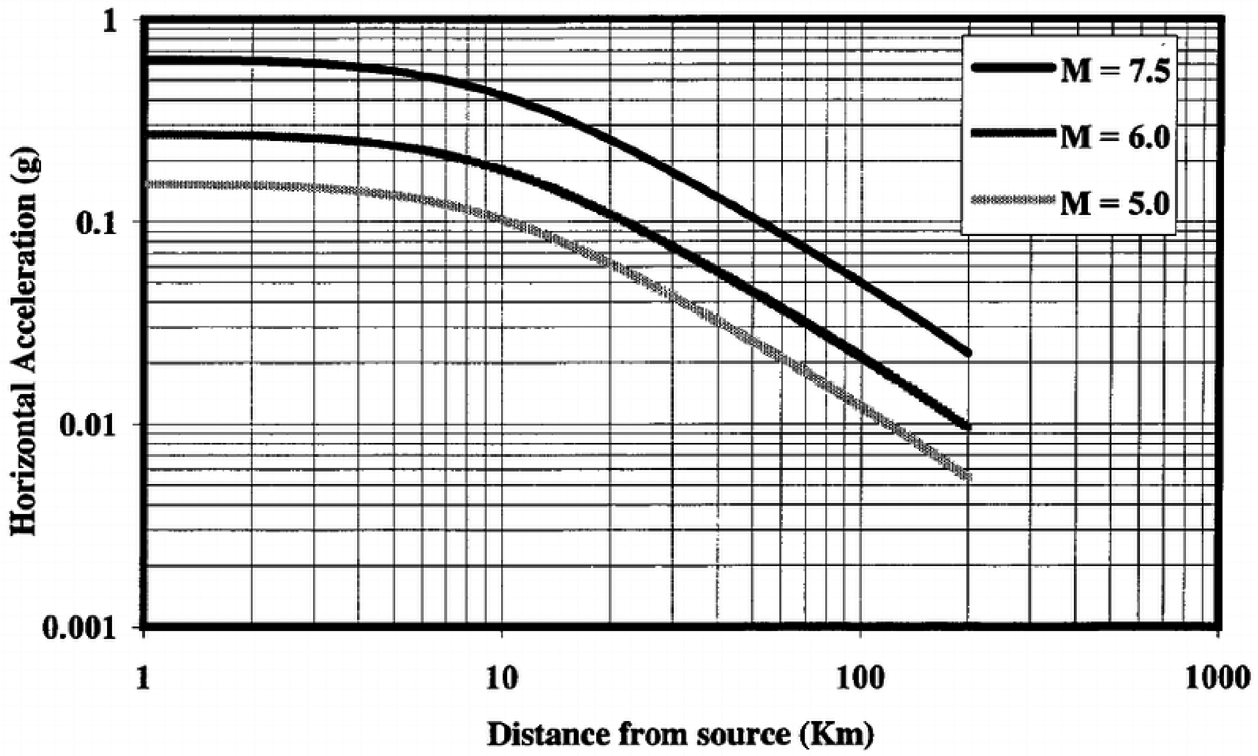
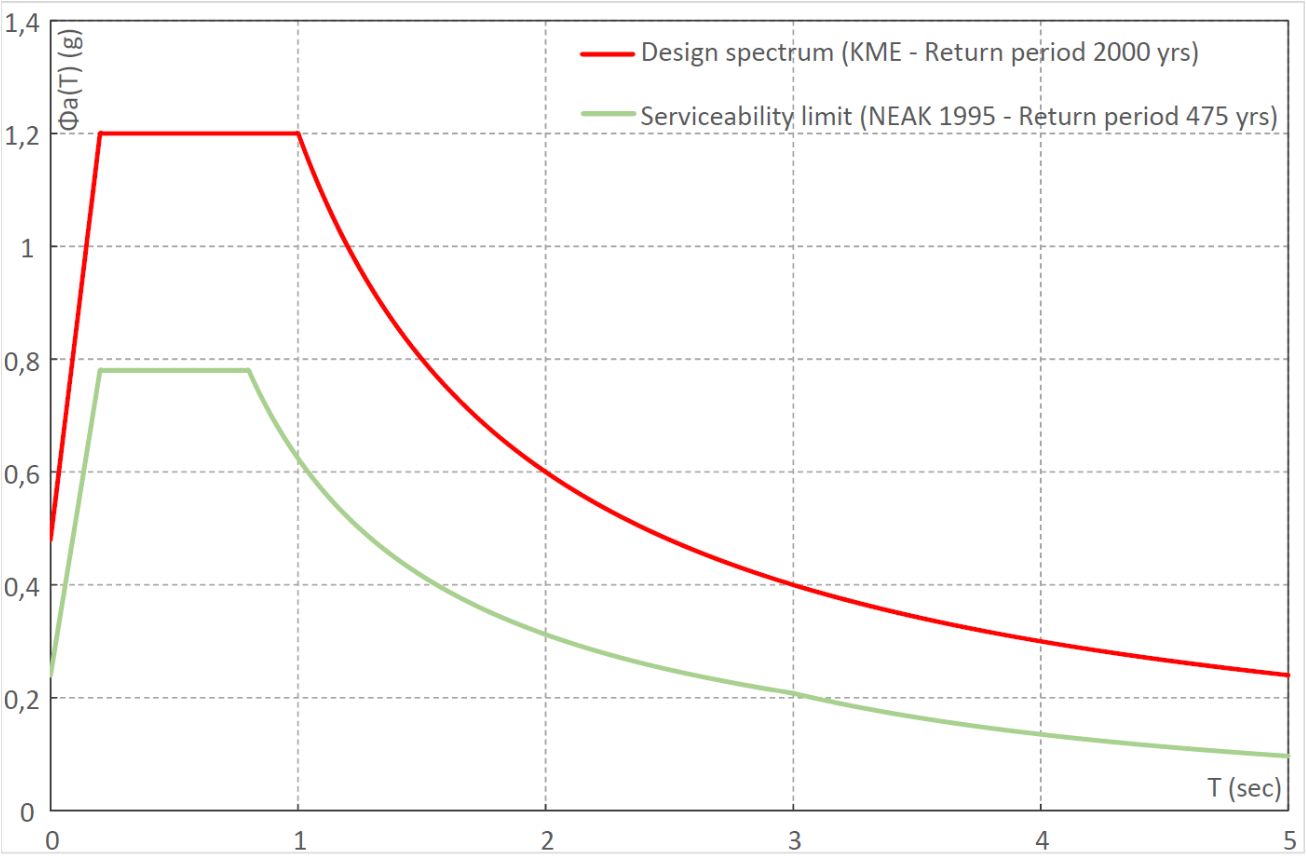
- First Step is the identification of seismic sources
    - Location
    - Size
    - Events Catalogue
    - Frequency and magnitude of events per source

SEISMIC HAZARD ANALYSIS OF RA BRIDGE



$$H(a) = \sum_i v_i \iint P\left[A > a \mid m, r\right] f_{M_i}(m) f_{R_i|M_i}(r; m)\, dr\, dm$$

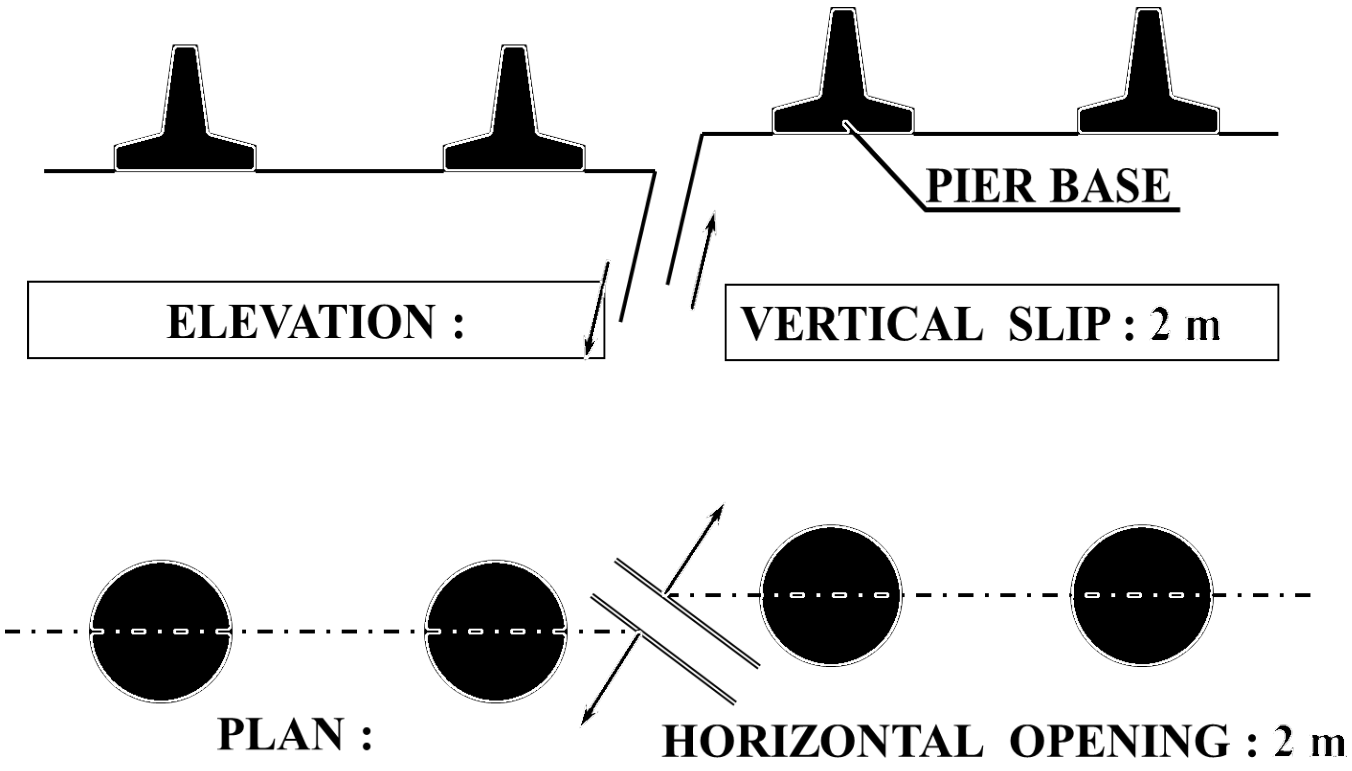
- Due to size and importance of Rion Antirrion Bridge, the Design Spectrum is calculated based on a more precise Seismic Hazard analysis, particular of the site (Corinth Rift)
- Use attenuation relationship models to estimate any intensity on the area of interest
  - Include all sources influence
  - Calculate annual frequency of events that yield to a seismic motion on site with intensity greater that a specified limit a
- For Rion Antirrion Bridge, the fault of Psathopyrgos contribute more to the Seismic Risk (Event of Mag ML=6,5 at <10 km distance)



- Due to size and importance of Rion Antirrion Bridge, the Design Spectrum is calculated based on a more precise Seismic Hazard analysis, particular of the site (Corinth Rift)
- Design Spectrum definition:
    - pga 48% g
    - Corresponds to an EQ event that has return period of 2000 yrs

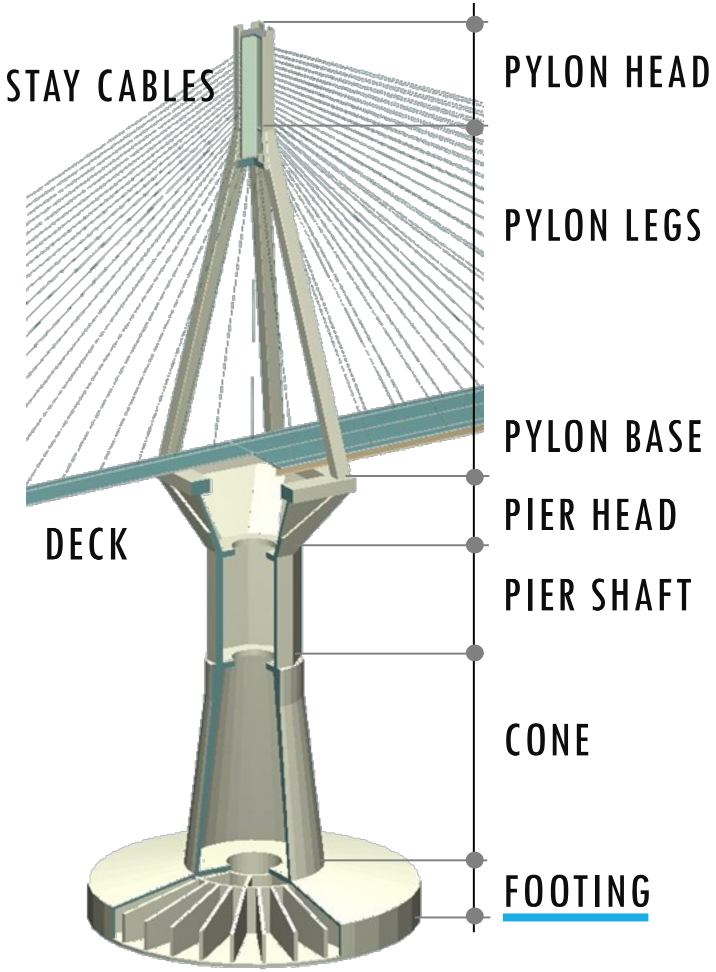
For more Detailed analysis, synthetic acceleration time histories have been prepared matching the Design spectrum.

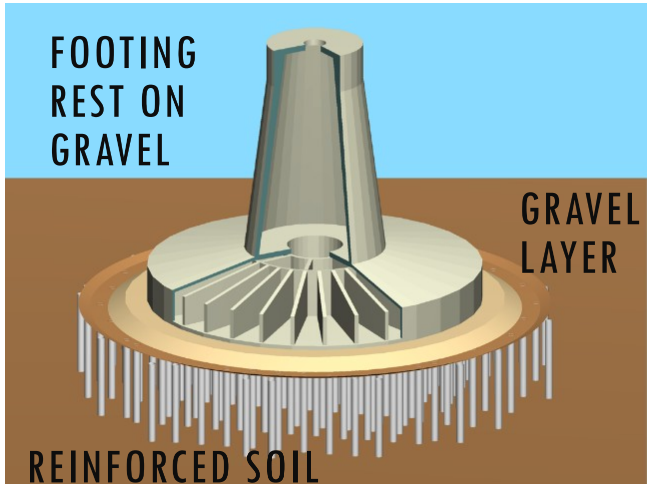
TECTONIC MOVEMENT



- Area tectonics indicate that there could be a permanent expansion of the strait.
- The expansion can occur either on a steady rate over the years, or suddenly during an EQ event
- A possible movement (2m) between pier foundation is considered as a loading situation over 120 yrs (in any direction)
- 50% of the above movement can occur in combination with the design earthquake

STRUCTURAL DESIGN: SOIL & FOUNDATION





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

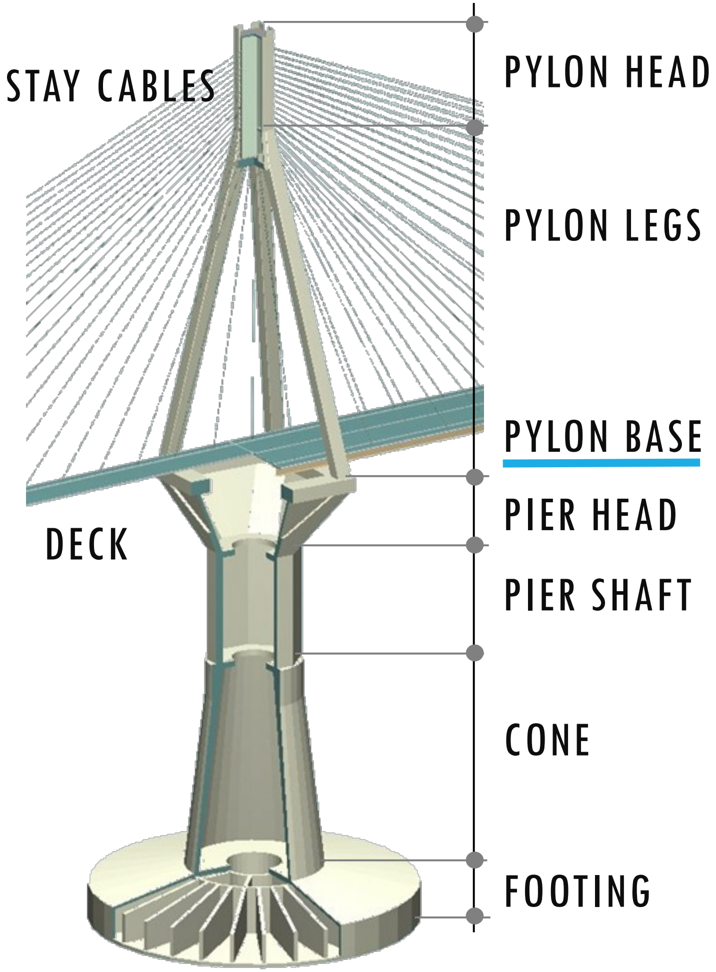
M1	M2	M3	M4
112	194	156	-

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)

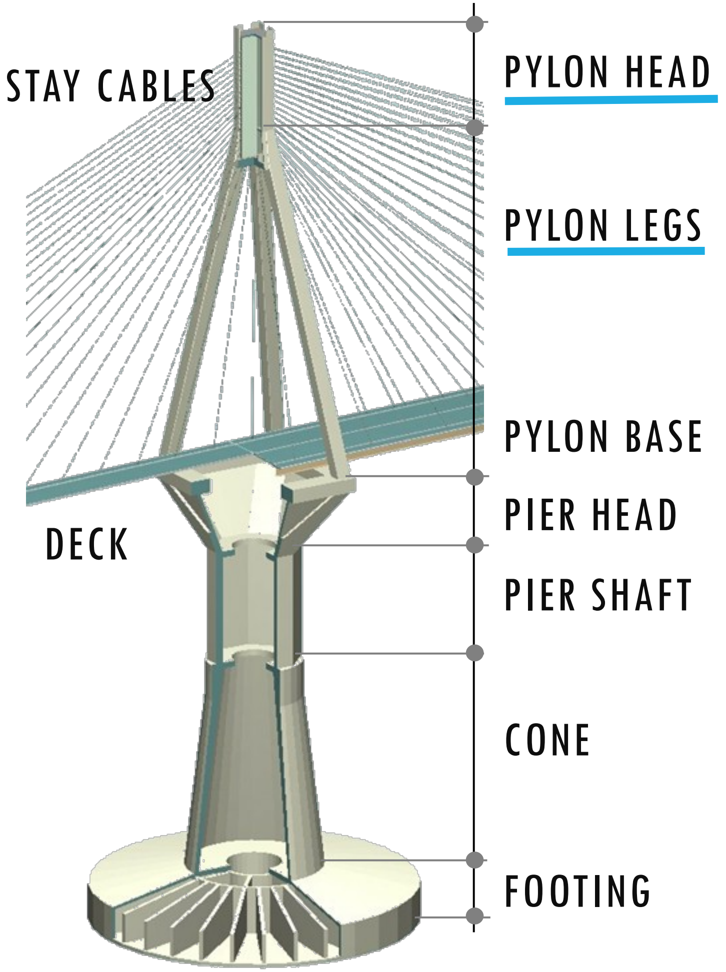
Preloading of soil to accumulate settlements during construction

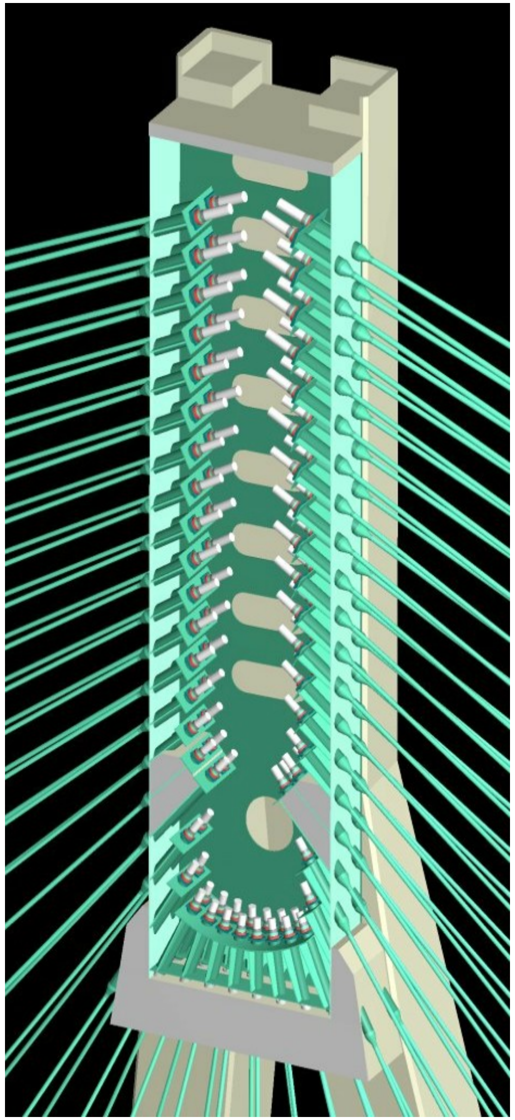


Square structure of high strength (C50/C60) pre-stressed concrete beams to rigidly connect pylon legs

- Beam section 6,0m x 3,5m
- Traffic and earthquake yield to significant forces transmitted through inclined pylon legs
- Pre-stressing also minimizes crack width improving concrete durability

STRUCTURAL DESIGN: PYLON LEGS & HEAD

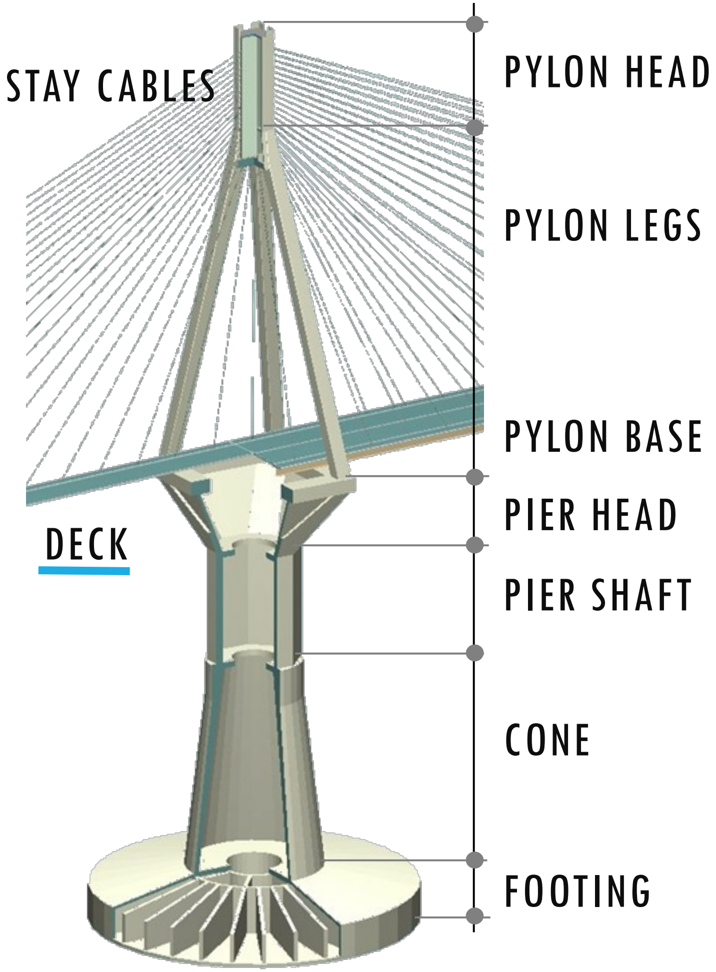


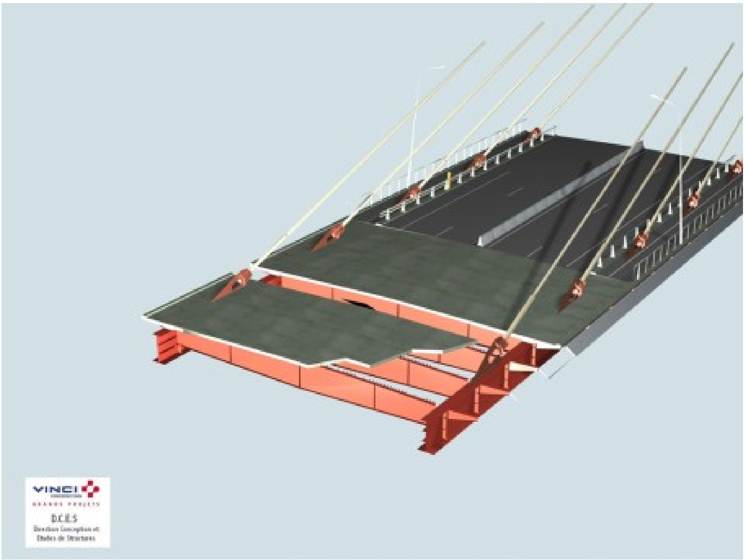


High strength concrete (C60/75) pylon legs support the steel pylon head anchorage device

- 4 pylon legs with hollow section 4mx4m, wall thickness 0,7m and total height ~82m are forming a pyramid shape
- Unique shape of pylon to resist overturning moment of an earthquake and eccentric traffic loading
- Pylon legs with special detailing of steel reinforcement to provide resilience to damages and accumulate large deformation without collapsing risk
- Cable anchorage device enclosed on two pre-stressed shells (east and west)

STRUCTURAL DESIGN: DECK

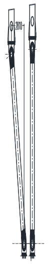


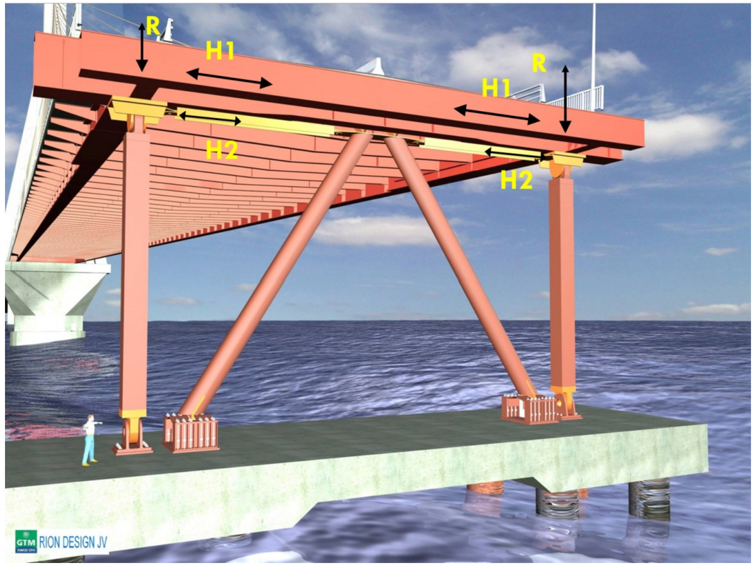


Deck: Continuous composite structure assembled with 12-m segments with total width 27m and fully suspended from pylon head

- Each prefabricated deck segment is supported by one pair of cables (East and West)
- Each deck segment consists of 2 main girders welded with the gussets, 4 transverse beams that are spaced every 4 meters and finally the concrete slab as topping
- The total weight of the 2252m-long deck is 70000 tons
- The concrete slab is C60/75
- Deck position can be reset through controlling cable tension (active anchorage on pylon top)

STRUCTURAL ELEMENTS: ROTATING FRAME





Rotating frame: steel device supporting deck edges and restraining lateral movements during normal operation conditions

- Rotating frame can accommodate in operation conditions the longitudinal movements of the deck through rotation of its pin connections
- Attached to the rotating frame are dissipation devices that can absorb the energy induced by a large earthquake
- 2 Dampers inside box 24 can absorb lateral deck motions up to ±2,6 m. 1 is equipped with a fuse (3500KN capacity)

STRUCTURAL ELEMENTS: EXPANSION JOINT

Expansion Joint: Device to accommodate tectonic movement, deck vibrations and any deck length variation

- The Expansion joint can undertake in operation conditions **1,22m** of closing and **1,26 m** of opening (SLS)
- In case of severe earthquake with tectonic movement between Rion and Antirion shore, the maximum closing can reach **2,20m** and the maximum opening **2,81m**, while the lateral movement between deck and viaduct can reach **2,6m** in both directions without collapsing but with limited damages (ULS)
- The expansion joint consists of longitudinal beams (supporting bars) that rest on bearings on both sides and transverse beams (center beams) that cover the gap of the joint and are elastically attached to these bars

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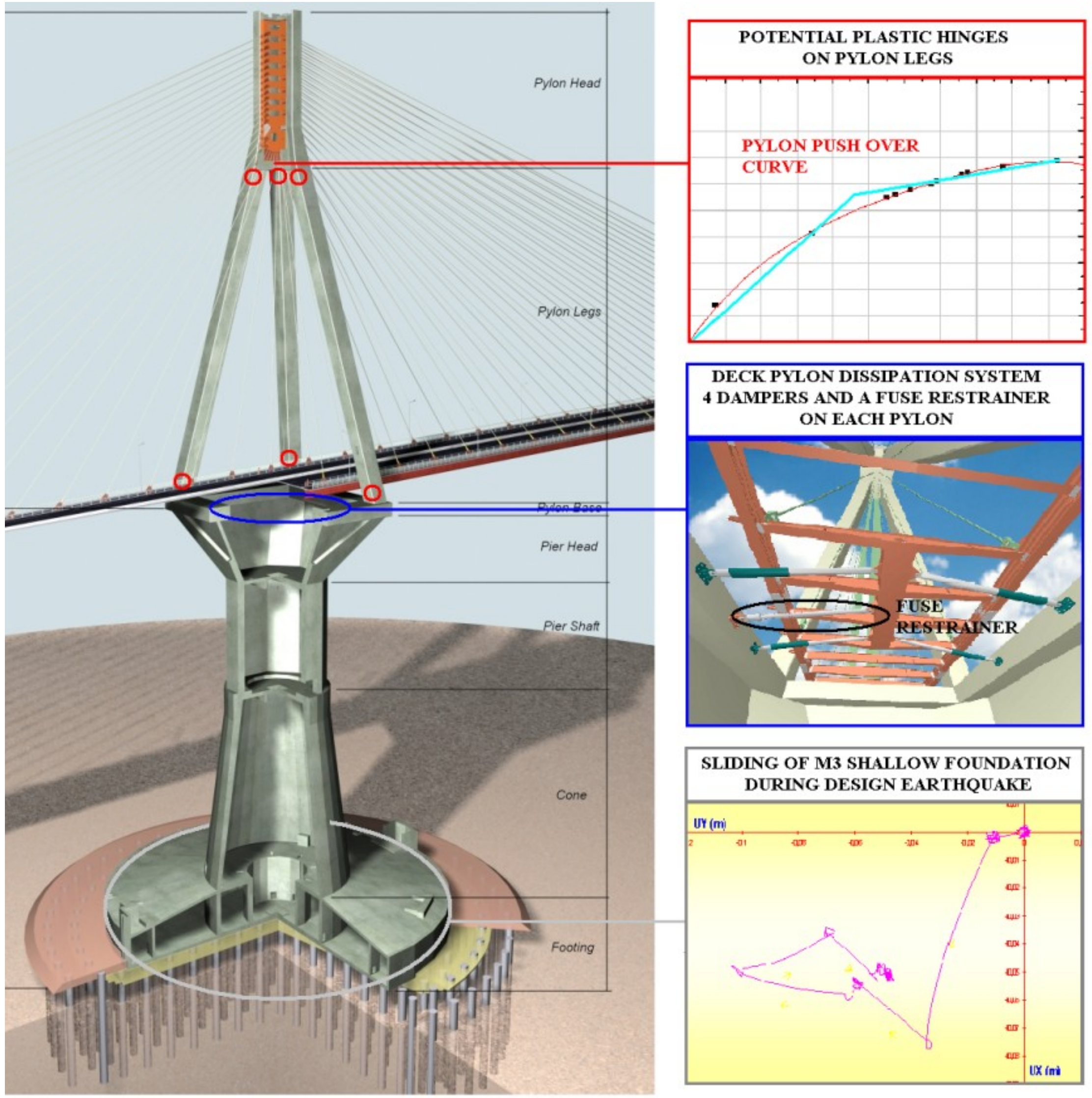
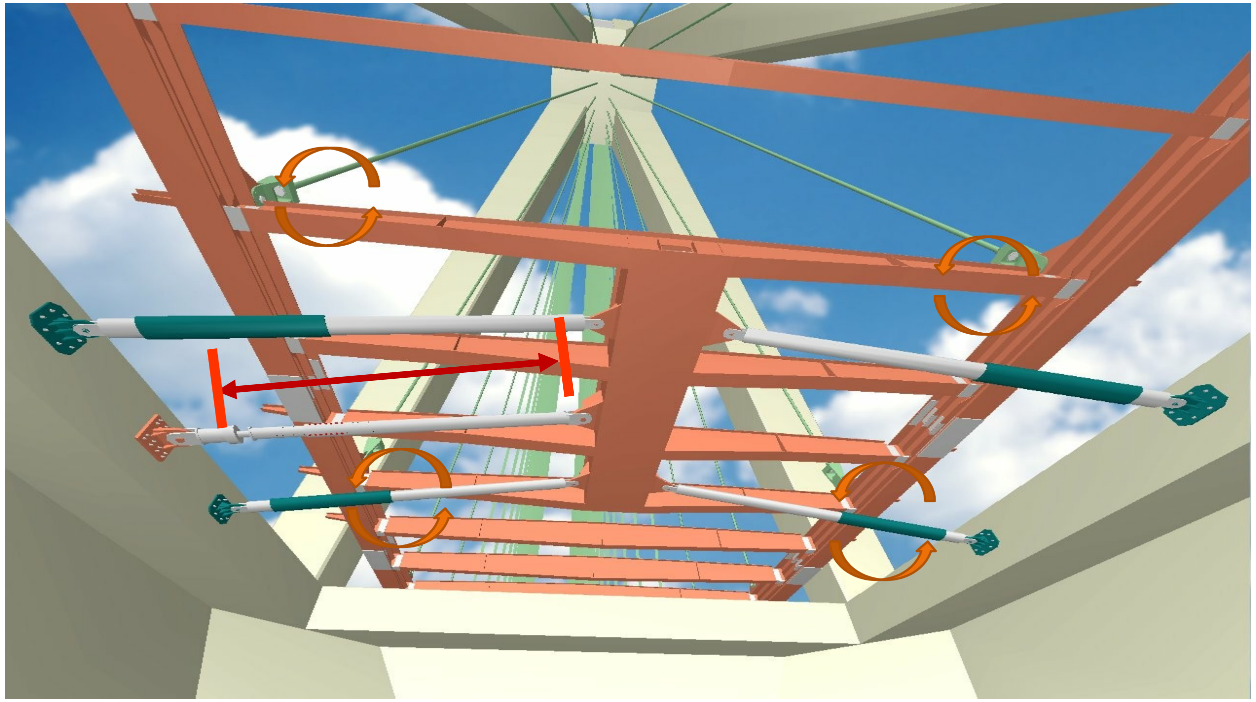


WHAT IF A GREATER EVENT OCCUR?

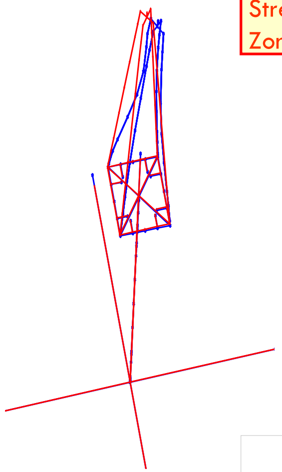
- Although a good effort is paid to calculate with a safety margin the expected loading of a structure during and EQ, it is still probable to have an EQ that exceeds this loading.
- Prevent collapse at each case.
- Design so the damages are located on specific places that can dissipate the kinetic energy trough plastic deformation
- Add dissipation systems
- Allow foundation sliding without exceeding soil capacity

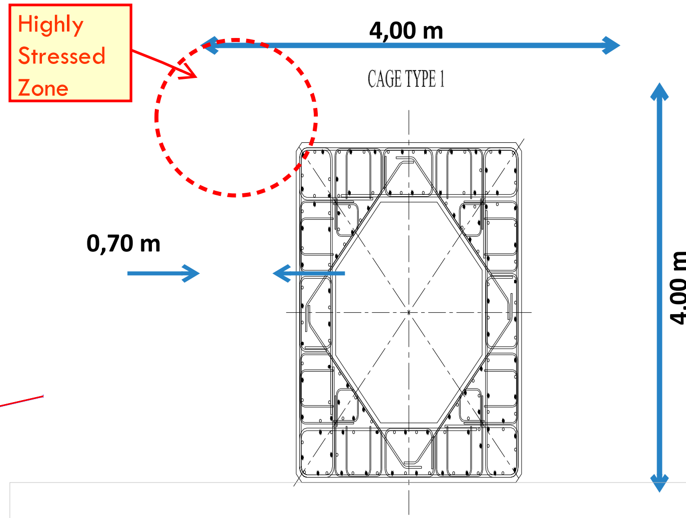
HYDRAULIC DAMPERS



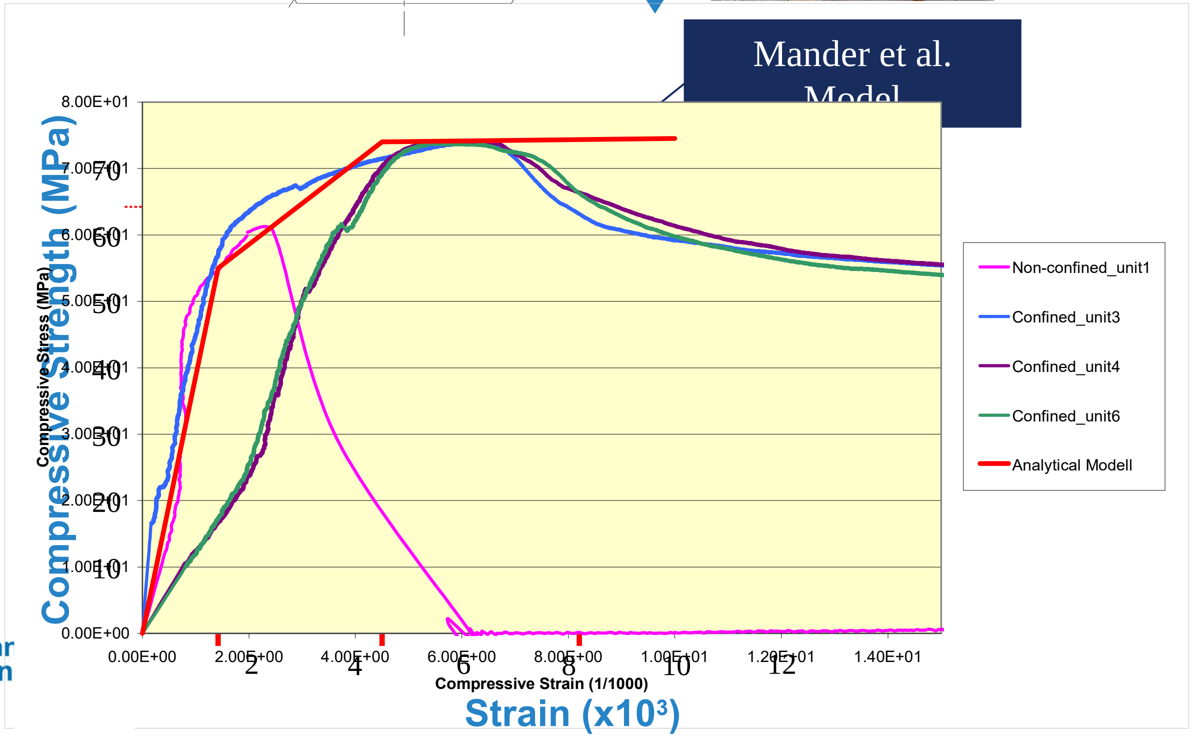
- Installation of Hydraulic Dampers between Deck and Piers at the transverse notion
- Prevent Dampers fatigue through restriction of lateral movement for daily winds and small EQ
- Release deck when load on restrainers exceeds (10500 kN)
- Hydraulic dampers displacements capacity ±1,65 m and force 3500 kN

CONCRETE PLASTIC HINGES

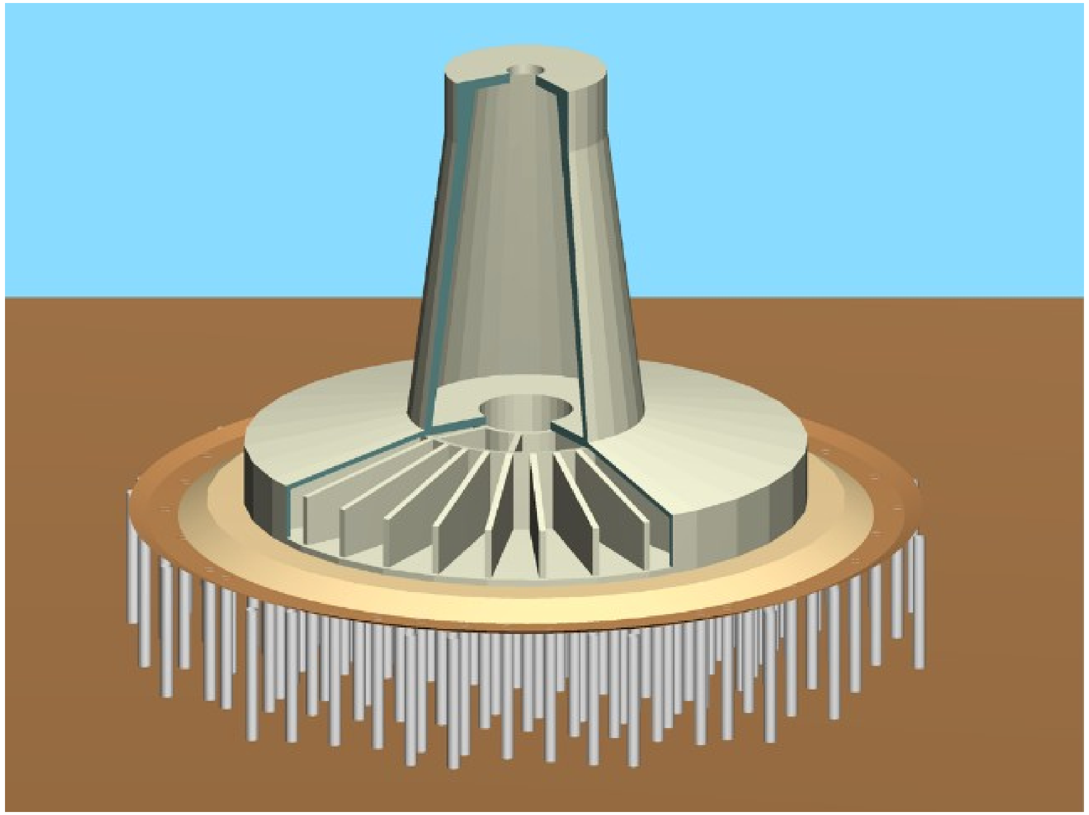




- Design particular zones appropriately to resist deformation and obtain greater strength
- Concrete confinement
- Energy dissipation through plastic deformation (damages) on top and bottom pylon legs



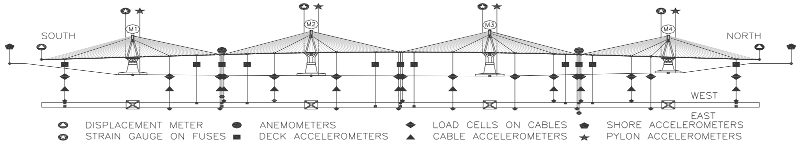
FOUNDATION SLIDING

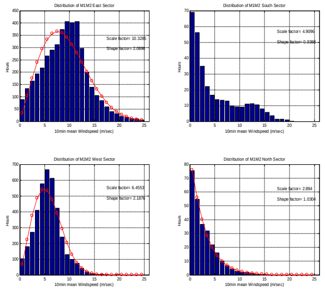


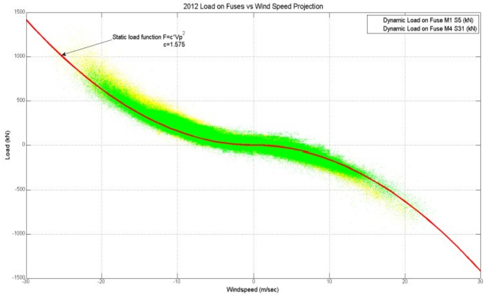
- Simply supported pier
- Control Friction by application of aggregates (gravel) on sea bed
- Avoid soil failure through shear strengthening
- Dissipate energy through friction
- “Isolate” extreme events

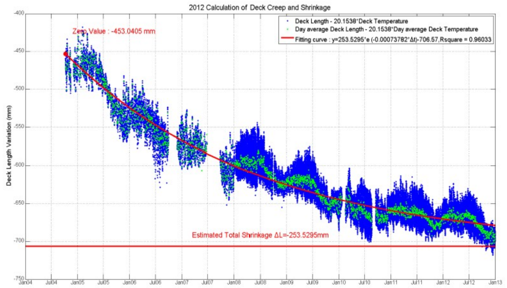
MONITORING SYSTEM OPERATION PROVIDES:

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



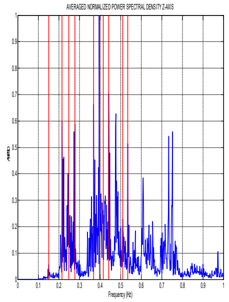


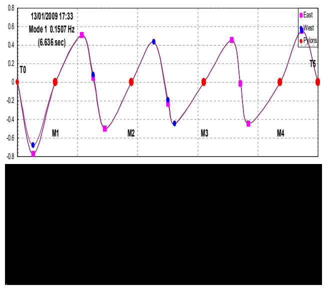


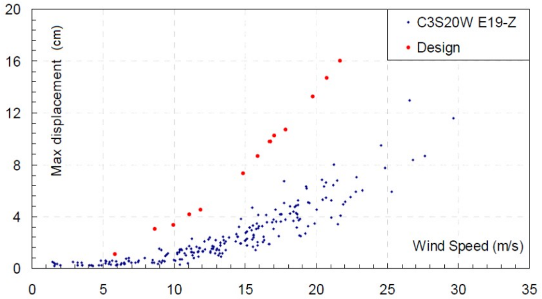


History Files analysis: Slow varying processes/statistical parameters of structural response

History files: 1 value every 30 sec



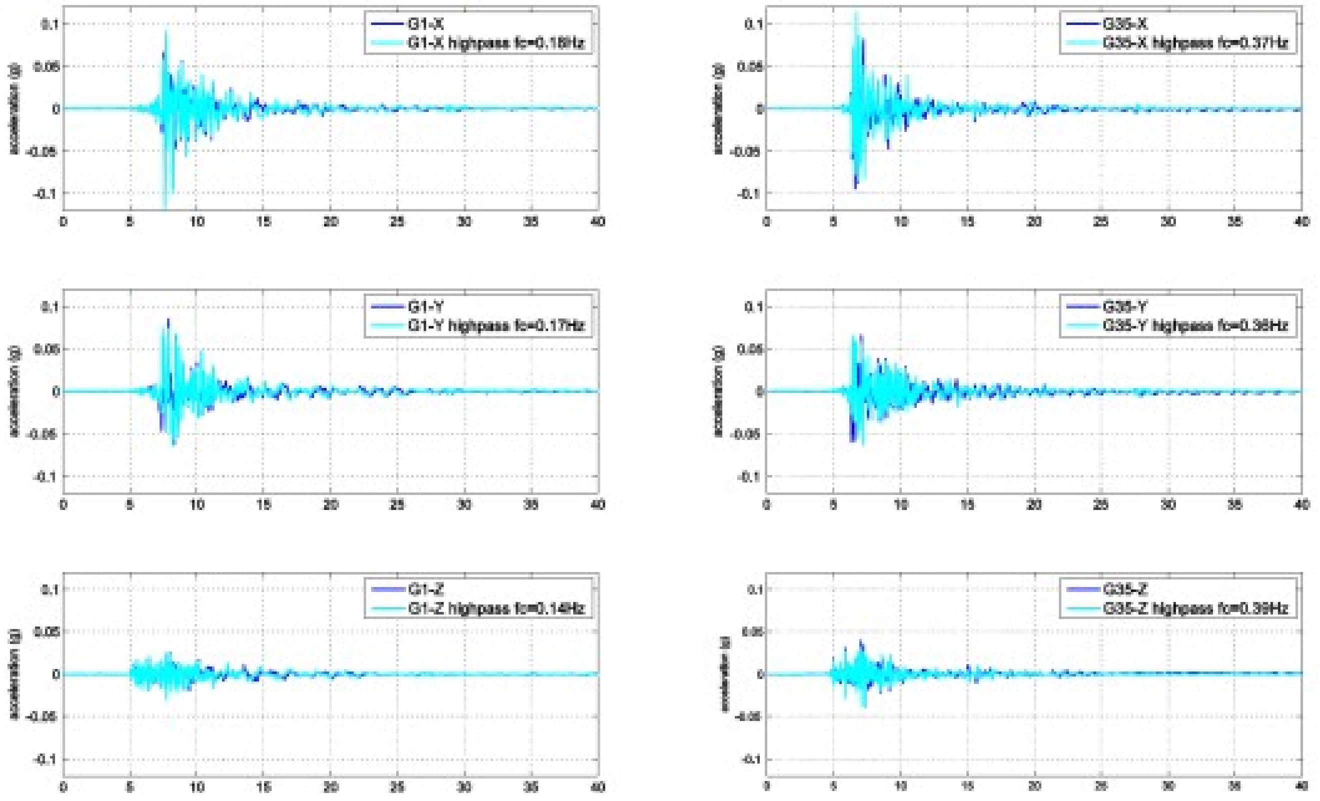




Dynamic Files analysis: Dynamic process/actual measurements of structural response

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

21st of September 03:43, ML=4.5, at 38 21′ 36″N 21 50′ 24″E



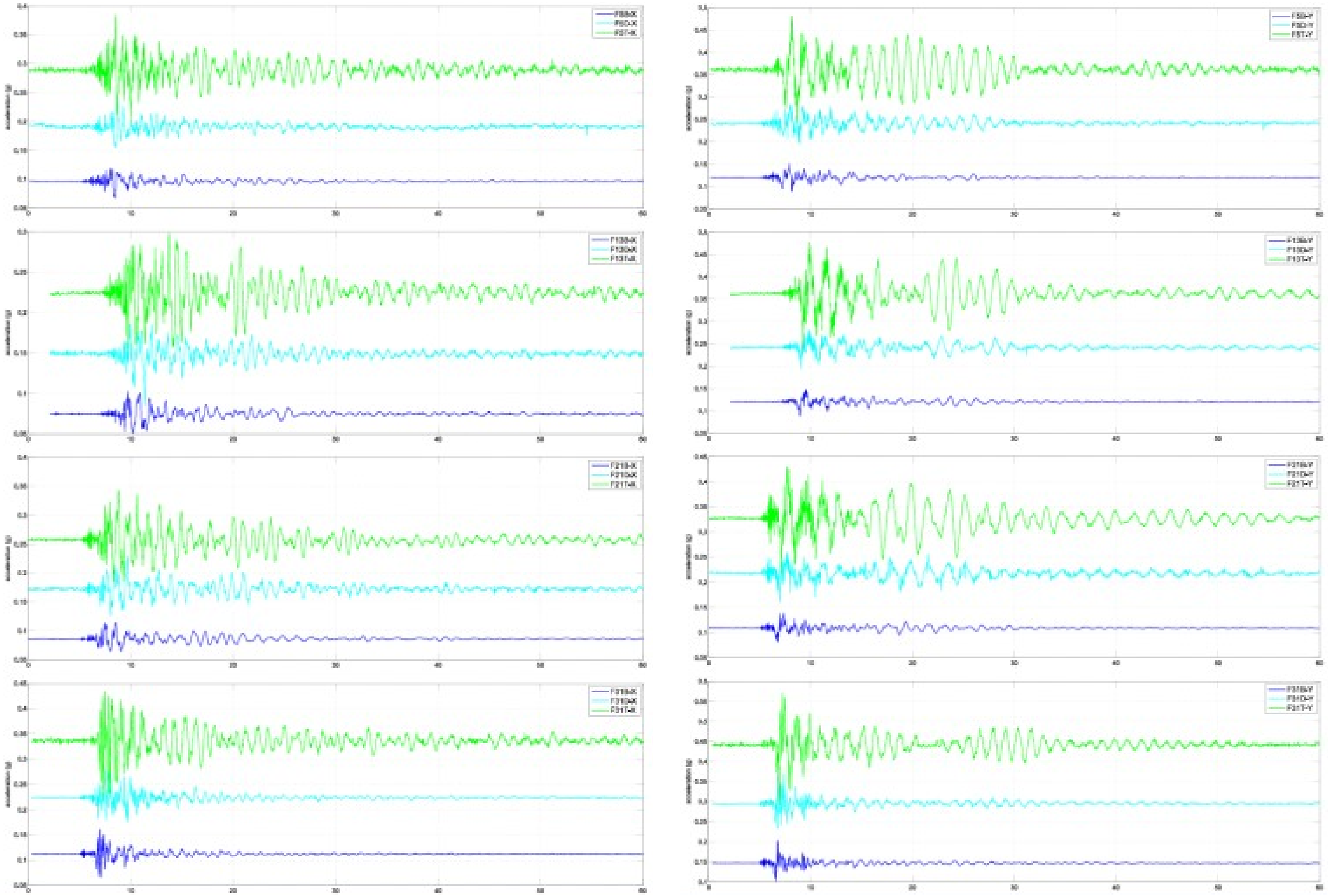
DATA: Dynamic-Alert

Analysis output

- Signal processing of baseline correction
- Ground motion parameters calculation
- Response spectrum calculation
- Response Velocity and displacement time histories
- Common reference graphs

	Intensity parameters	Arias intensity (m/sec)	Arias intensity-Processed (m/sec)	Strong Motion Duration (sec)	Strong Motion Duration-Processed (sec)	CAV (m/sec)	CAV-Processed (m/sec)
Shore Accelerometers	**Rion accelerometer G1-X**	0.0561	0.0561	6.380	6.700	2.48	2.47
	Rion accelerometer G1-Y	0.0488	0.0488	9.080	9.400	2.51	2.47
	SUM	**0.1049**	**0.1049**				
	Antirion accelerometer G35-X	0.0630	0.0606	14.300	5.500	3.44	2.22
	Antirion accelerometer G35-Y	0.0405	0.0383	50.840	11.080	3.37	2.25
	SUM	**0.1035**	**0.0989**				

21st of September 03:43, ML=4.5, at 38 21’ 36”N 21 50’ 24”E



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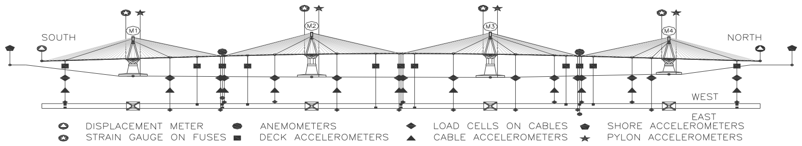
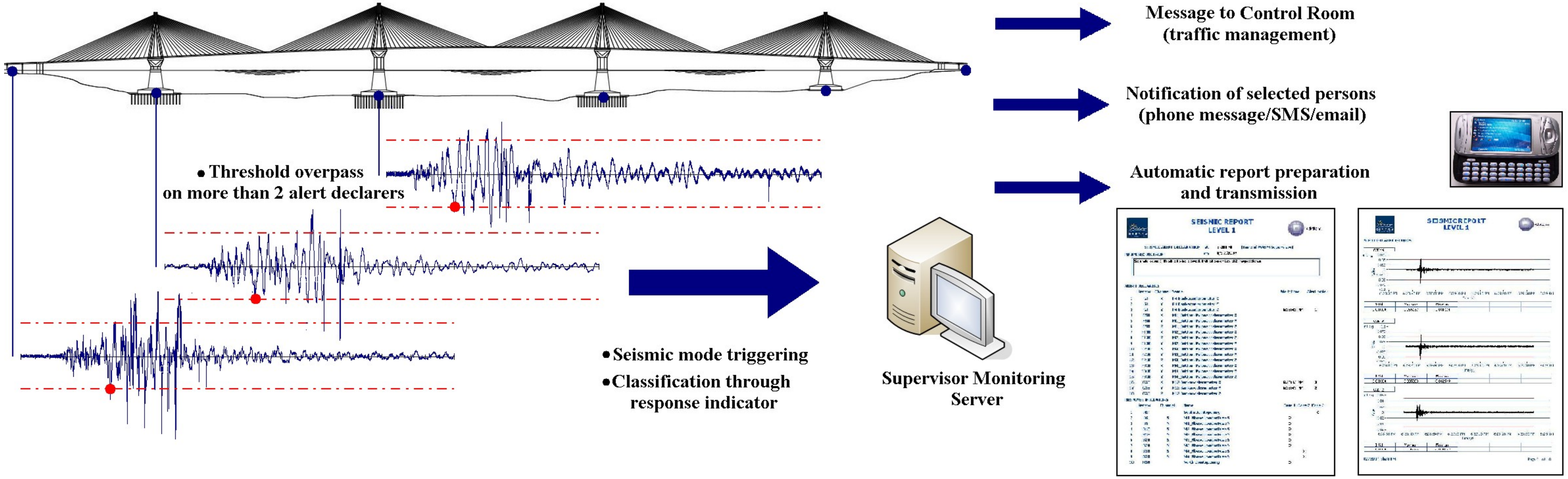


Automated event management (Smart monitoring):

1. Automated detection of earthquake events
2. Classification of structural response
3. Proposed decision on traffic management (Real time)
4. Automated report preparation and transmission



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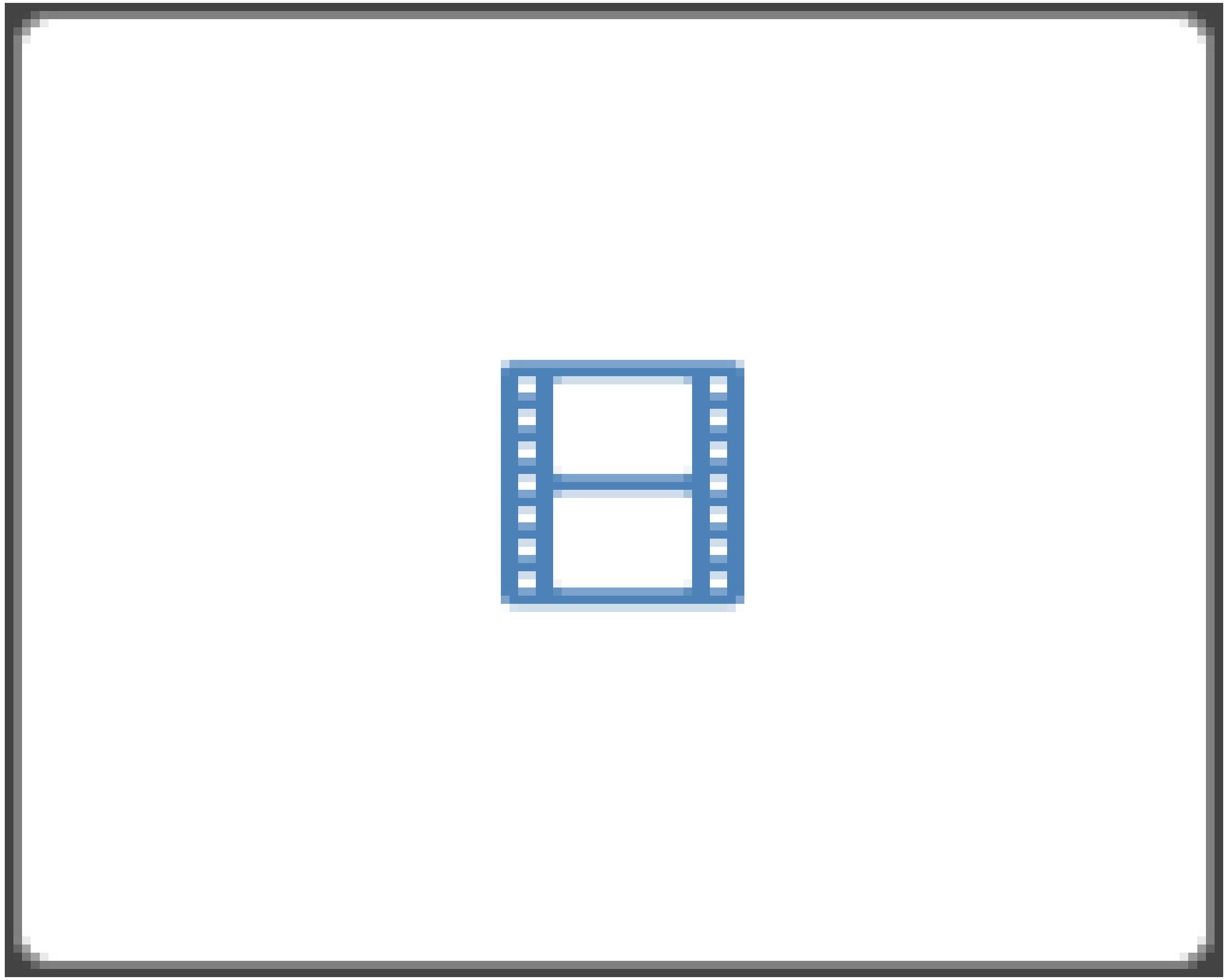
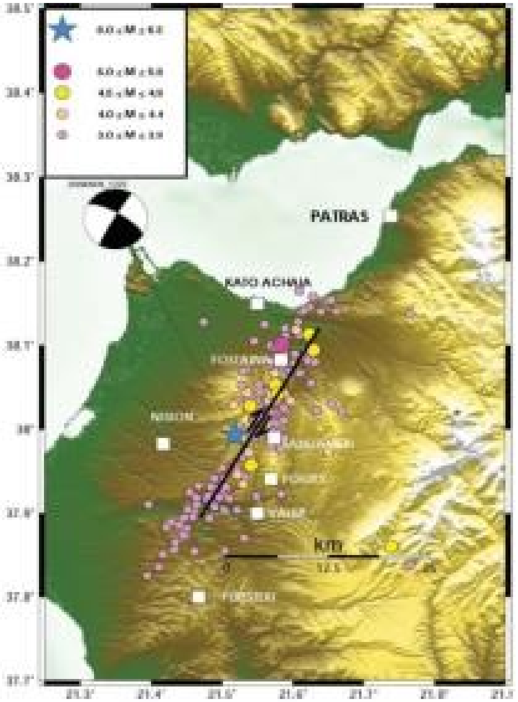


- Magnitude Mw=6,4
- 36km from Rion-Antirion site.
- Focal depth:31km
- Max PGA recorded from on-shore accelerometers:0.127g (at Rion bank)



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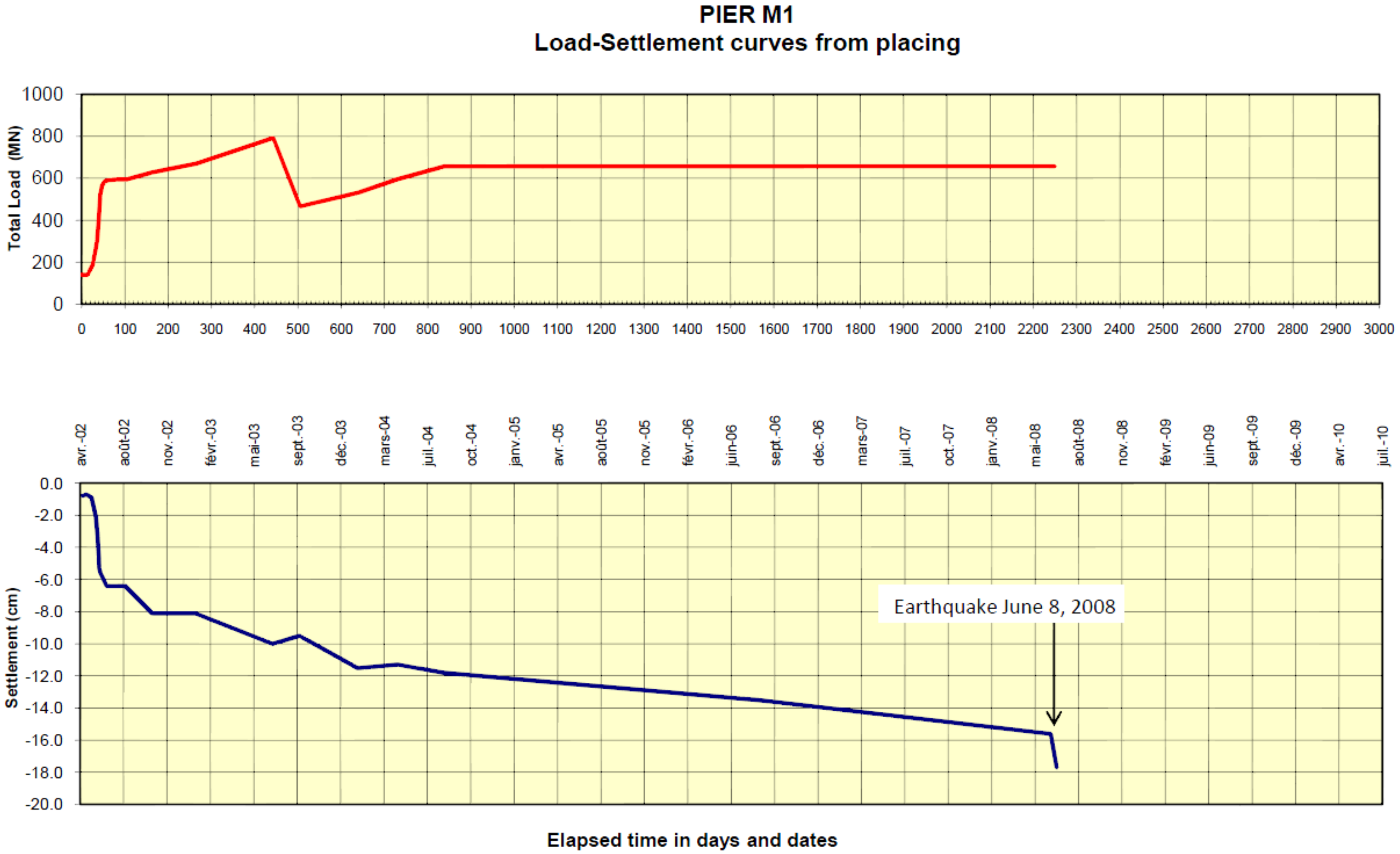

- No significant shore movement residuals (<3mm)
- Pylon top displacement <15mm
- Max settlement: 21mm (at M1)

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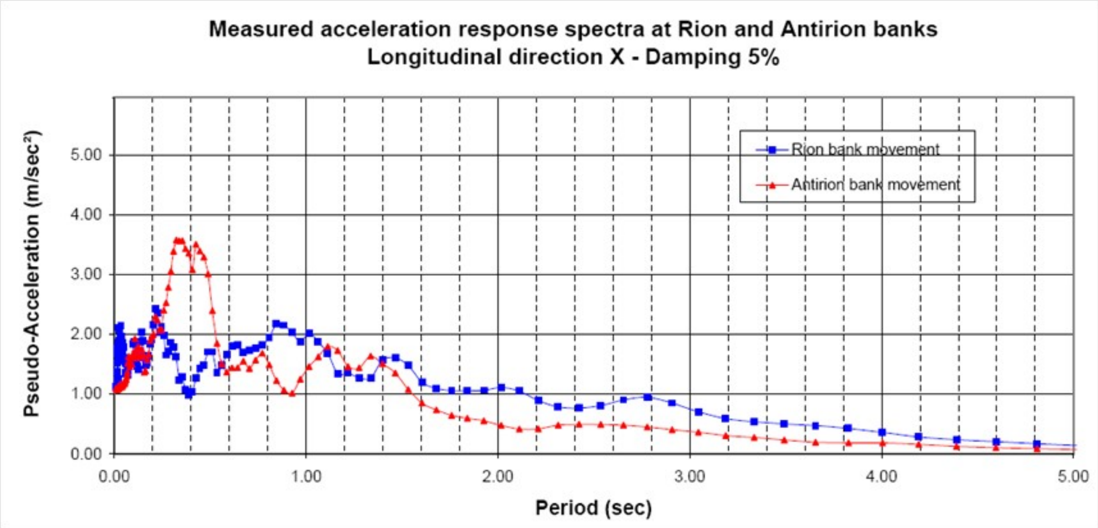
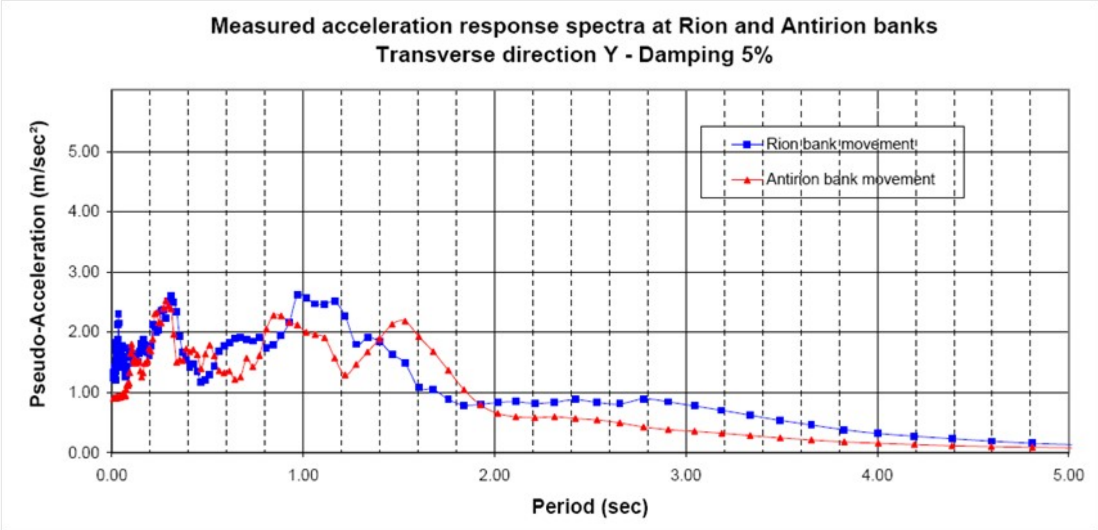
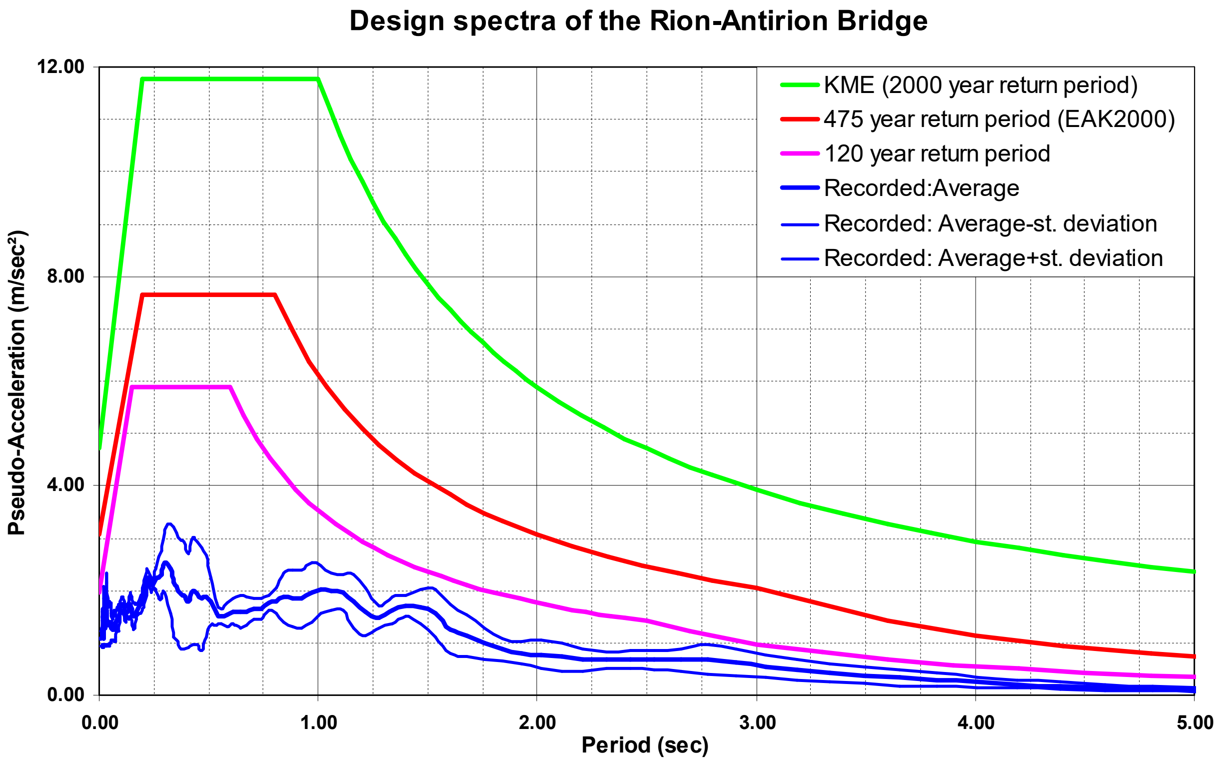
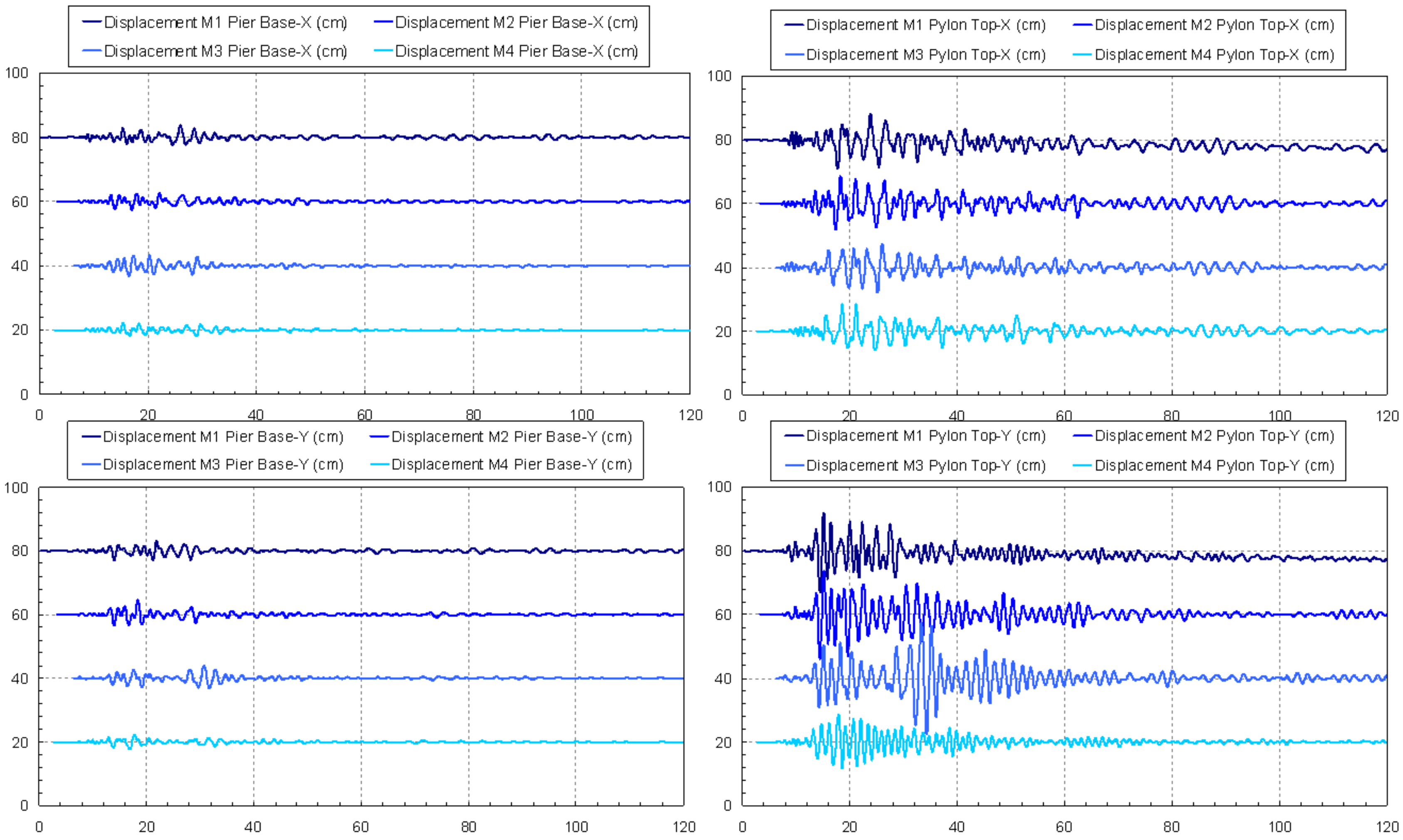


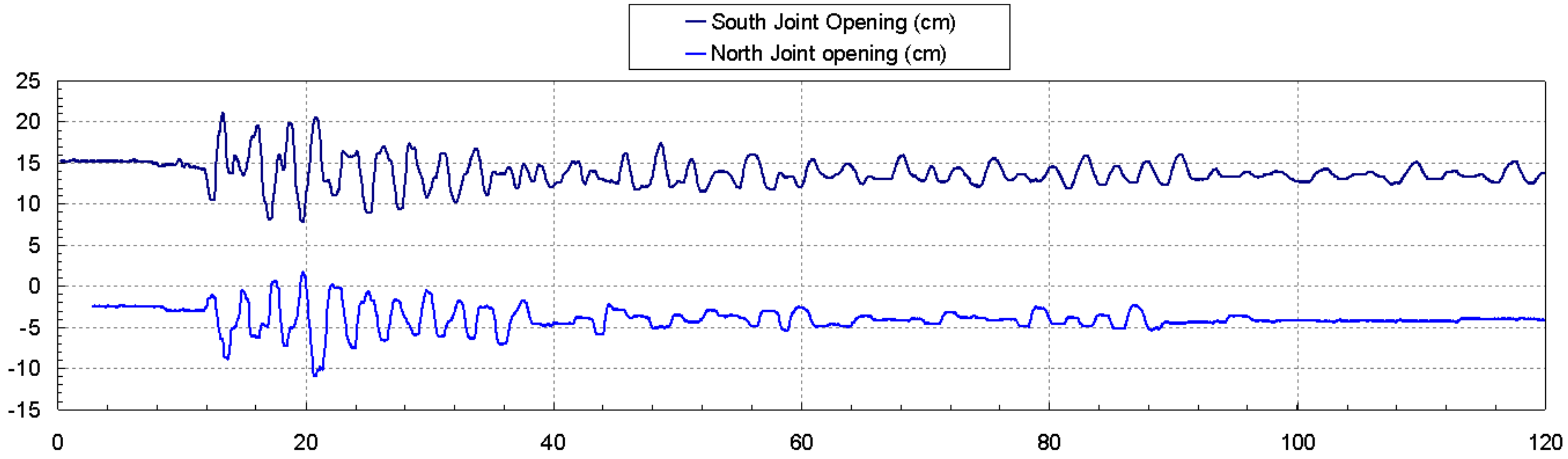


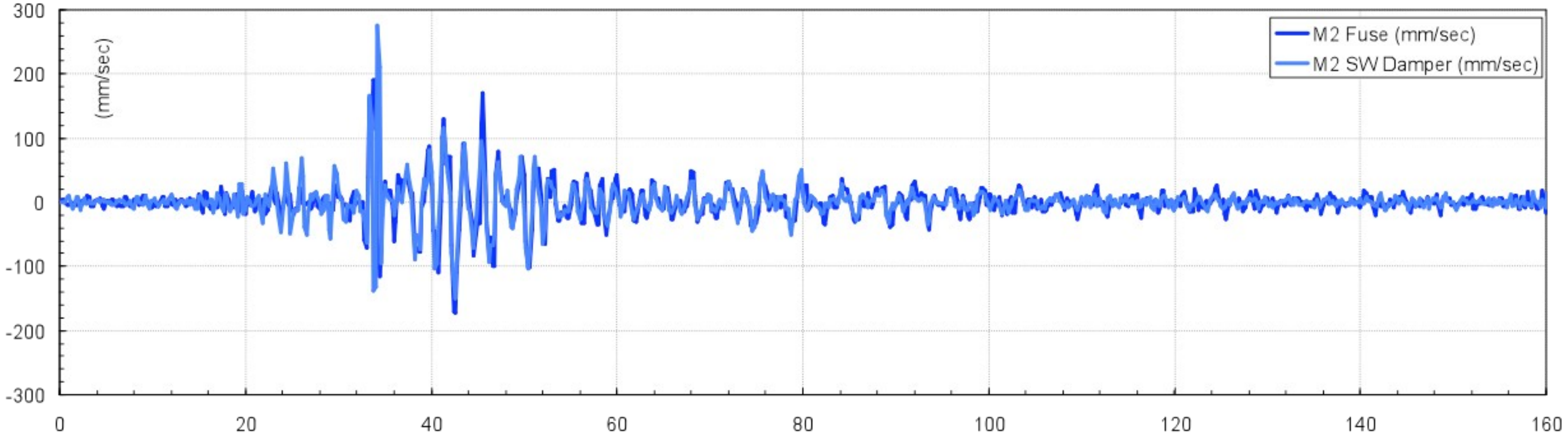
- Max pga=0.127 (g) at Rion transverse direction (Y-axis)
- High values of PSA around 1 sec period
- Max. PSA on Antirion longitudinal direction (X-axis)
- The recorded spectra are comparable but always lower than the elastic spectra of 120 return period earthquake





- Displacement amplification up to 4.9 times (M3-Y)
- Greater excitation on transverse axis, up to 17.5 cm (M3-Y)





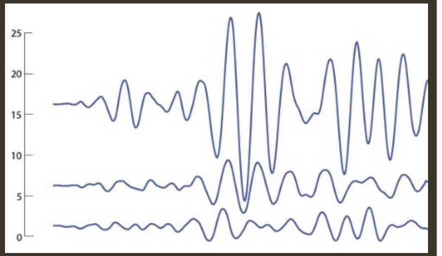
- Longitudinal excitation limited at 140 mm (range) as recorded on Expansion Joints
- Transverse excitation (range) evaluated through video processing on pylon locations reached 152 mm, while maximum velocity reached 277 mm/sec

Monitoring Report

First review of monitoring data recorded

SLS was not exceeded

Indication of deck release (fuses)

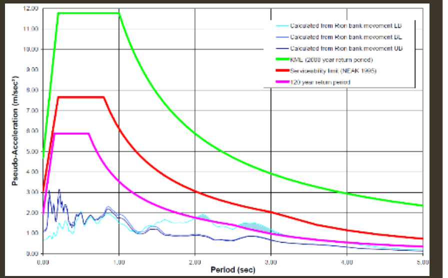


Analysis of Monitoring data

Expertise analysis on collected data

Evaluation of similar EQ's return period

T= 80 to 120 years



Deck re-alignment and fuse replacement

	Level 1 Inspection	Level 2 Inspection	Level 3 Inspection	Level 4 Inspection & geometric control	Final step Remedial works
Elapsed time	**15 min**	**4 hours**	**2 days**	**2 months**	**5 months**
Inspector	**On duty Officer (non technical)**	**Trained structural inspectors**	**Trained structural inspectors**	**Trained structural inspectors and specialized suppliers**	
Findings	**No findings**	**Sign of movement on fuses (Pylon)**	**Minor non structural damage**	**Minor non structural damage**	

European Geosciences Union

Thank you!