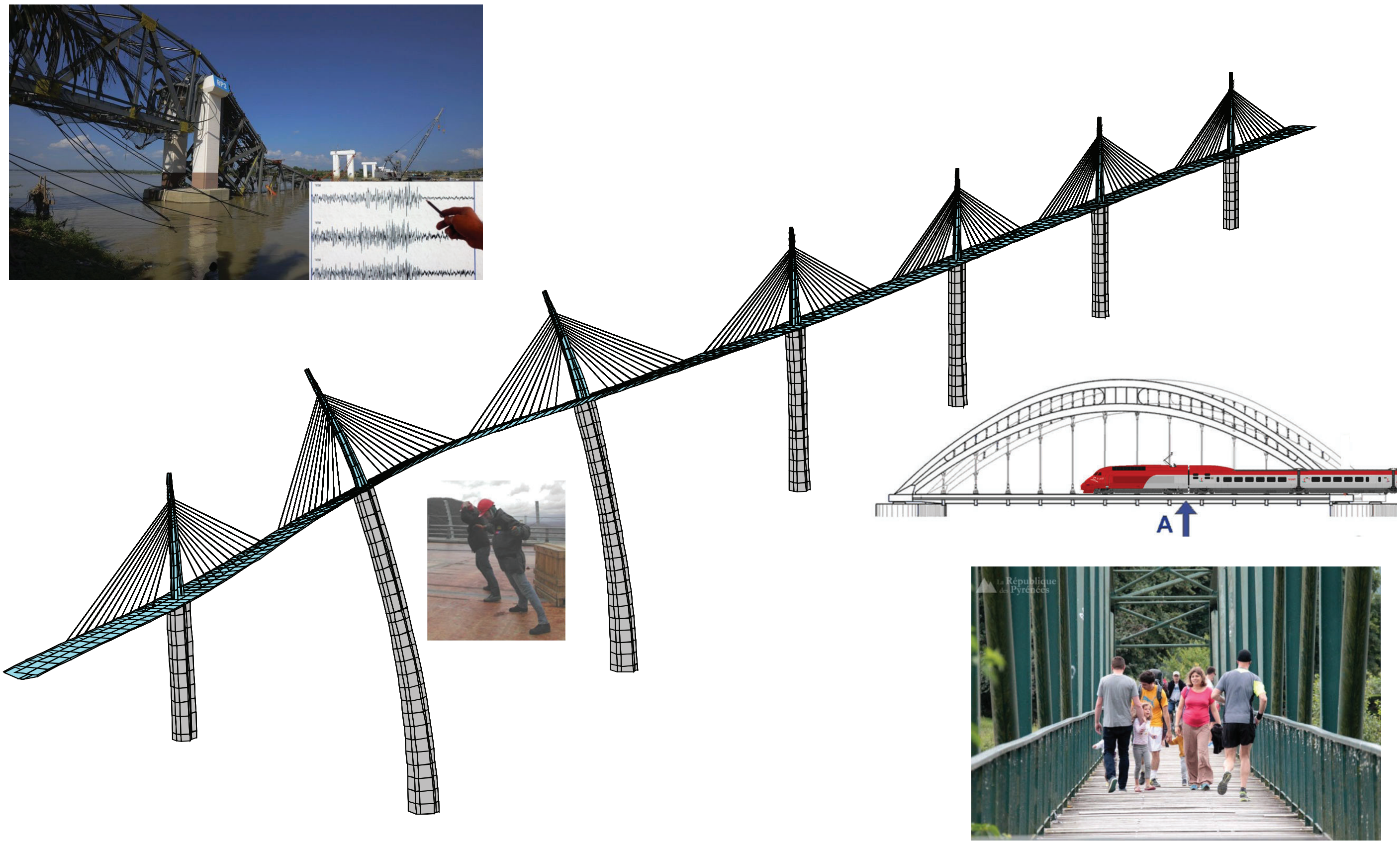


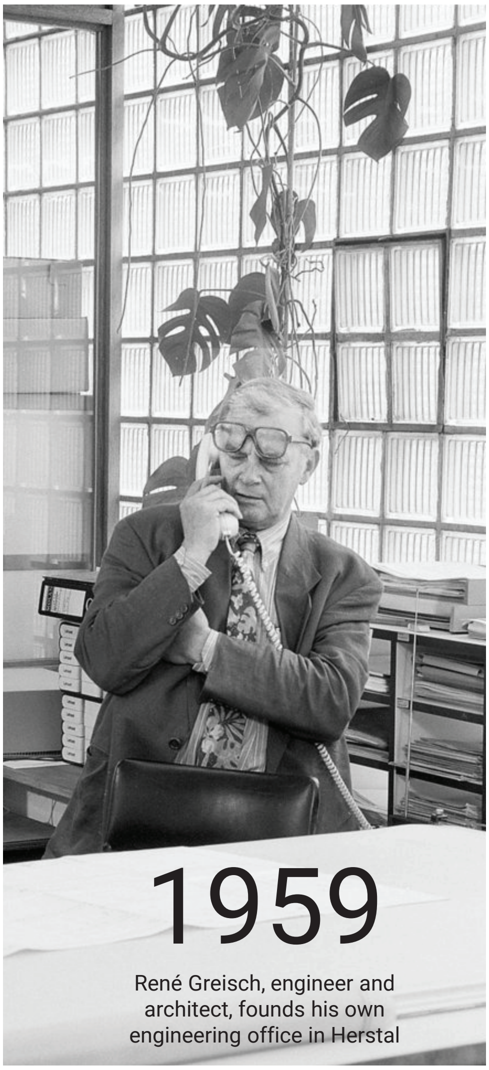
11 may 2022

VUB ULB

The dynamics of structures
Civil Engineering

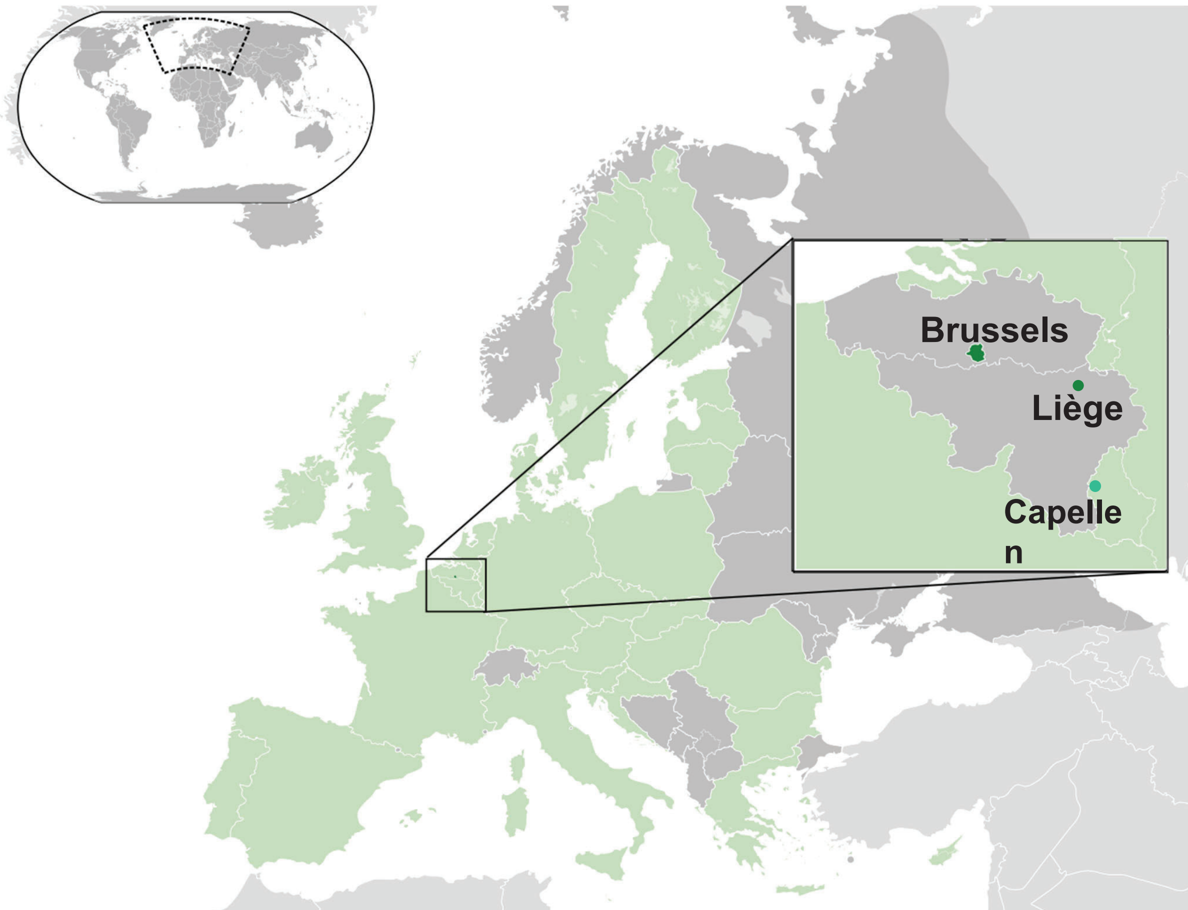
V. de VILLE de GOYET, dr.ir.
Scientific Director, Greisch
Prof. ULiege, CHEC

greisch



presentation

Where do we come from ?



greisch at Liège

Liège Science Park
Allée des Noisetiers 25
B-4031 Angleur
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greisch at Brussels

Omega Court
Rue Jules Cockx 8-10
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greisch in Luxembourg

Parc d'Activités, 2-4
L-8308 Capellen
tél.:+352 691 203 915

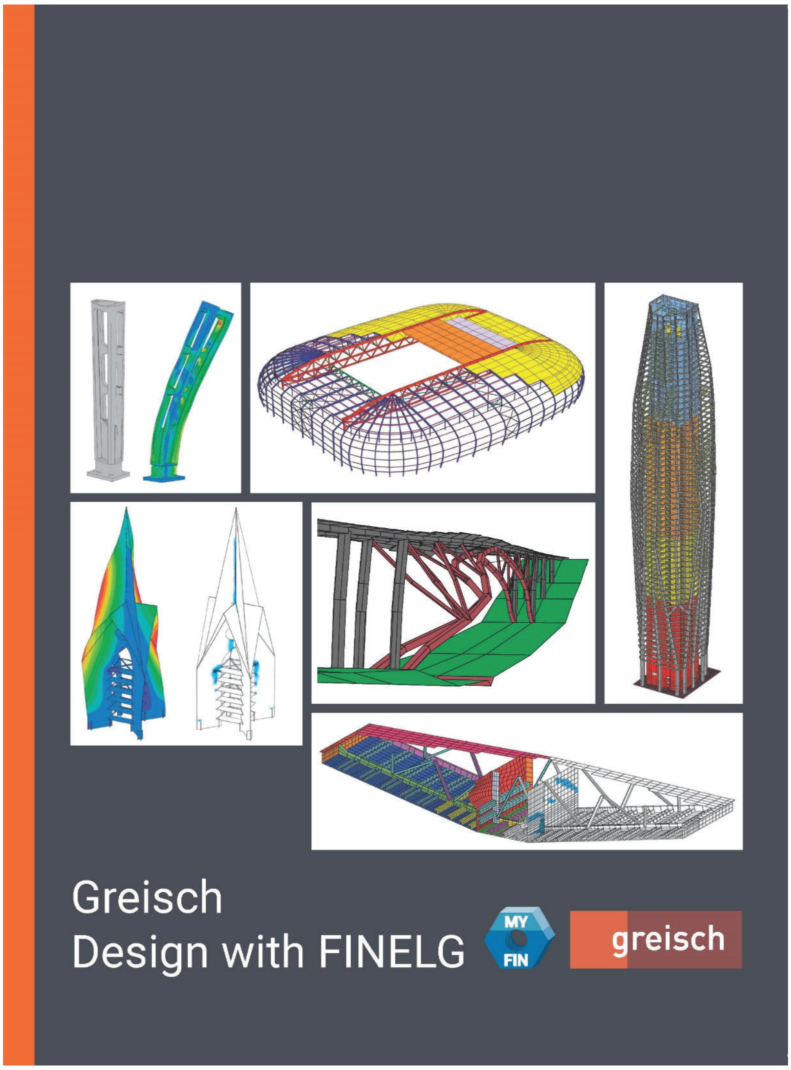
bureau@greisch.com

www.greisch.com

A strong network of experts

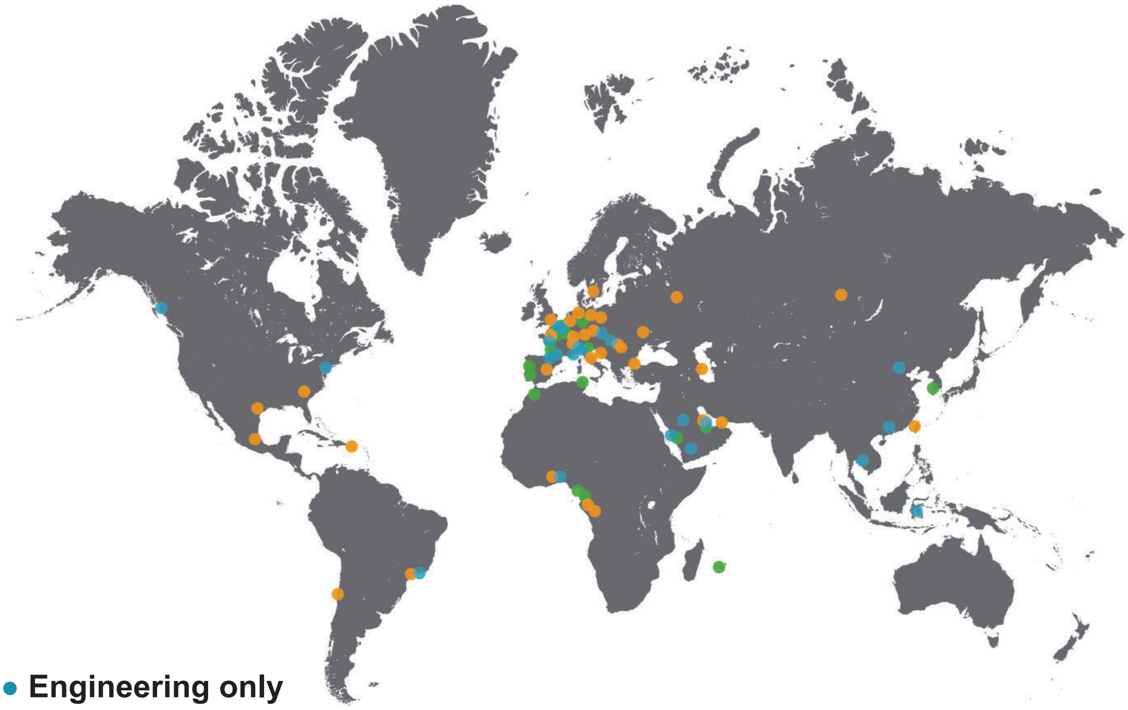
FINELG
our homemade calculation program

- developped in FULL collaboration with LIÈGE université
- statical linear computations – beam & shell elements
- non-linear computations
  large displacements, instability
  and elasto-plastic constitutive laws
- dynamic computations
- eigen modes, spectral analysis, any time history
- seismic computations, dynamic fatigue computations
- turbulent wind for 1D, 2D and 3D structures
- erection stages computations
- time-dependant computations for concrete behaviour, cracking, creep, shrinkage included



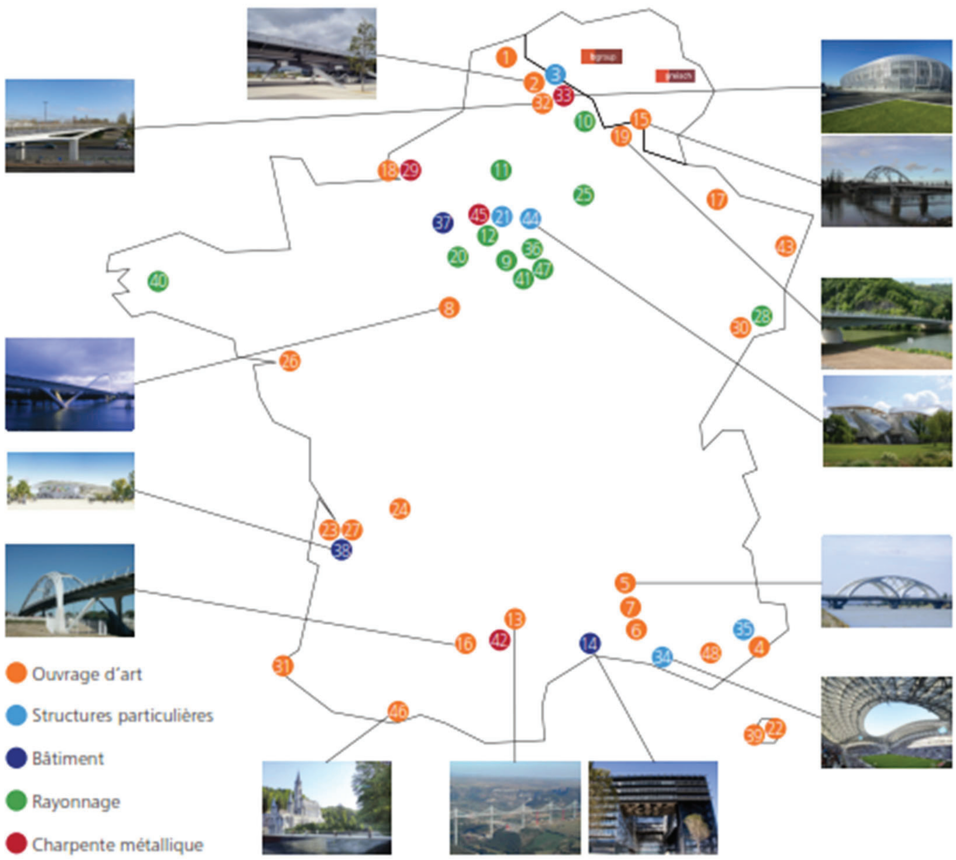
250 persons :
140 engineers - 12 architects – 80 technicians
2 graphic designers - 8 IT's - 8 administrative employees

references



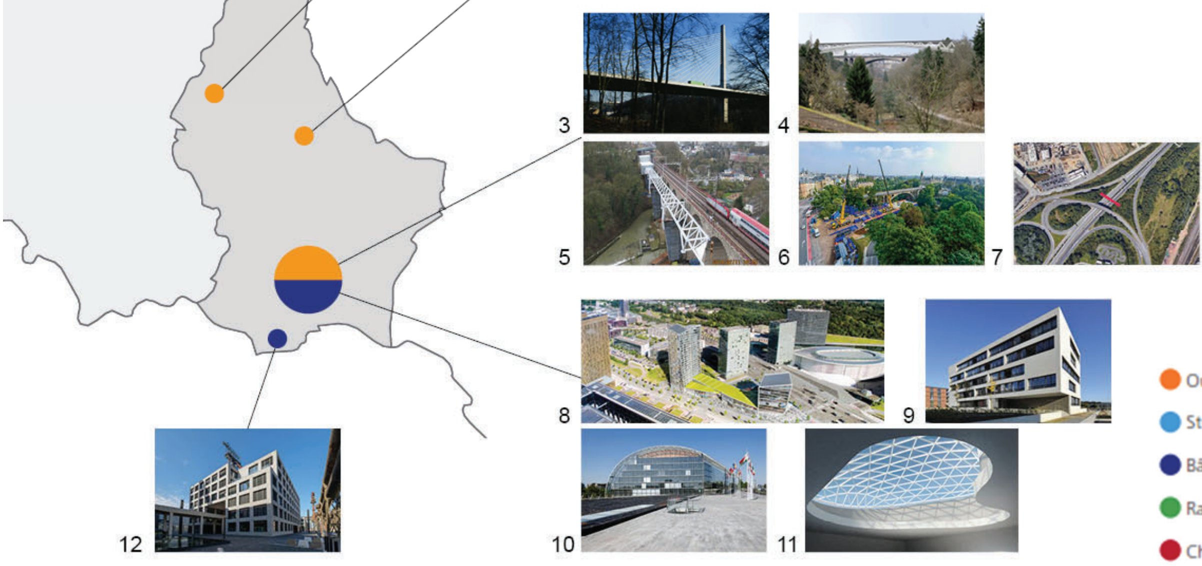
- Engineering only
- Works
- Works with site follow-up

Références



Références

1. Remplacement des ponts du lac d'Esch
2. Remplacement du pont rivière pour les CFL
3. Pont de l'Alzette
4. Remplacement du pont Adolphe
5. Pont de Pulvermühle
6. Pont provisoire à proximité du pont Adolphe
7. Ban de Gasperich
8. Infinity - îlot mixte, porte de l'Europe
9. Immeuble à appartements - quartier du Grünewald
10. Immeuble de la BEI
11. Cloche d'Or - charpente des verrières
12. Maison de l'innovation à Esch-sur-Alzette



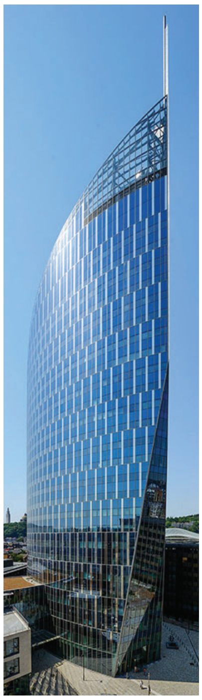
Ouvrage d'art
Structures particulières
Bâtiment
Rayonnage
Charpente métallique

CIVIL WORKS

BRIDGES

Engineering office

- High rise buildings, hospitals
- Industrial buildings, large roofs
- Architecture, renovation
- Town planning: metro, tram
- Technical equipment and energy design for buildings

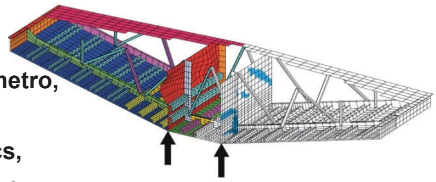


www.greisch.com employees

Since 1959, 175

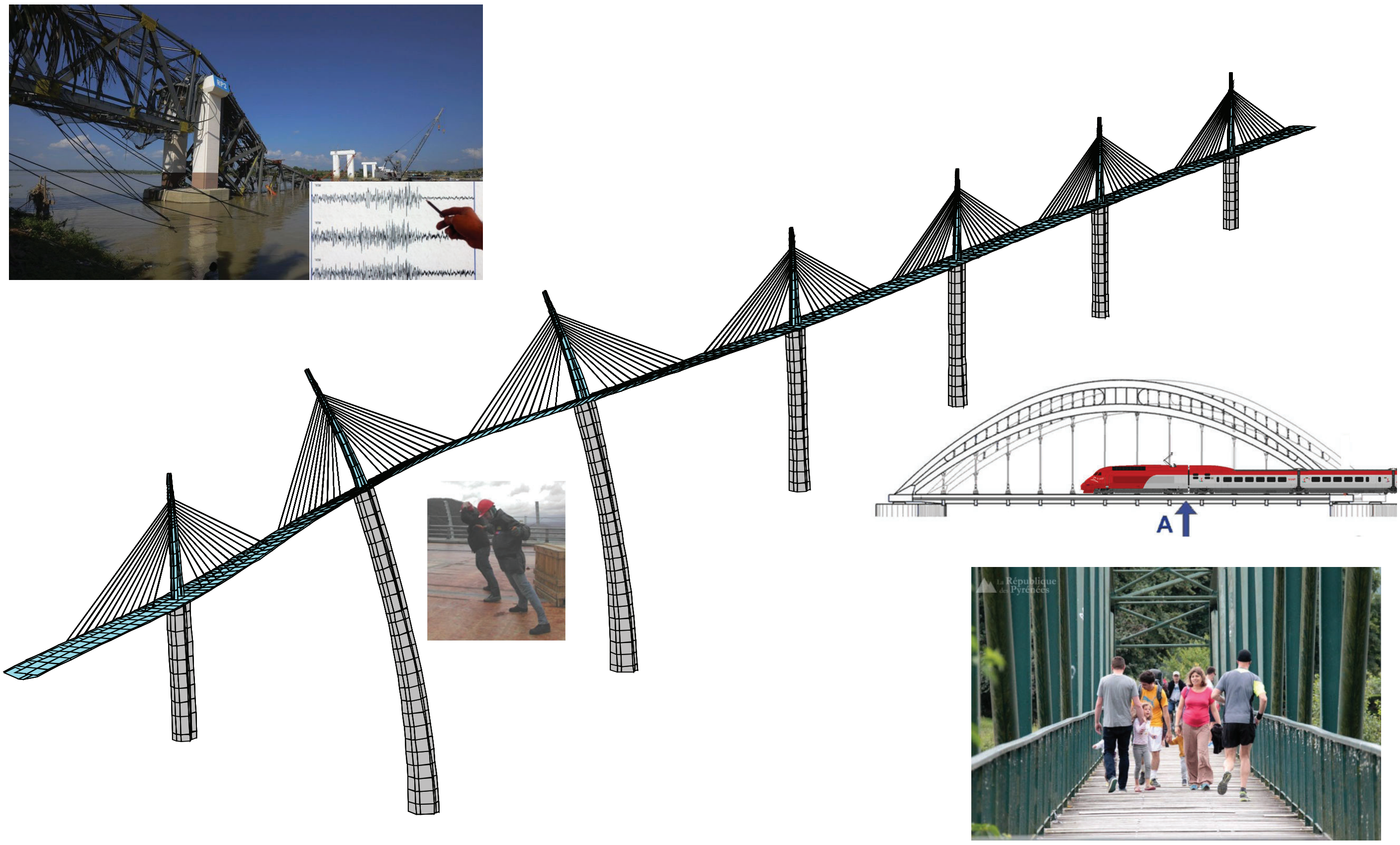
Engineering office

- Road bridges, HST bridges, footbridges
- Civil works engineering
- Roads, locks, airports, tunnels, metro, railway stations
- Special studies : statics, dynamics, instability, seismic, wind engineering



www.greisch.com

Since 1959, 175 employees



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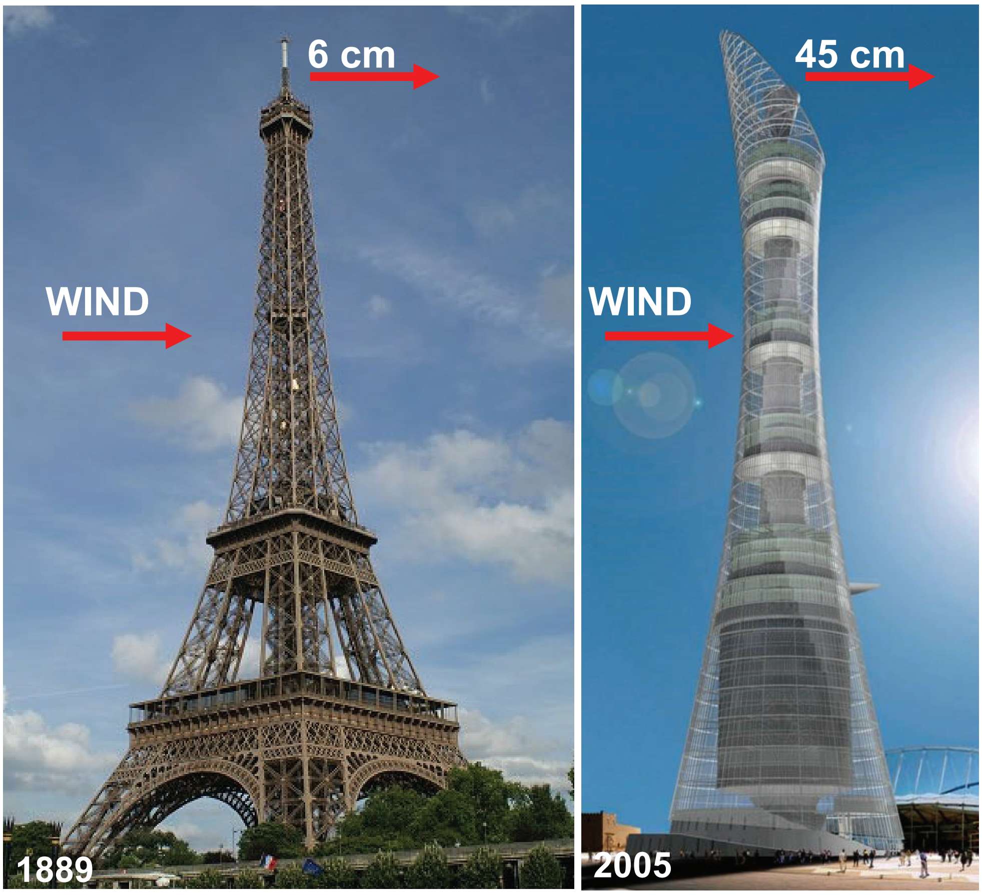


Statics – Dynamics

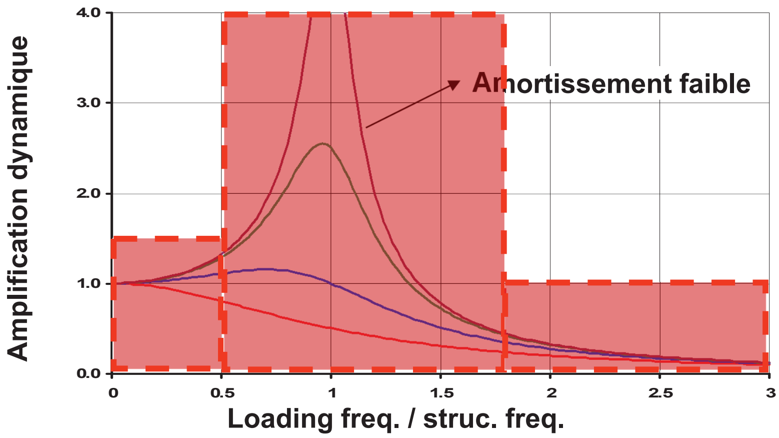
Civil Engineering

Fixed structures

1) larges loads
2) permanent loads
3) **variables laods**

YESTERDAYS
- **rigid structures**
➔ **static…**

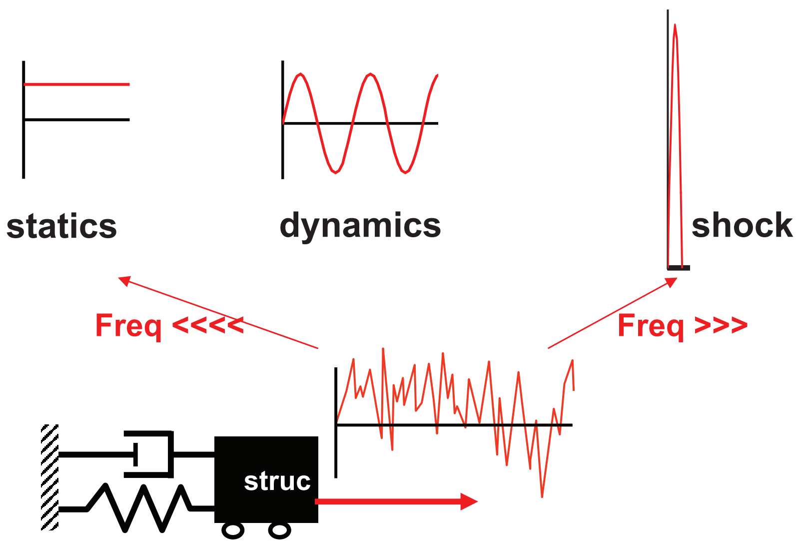
TODAY
- **slender structures**
➔ **dynamic**



Statics – Dynamics

The nature

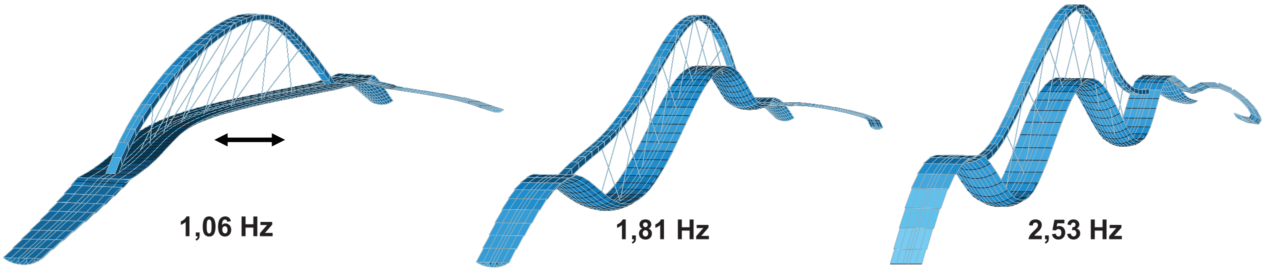
The activities induced by man



DYNAMICS

Frequencies

$$Freq = \frac{1}{2\pi} \cdot \sqrt{\frac{K}{M}}$$

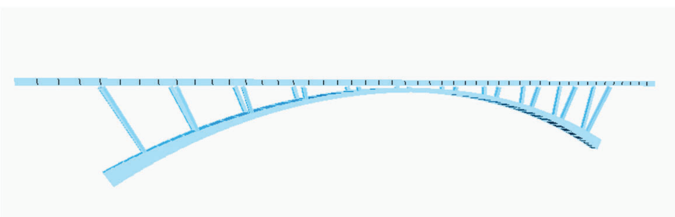


DYNAMICS

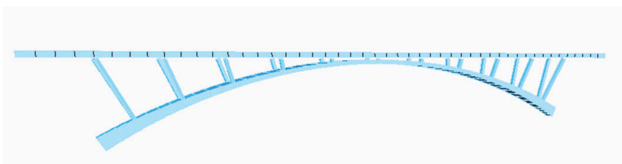
Frequencies

$$Freq = \frac{1}{2\pi} \cdot \sqrt{\frac{K}{M}}$$

0,63 Hz



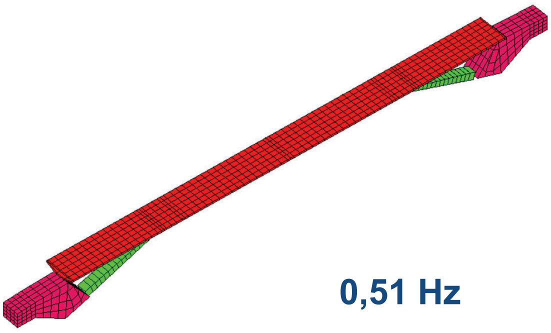
0,77 Hz



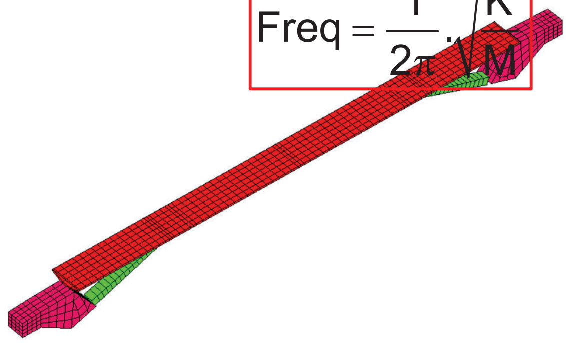
DYNAMICS

Frequencies

$$Freq = \frac{1}{2\pi} \cdot \sqrt{\frac{K}{M}}$$



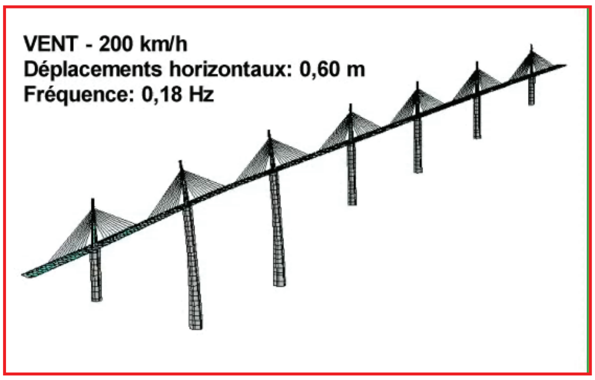
0,51 Hz

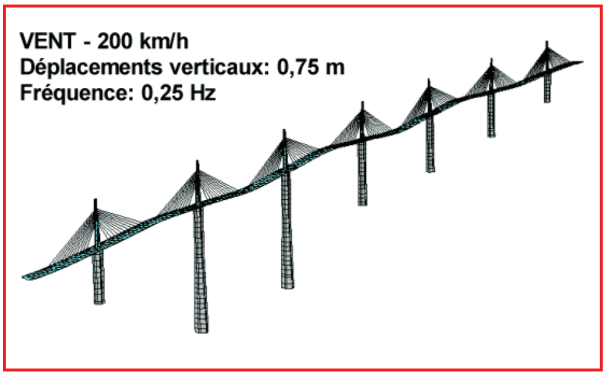


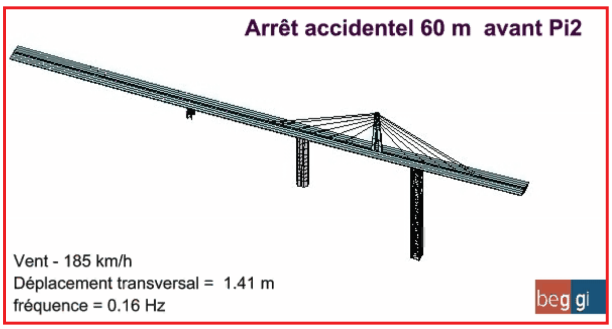
0,78 Hz

DYNAMICS

Frequencies







Simple estimation of frequencies

$$(K-\omega^2 M).\phi = 0$$

$$K.d = M.g \quad with \;\; g = gravity$$

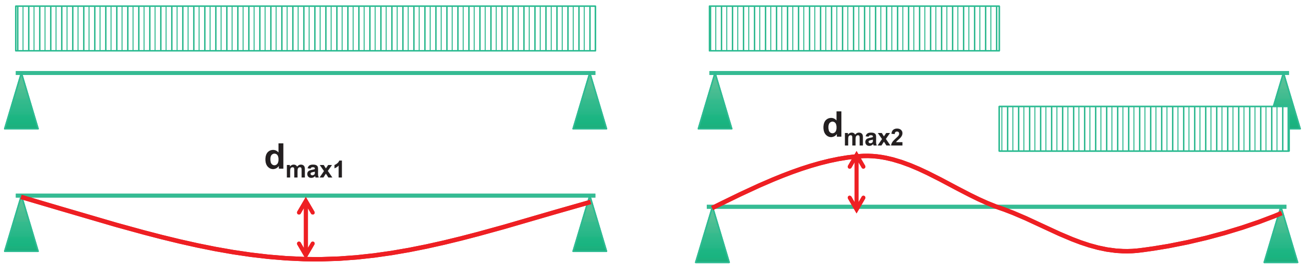
$$K = \frac{M.g}{d_{max}} \quad with \; d_{max} = \max.deflection$$

$$-->$$

$$\left(\frac{M.g}{d_{max}} - \omega^2 M\right) = 0 \quad and \quad \boxed{frequency = \frac{1}{2\pi}.\sqrt{\frac{g}{d_{max}}}}$$

Frequencies of « classical briges »
0,2 → 0,5..1,0 Hz

Dead load= M.g | **In the same direction as the mode shape**



d_{max1} → freq1 | **d_{max2} → freq2**

Frequencies and vibration modes

The best solution

- for the **verification of the FEM model** !!
- for the **comparison between the loading tests** (after the construction) **and the model**

WHY ?

It is the best tool for the evaluation of the global behaviour of the structure

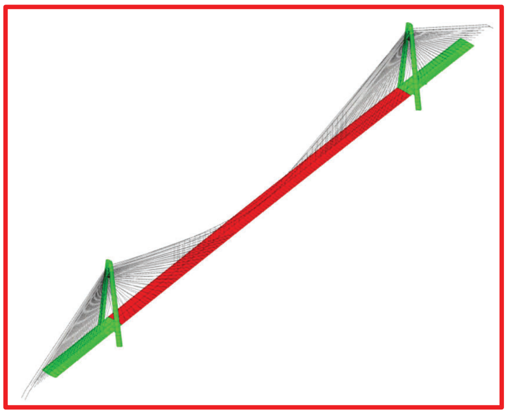
For the loading tests, a comparison of the stresses with strain gages on one point
- of the built structure
- and of the FEM model is too complicate.

Frequencies of « classical briges »
0,2 → 0,5..1,0 Hz

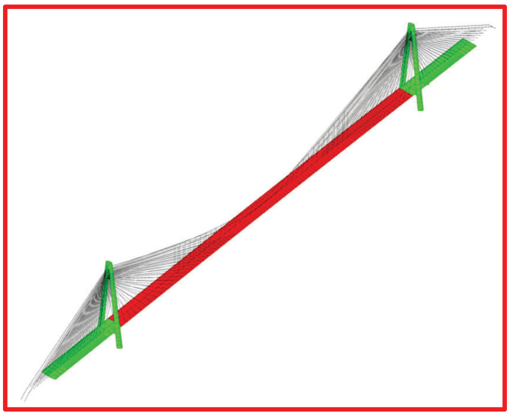
BRIDGE - Service

- Eigen modes

Frequencies

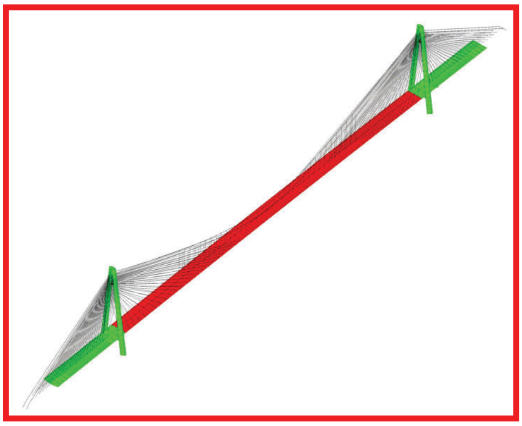


0,094 Hz
(mode 1)



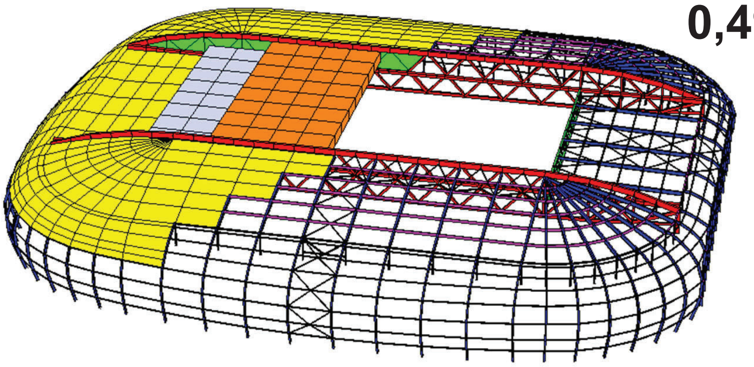
0,166 Hz
(mode 2)

0,300 Hz
(mode 11)

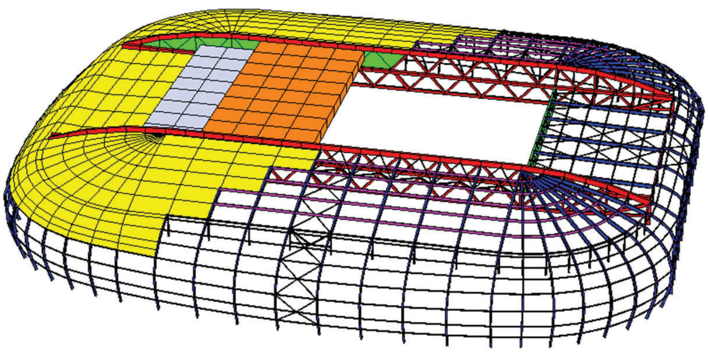


0,49 Hz

Frequencies



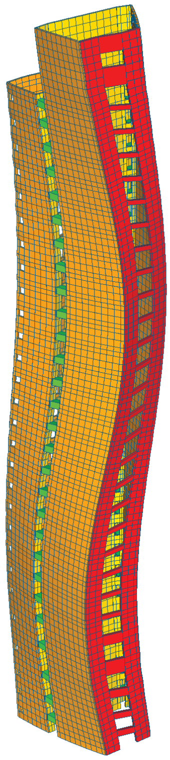
0,52 Hz



29

DYNAMICS

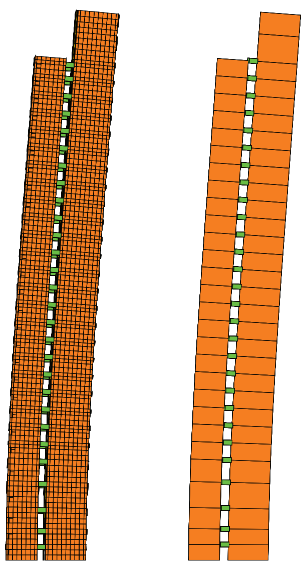
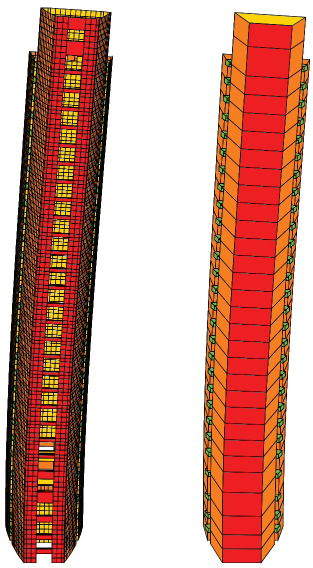
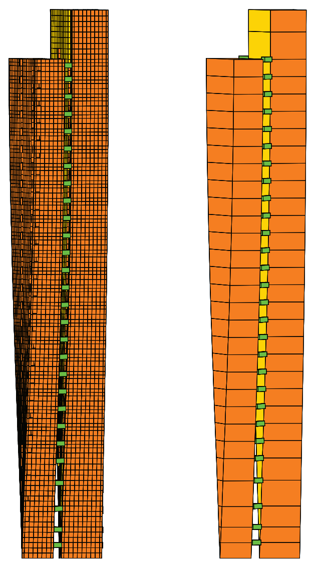
Frequencies



30

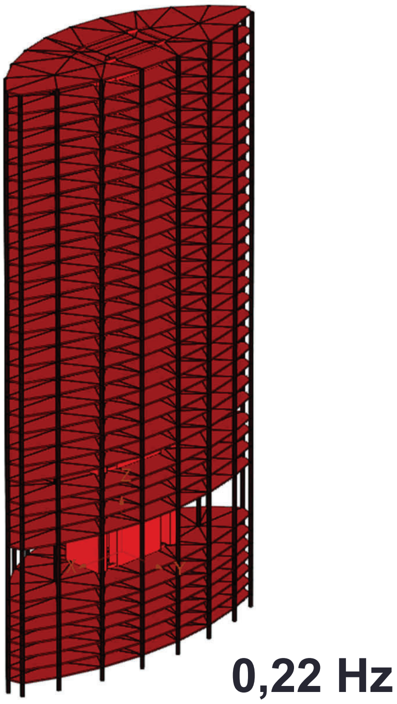
DYNAMICS

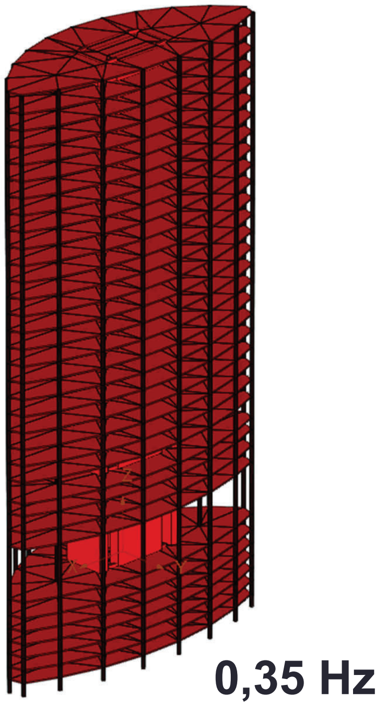
Frequencies

mode propre 1		mode propre 2		mode propre 3	
					
$n_1 = 0.361$Hz	$n_1 = 0.367$Hz	$n_2 = 0.372$Hz	$n_2 = 0.371$Hz	$n_3 = 0.765$Hz	$n_3 = 0.717$Hz
$\Delta = 1.66\%$		$\Delta = 0.27\%$		$\Delta = 6.27\%$	

DYNAMICS

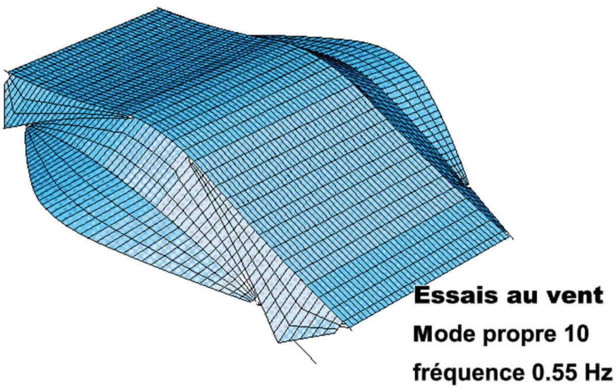
Frequencies

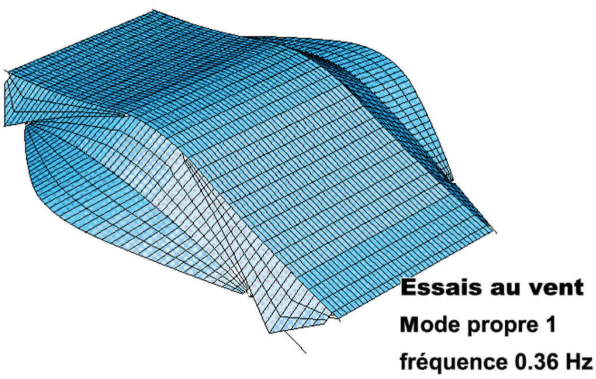




DYNAMICS

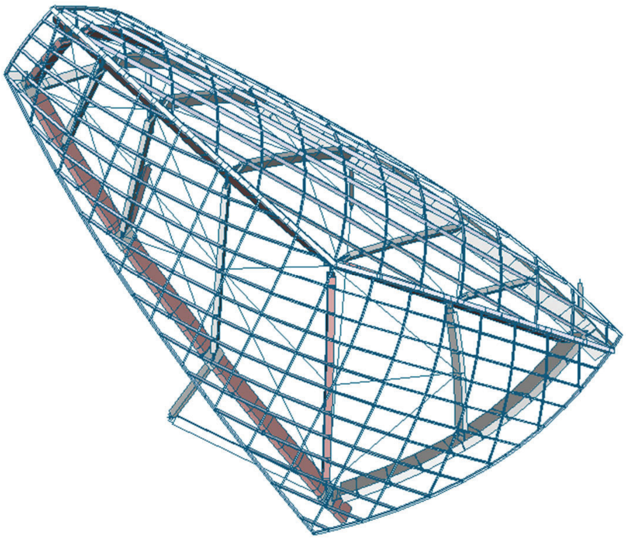
Frequencies



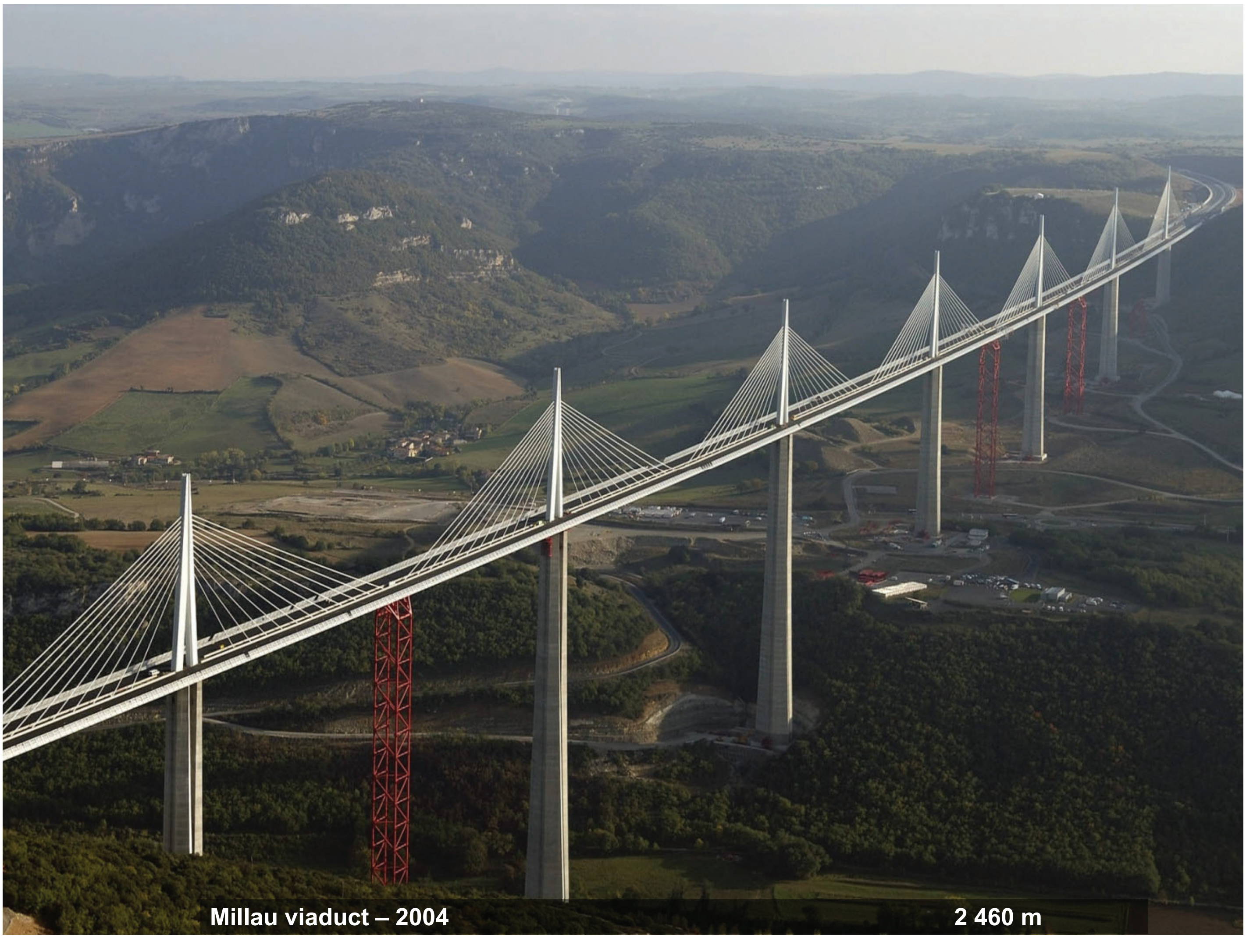


DYNAMICS

Frequencies



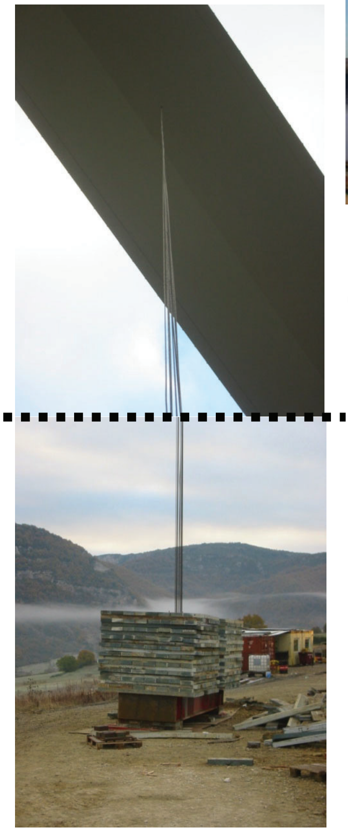
2,5 Hz



Millau viaduct – 2004 2 460 m

DYNAMICS

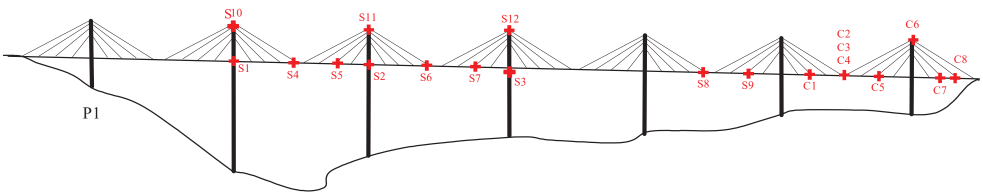
Nature
Wind



Rupture of cable
➔ impact effect : dynamics

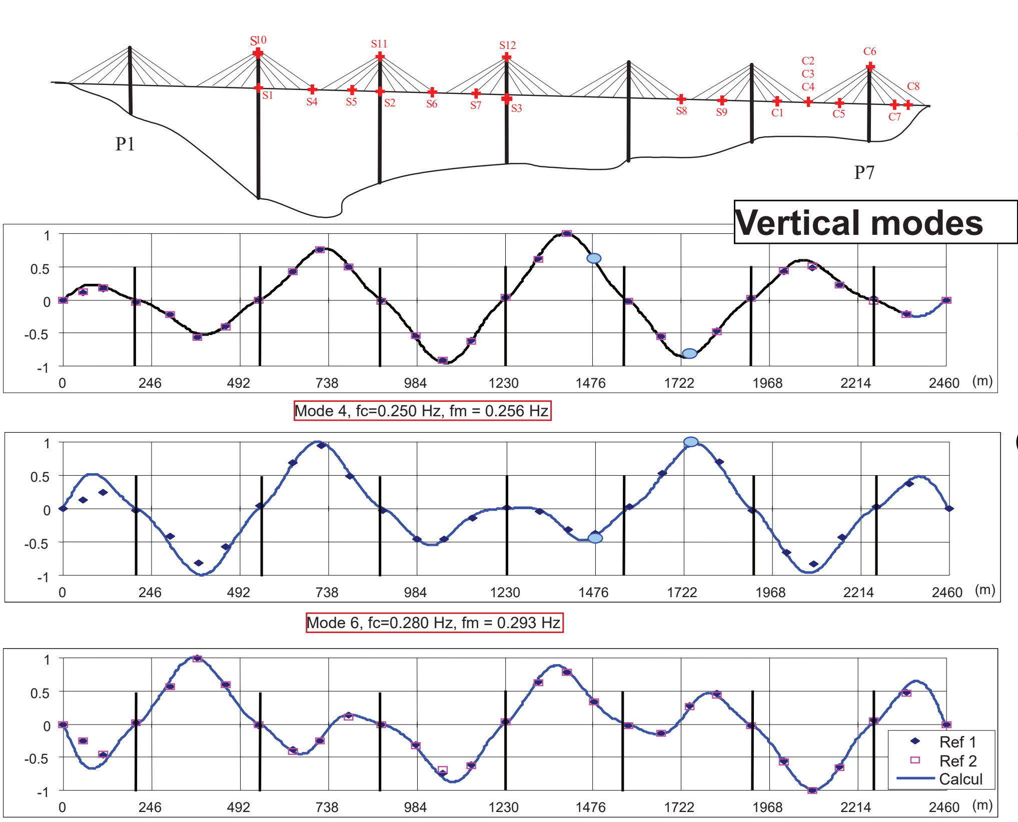
➔ **Identification of vibration modes**
➔ **verification of computation**

Dynamics
=
verification



DYNAMICS

Nature
Wind



Mode 4, fc=0.250 Hz, fm = 0.256 Hz

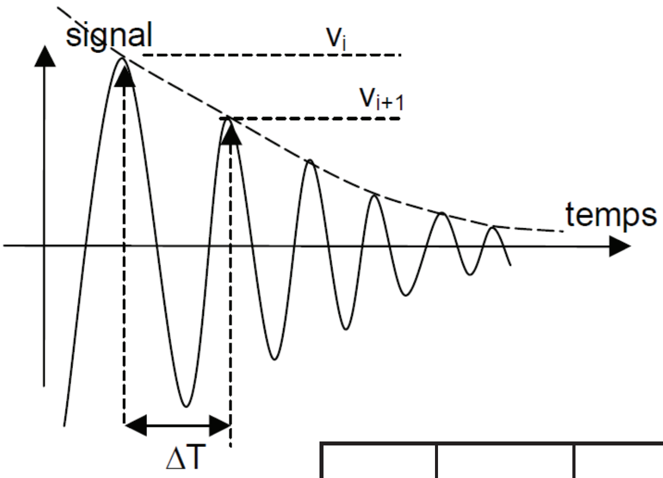
Mode 6, fc=0.280 Hz, fm = 0.293 Hz

Mode 8, fc=0.321 Hz, fm =0.336 Hz

computation
measurements

Dynamics = verification

25 measured modes : differences, 2 to 10 % !



ΔT= 1 / fréquence du mode

$\zeta_{structurel} = 1/2\pi \,.\, \log (v_i / v_{i+1})$

mode	fréquence (Hz)	amortissement moyen (% du critique)
4	0.260	0.36
6	0.299	0.43
8	0.336	0.79
10	0.386	0.51
12	0.433	0.75
15	0.493	0.68
17	0.546	0.53
21	0.603	0.38
26	0.654	0.44
28	0.707	0.35
29	0.747	0.48
34	0.812	0.51
36	0.832	0.30

Dynamics					Impact
MAN		NATURE			
trains cars	pedestrians	wind	earthquake	wave	

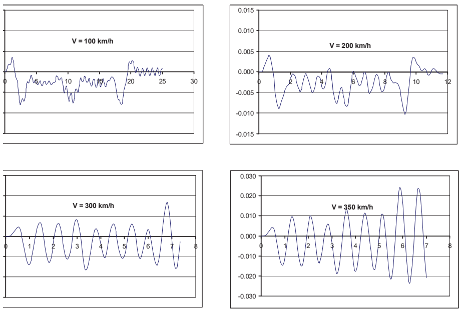
	MAN	NATURE
sollicitations	known ←	random →
criteria	Fatigue safety — confort	← Resistance → confort
theories	psychology Medicinal Science	weather Aerodynamics Wind tunnel — Geology — Hydrodynamics Lab tests
	←	Probabilities →
analyse results	← Time steps →	← Spectral analysis → ← non concommitants - large quantiies of results →
solutions	←	Dampers →

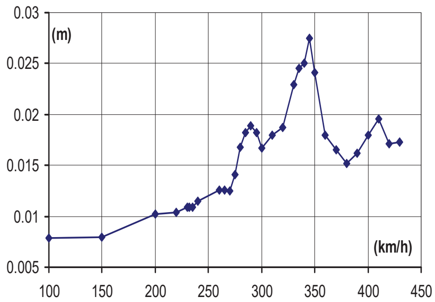
41

MAN		NATURE		
trains cars	pedestrians	wind	earthquake	wave

Railway viaducts …

greisch

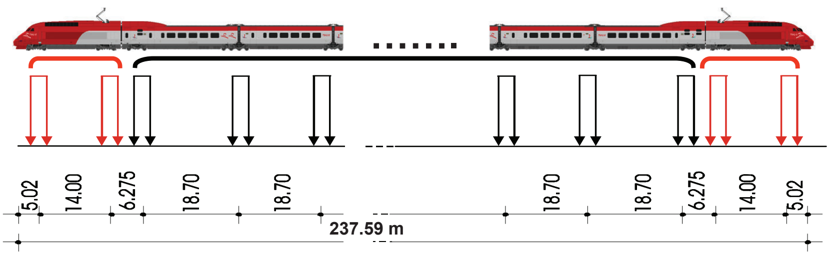




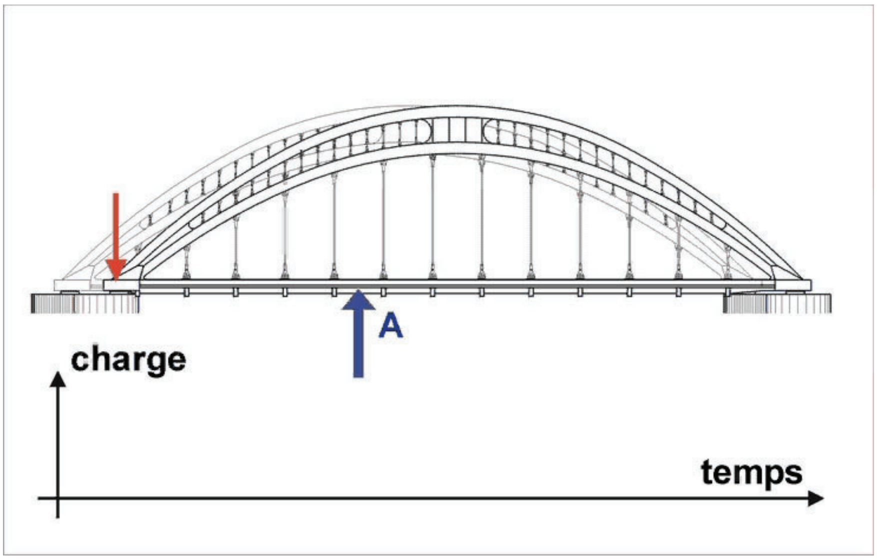
DYNAMICS

MAN
Trains - cars

DYNAMICS

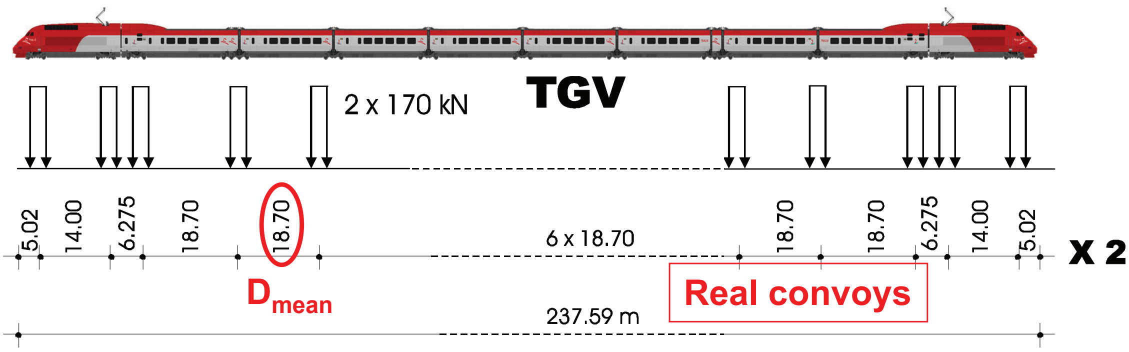


MAN
Trains - cars



FATIGUE

SAFETY

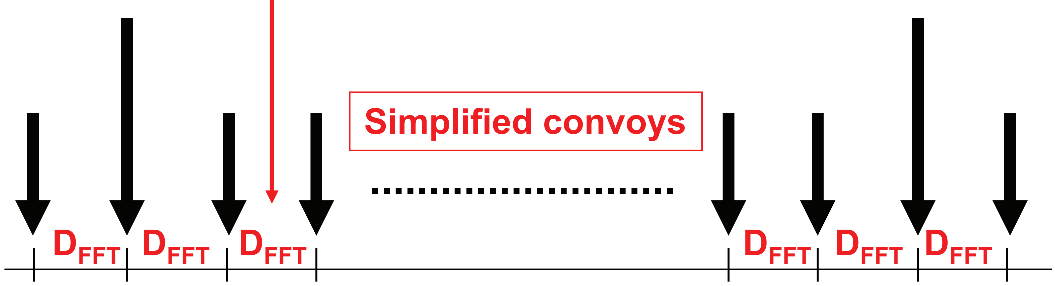


$$Time = D_{FFT} / V_{train}$$

$$V_{train} = D_{FFT} / Time$$

$$1/Time = Frequency$$

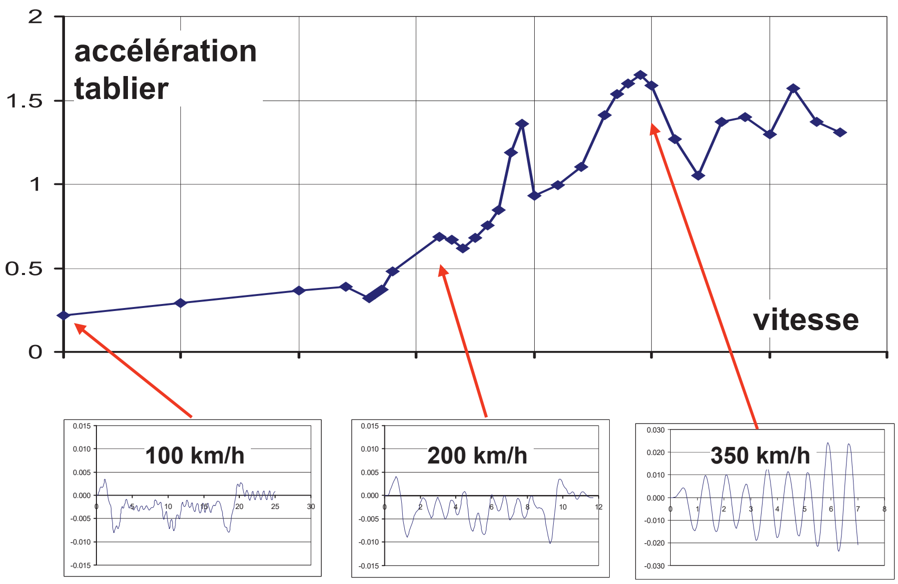
IF $V_{train} = D_{FFT}$ x Frequency of bridge → V_{cr}



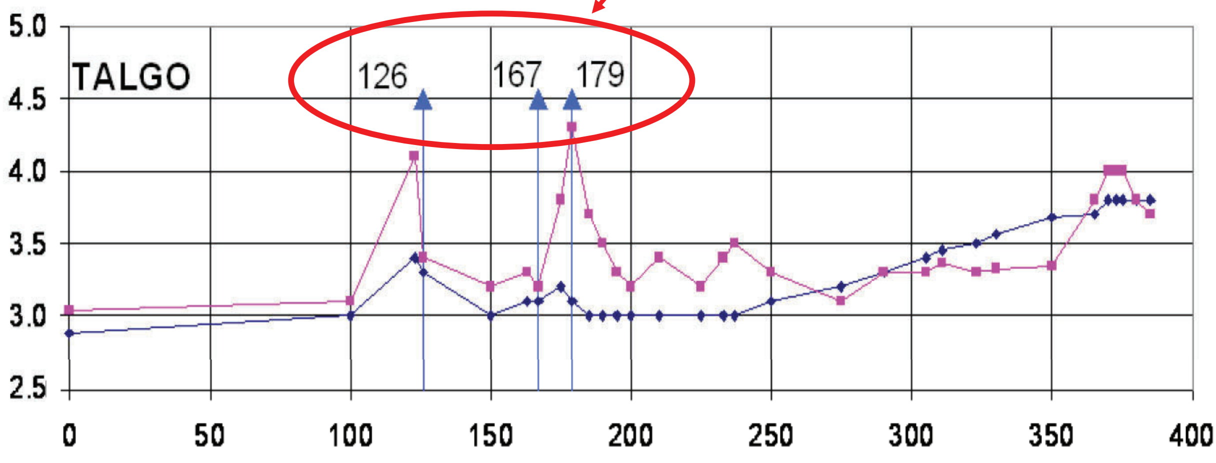
Structure: linear behaviour

Response: NO proportionnal !!

MAN
Trains - cars



Convoi	ETR	ETR 460	Eurostar	ICE2	ICE3	Talgo	TGV	Thalys	Virgin
D_{convoi} (m)	26,10	28,60	19,50	26,40	24,78	13,10	18,70	18,70	23,90
Fr (Hz)	**Critical speed (km/h)**								
2,65	249	273	179	252	237	126	179	179	228
3,53	332	363	238	335	315	167	238	238	304
3,78	355	389	254	359	337	179	254	254	325
5,02	472	517	338	477	448	237	338	338	432
6,58	619	678	443	626	587	311	443	443	567



CRITERIA

- Fatigue !!

- Vertical displacements

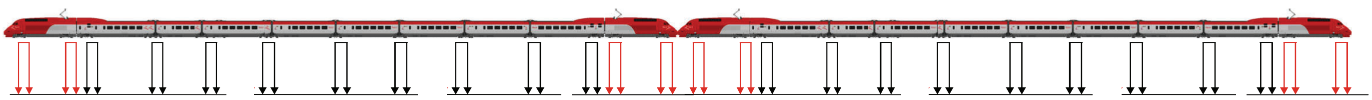
- **< 1/1000 à 350 km/h if isostatic, L < 100m**
- **< L/1600 à 350 km/h if continuous , Li < 100 m**

- vertical acceleration < 0,35 g

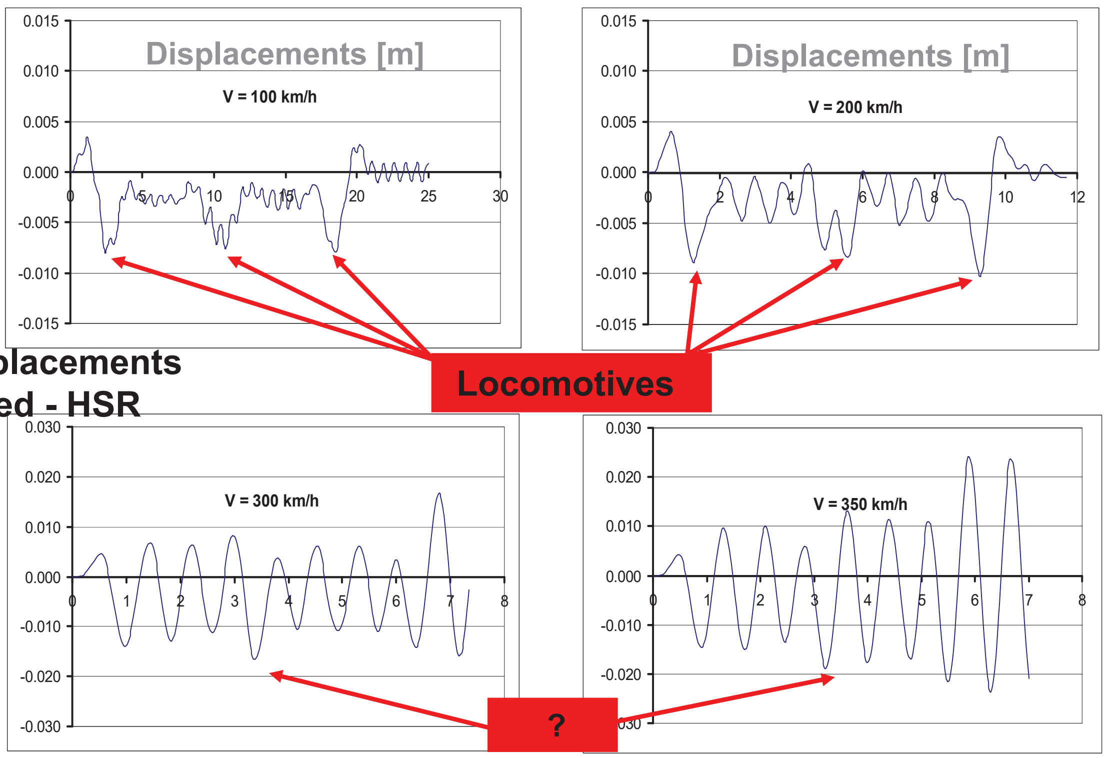
- rotations at end bearings < 2,0 x 10^{-3} /H radians

if H= distance
between the upper surface of the deck
and rotation axle of the bearing

- limitation of the dynamic warping: 1,2 mm on 3 m



Vertical displacements several speed - HSR

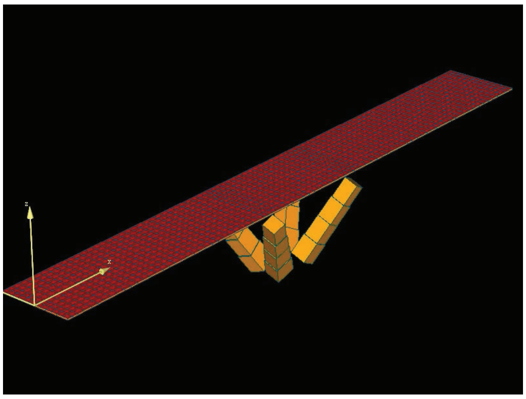


DYNAMICS

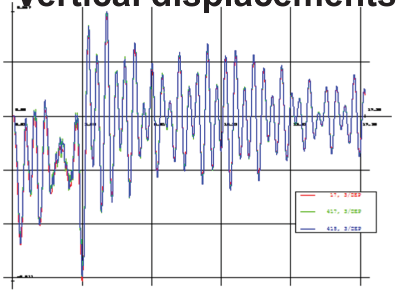
Response: not possible to understand

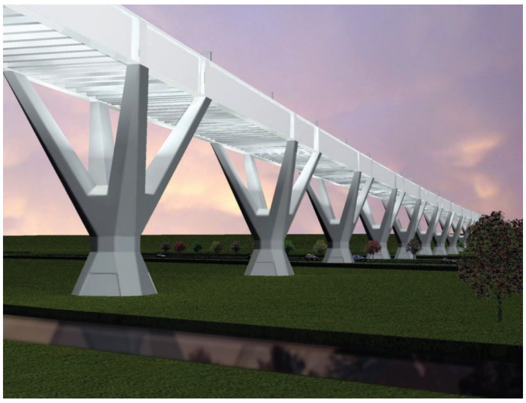
Necessity: MATHEMATIC TOOLS

MAN
Trains - cars



Vertical displacements



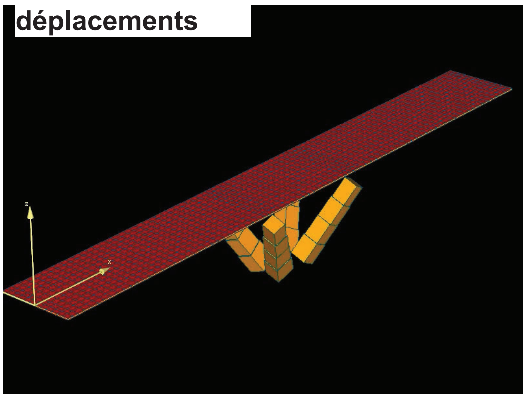


DYNAMICS

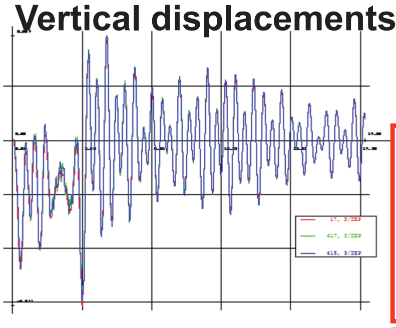
Réponse: illisible

Nécessité: OUTILS MATHEMATIQUES

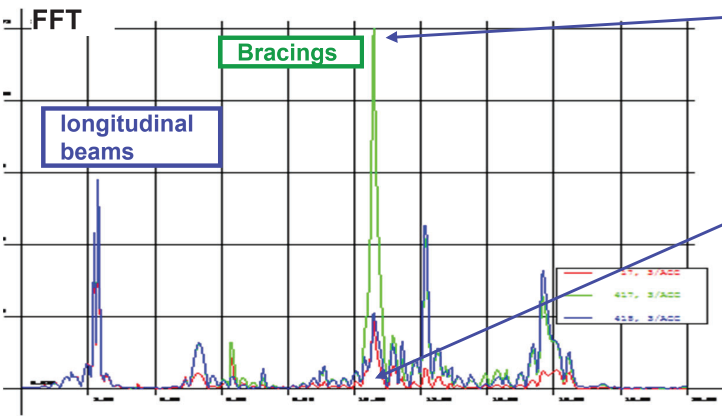
MAN
Trains - cars



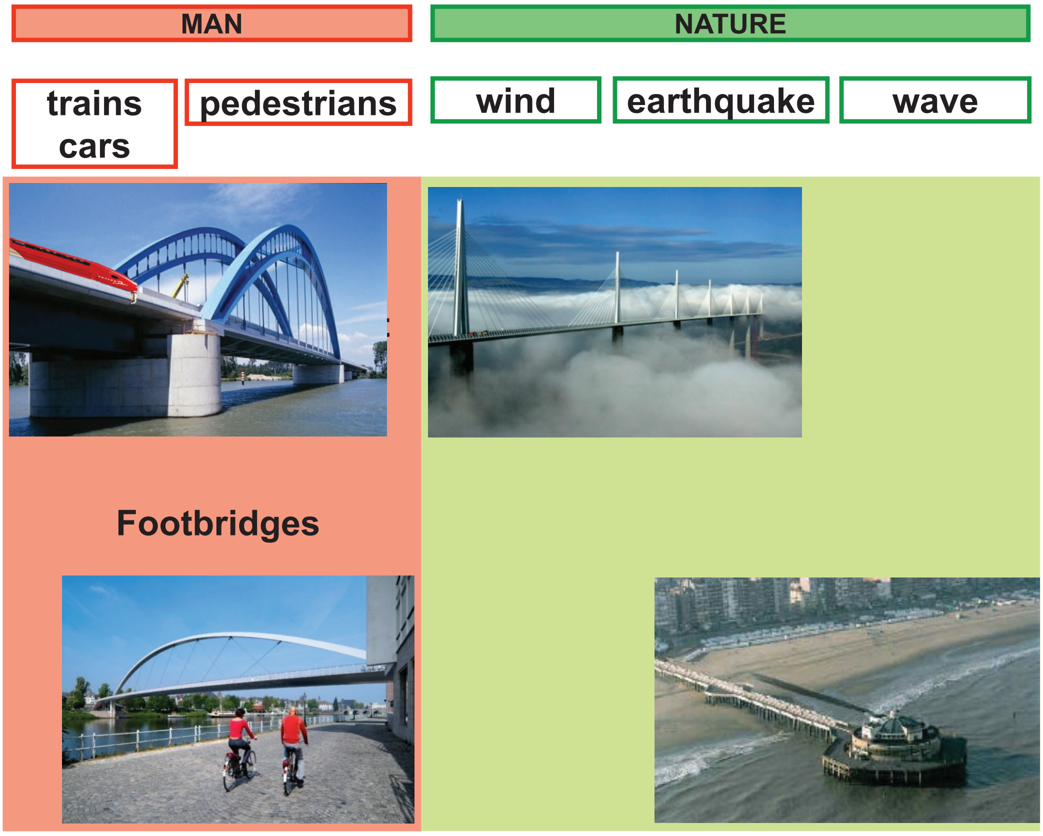
Vertical displacements



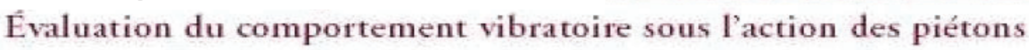
FFT:
➔
Response (t)=
$\Sigma_i A_i \text{sinus}(2\pi.\text{fréq}_i t)$



= bracing beams
➔
IDEA for the DESIGN



Footbridges - pedestrians



FOOTBRIDGES

Variety of design

FOOTBRIDGES

Variety of design

FOOTBRIDGES

Variety of design


Passerelle des Trois Pays sur le Rhin

FOOTBRIDGES

Variety of design


DURBUY

CONCEPTION

•Système statique

Bowstring arc unique

ACCESSIBILITE

•Rampe, marches, ascenceur

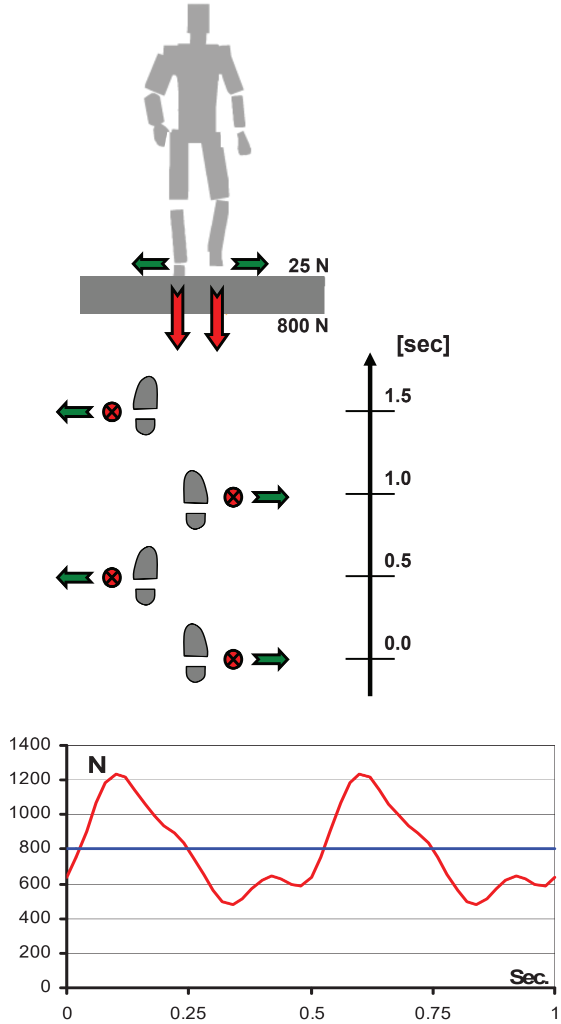
DYNAMICS

Men
Pedestrians

Sollicitations

~~Determinist~~

Random



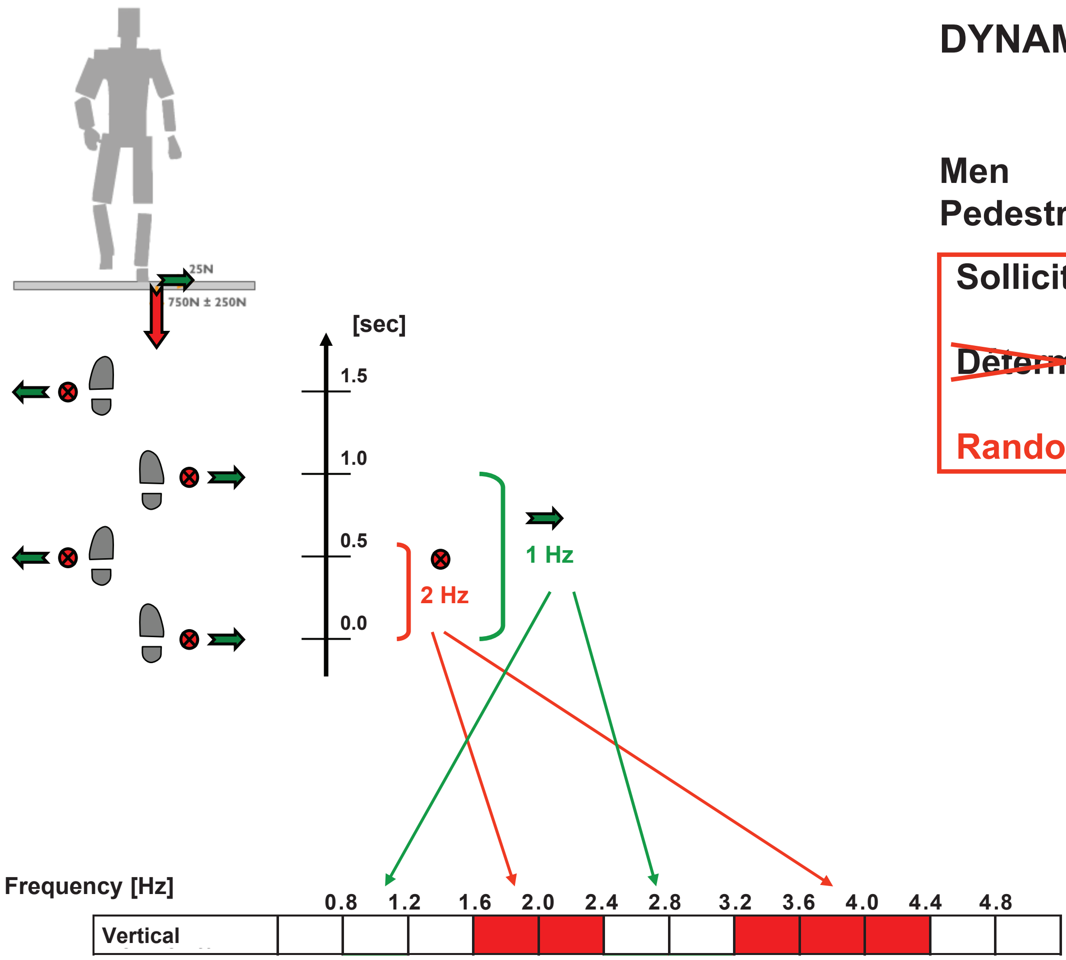
DYNAMICS

Men
Pedestrians

Sollicitations

~~Determinist~~

Random



DYNAMICS

Men
Pedestrians

A crowd

Transversal modes : 0,50 < freq. < 1,5 Hz ➔ risk of divergence
« Millenium » effect
Vertical modes (+ torsion): 1,3 Hz < freq. < 2,2 Hz ➔ unconfortable

DYNAMICS

Men
Pedestrians

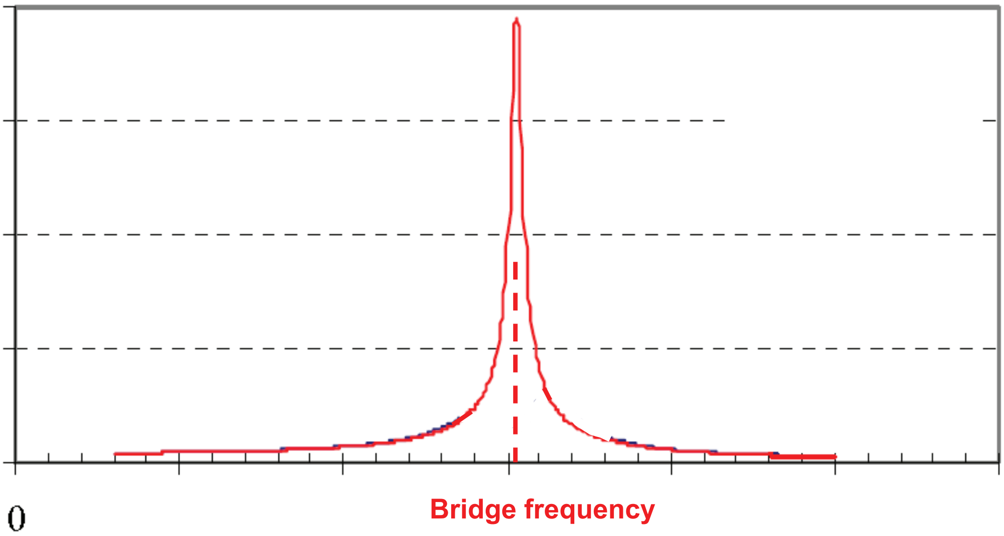
Ah ! Efficient vandals !

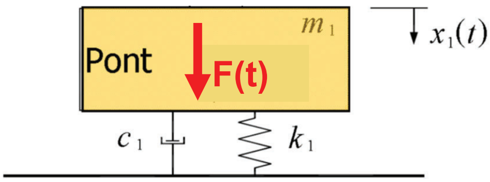
Vandals, their hands in the pockets!

Transversal modes : 0,50 < freq. < 1,5 Hz ➔ risk of divergence
« Millenium » effect
Vertical modes (+ torsion): 1,3 Hz < freq. < 2,2 Hz ➔ unconfortable

DYNAMICS

Men
Pedestrians





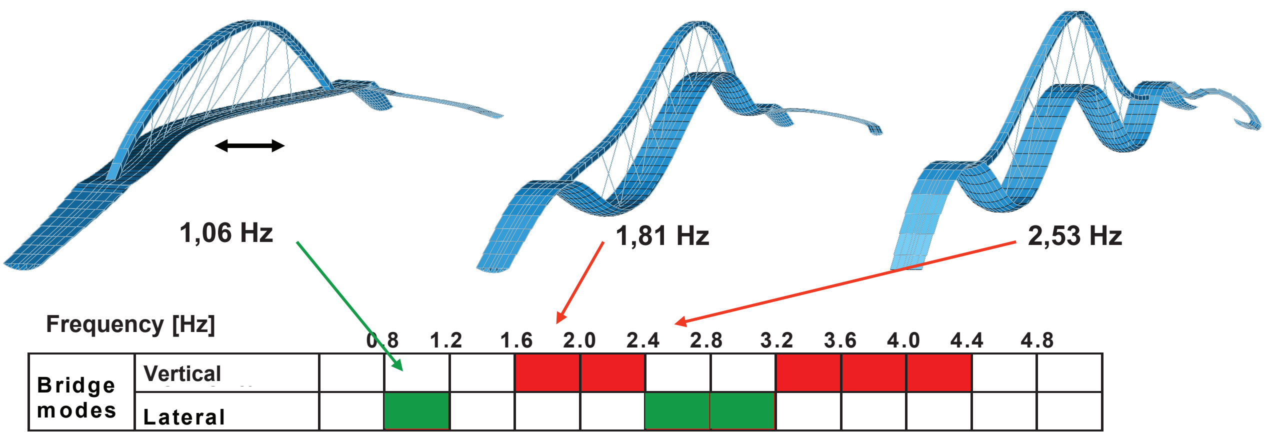
DYNAMICS

Men
Pedestrians

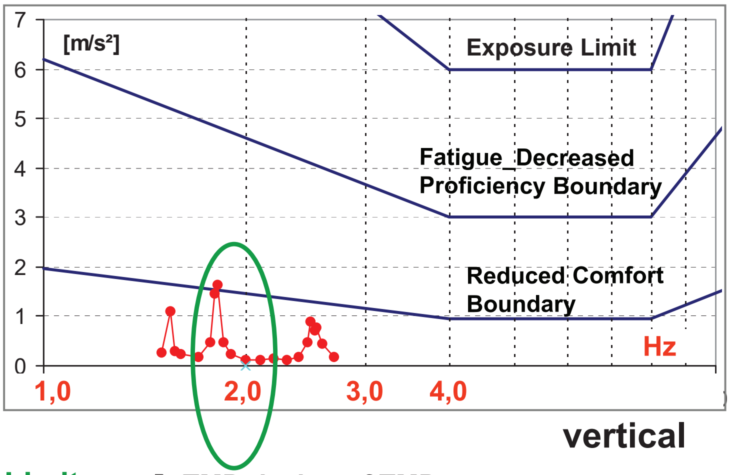
Sollicitations

~~Determinist~~

Random



DYNAMICS



vertical

Men
Pedestrians

Sollicitations

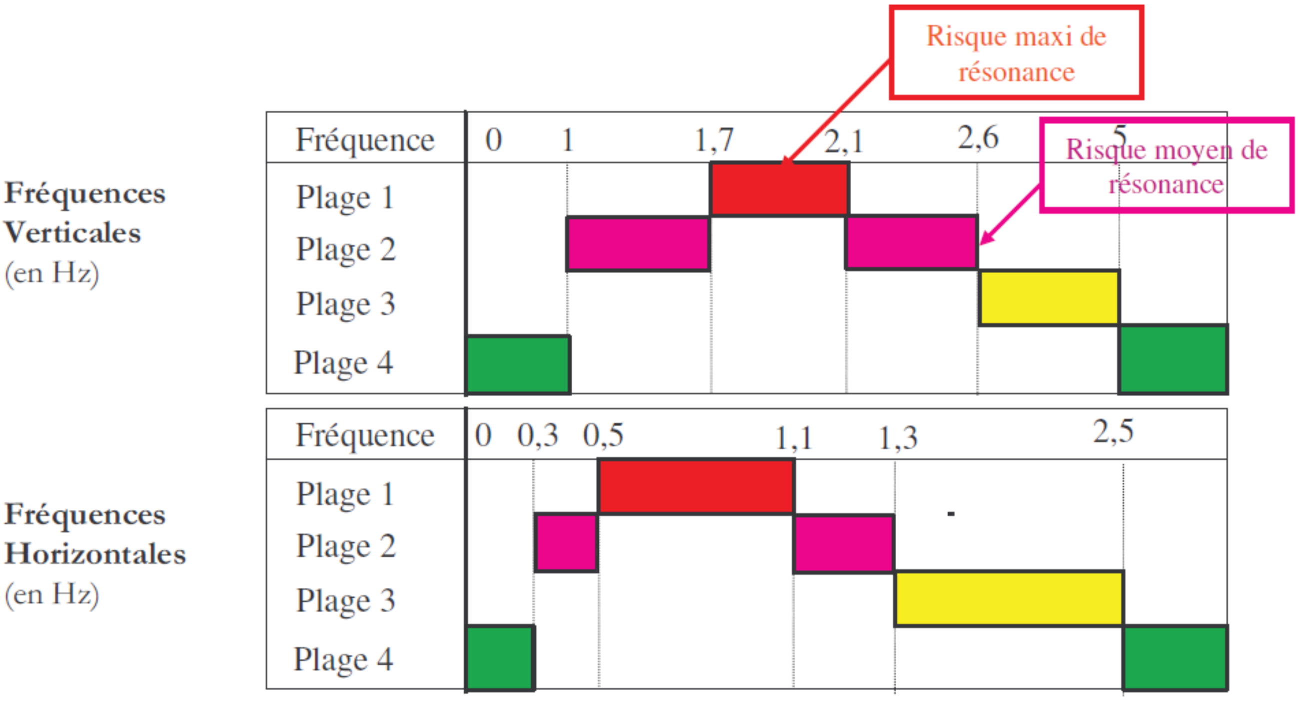
~~Determinist~~

Random

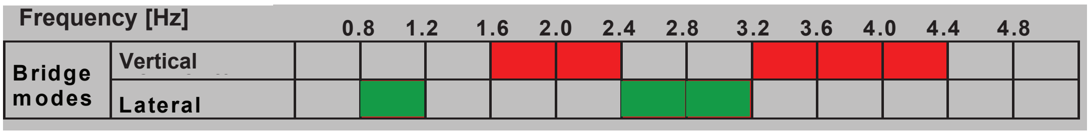
Limit
- → TMD design of TMD
- → tests in situ
- → decision for the damping level

SETRA Recommandations

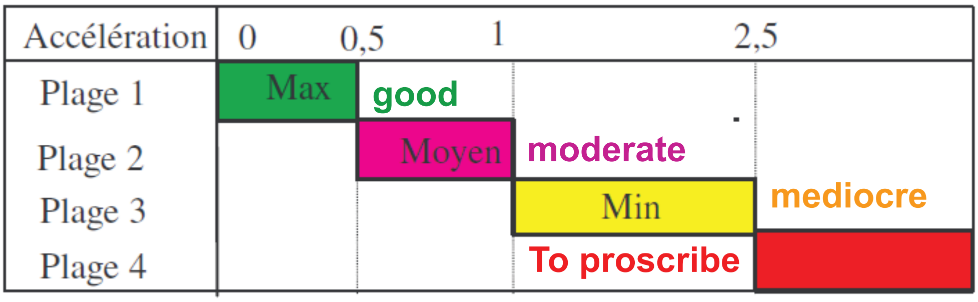
Frequency [Hz]		0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6	4.0	4.4	4.8
Bridge modes	Vertical											
	Lateral											



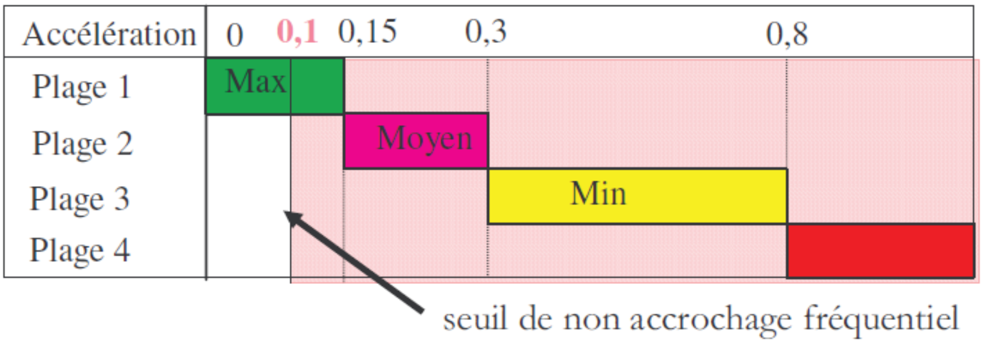
SETRA Recommandations



Accélérations Verticales (m/s^2)



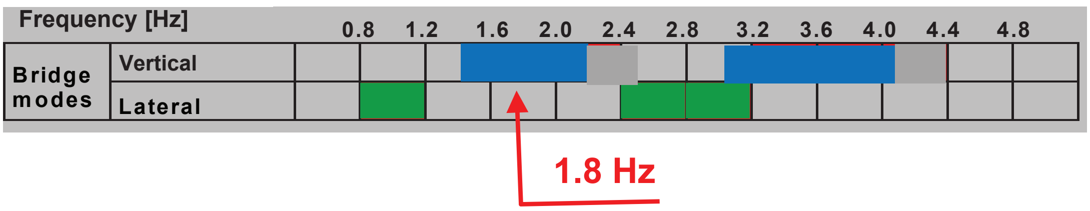
Accélérations Horizontales (m/s^2)



3

SETRA Recommandations

HIVOSS – European Researches

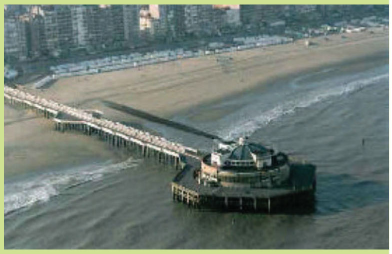


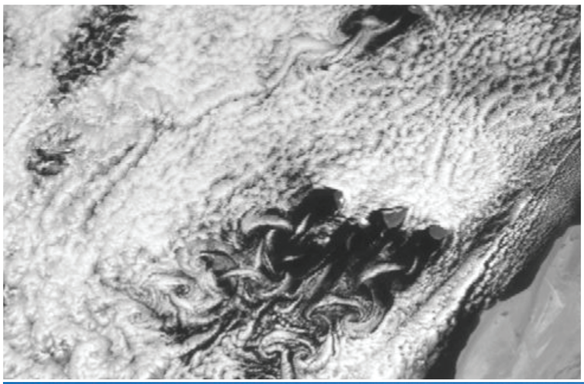
https://www.researchgate.net/publication/256455955_Human-induced_vibration_of_steel_structures_Hivoss

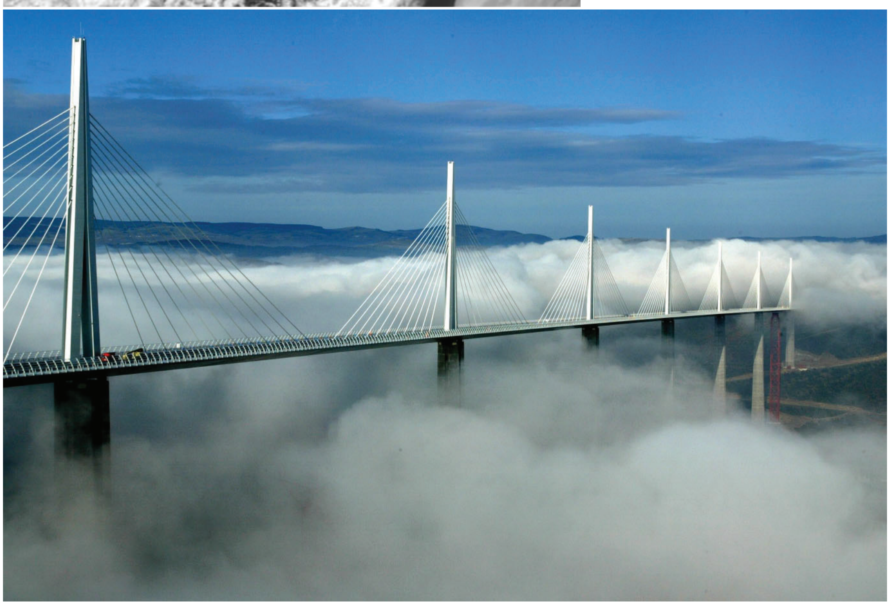
Free access on web

MAN		NATURE		
trains cars	pedestrians	wind	earthquake	wave

Earthquake







DYNAMICS

Nature
Wind

Sollicitations

~~Determinist~~

Random

DYNAMICS

Nature
Wind

Sollicitations

~~**Déterminist**~~

Random

WIND TUNNEL TESTS

- **Wind Assumptions**
  - **speed**
  - **spatial distribution**
  - **time distribution**
- Aerodynamic coefficients
- Aeroelastic stability

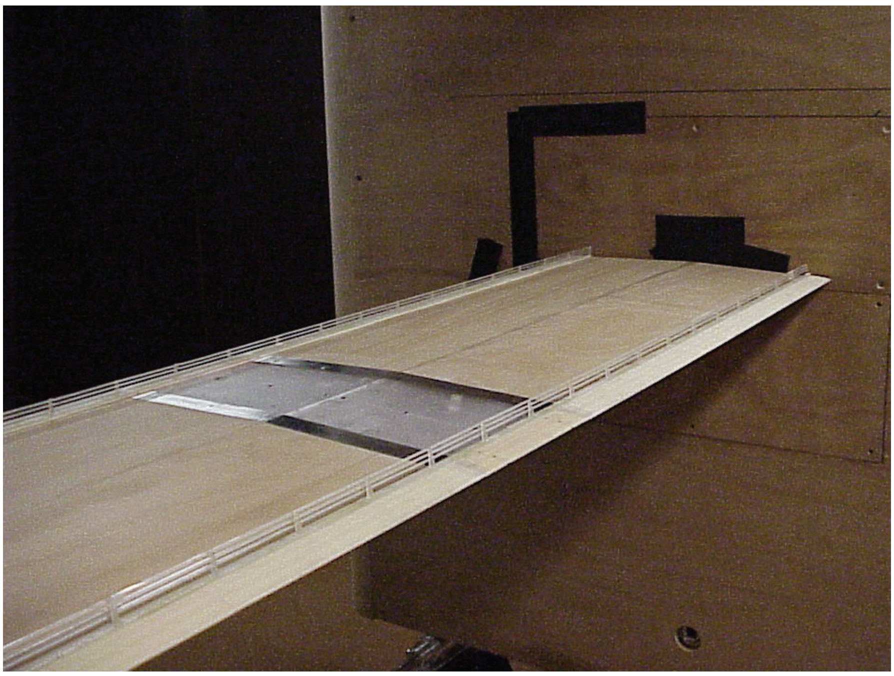
DYNAMICS

Nature
Wind

Sollicitations

~~**Déterminist**~~

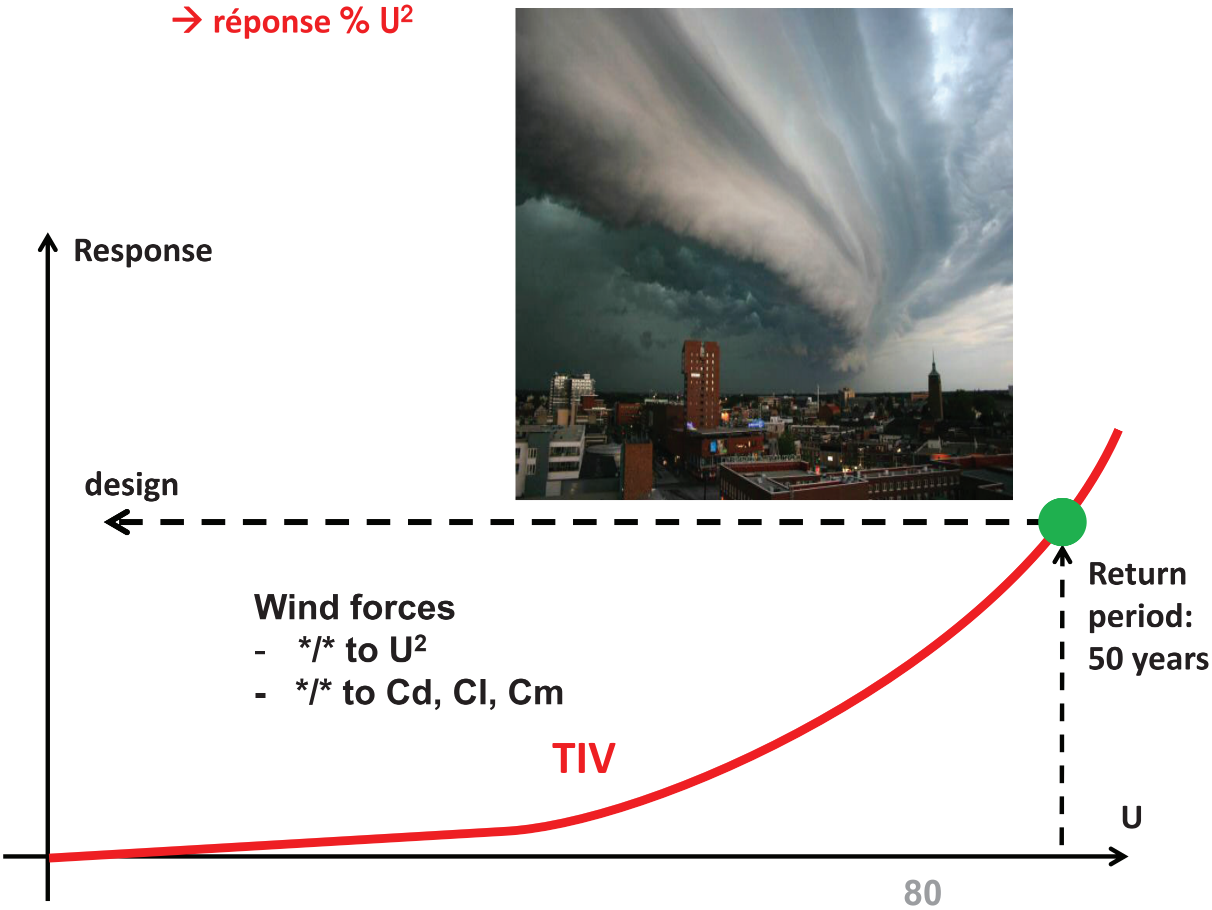
Random



WIND TUNNEL TESTS

- Wind Assumptions
  - speed
  - spatial distribution
  - time distribution
- **Aerodynamic coefficients**
- Aeroelastic stability

TIV: Turbulence Induced Vibrations
→ réponse % U^2



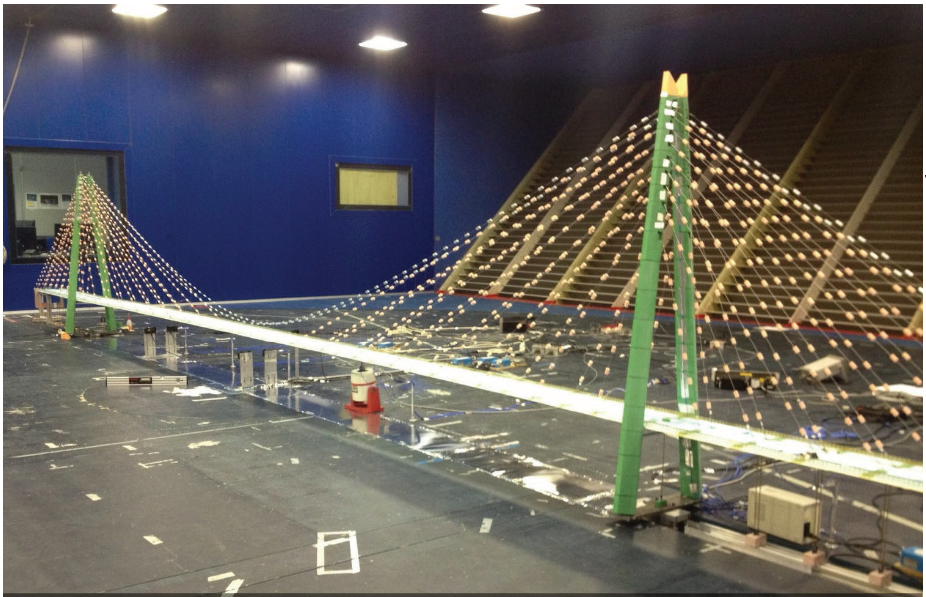
DYNAMICS

Nature
Wind

Sollicitations

~~Determinist~~

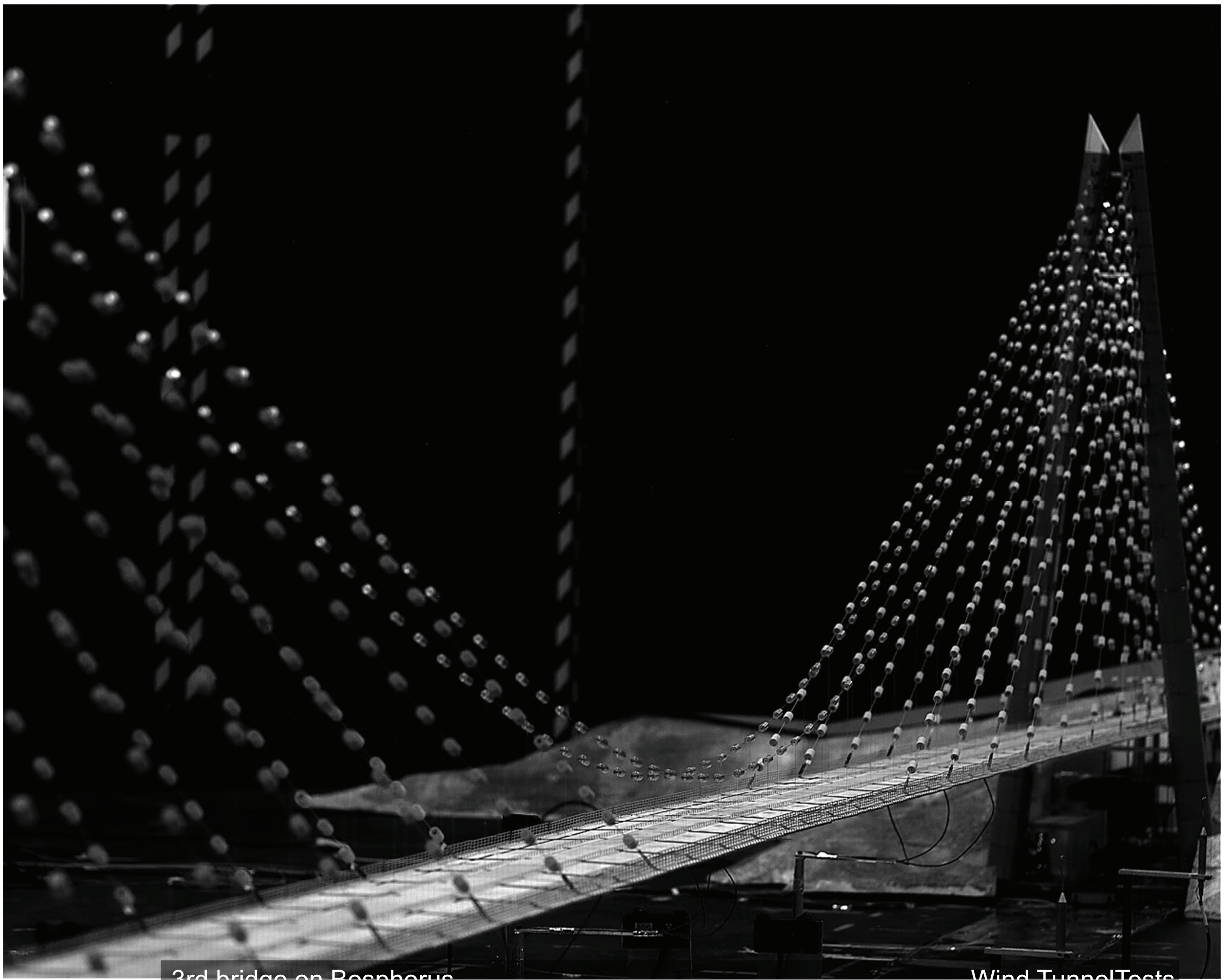
Random



3rd bridge on Bosphorus
TunnelTests

WIND TUNNEL TESTS

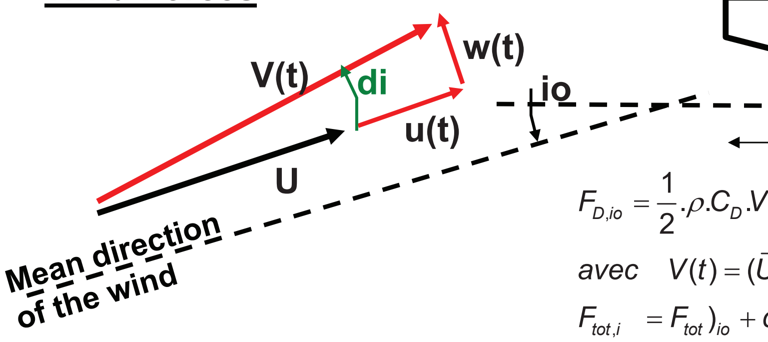
- Wind Assumptions
  - speed
  - spatial distribution
  - time distribution
- Aerodynamic coefficients
- **Aeroelastic stability**

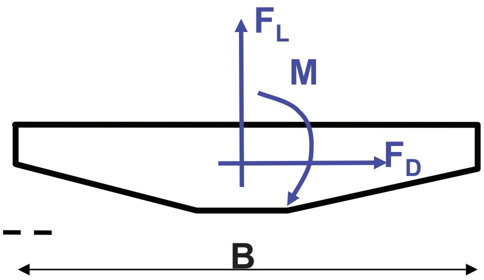


3rd bridge on Bosphorus Wind TunnelTests

TURBULENT WIND

Wind Forces





$$F_{D,io} = \frac{1}{2}.\rho.C_D.V(t)^2.B$$

avec $V(t) = (\bar{U} + u(t))$ et $V(t)^2 = \bar{U}^2 + 2.u(t).\bar{U} + \cancel{u(t)^2}$

$$F_{tot,i} = F_{tot})_{io} + dF_{tot})_{io}.di$$

$$F_{D,i} = \frac{1}{2}.\rho.B.[C_D.V(t)^2 + \tfrac{dC_D}{di})_{io}.V(t)^2.di]$$

$$= \frac{1}{2}.\rho.B.[C_D.V(t)^2 + \tfrac{dC_D}{di})_{io}.V(t)^{\cancel{2}}.\frac{w(t)}{\cancel{V(t)}}]$$

$$= \frac{1}{2}.\rho.B.[C_D.V(t)^2 + \tfrac{dC_D}{di})_{io}.(\bar{U} + \cancel{u(t)}).w(t)]$$

$$F_{D,i} = \frac{1}{2}.\rho.B.[C_D.\bar{U}^2 + C_D.2.u(t).\bar{U} + \tfrac{dC_D}{di})_{io}.\bar{U}.w(t)]$$

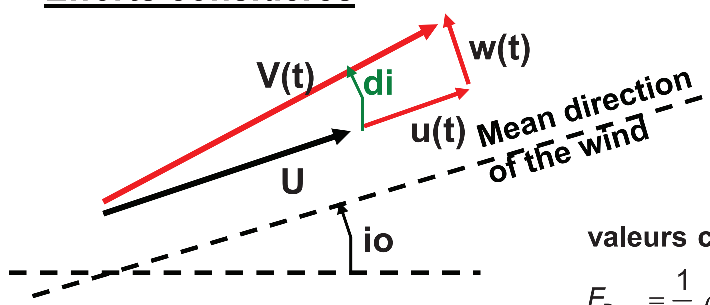
Same for F_L et M

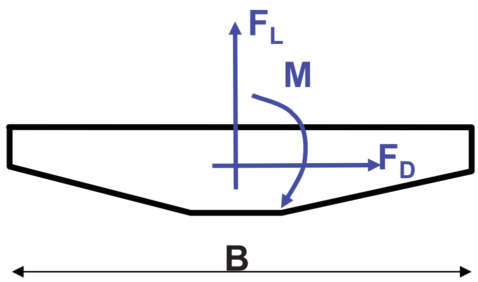
$\Rightarrow$ **caractéristiv values:** $u(t) \rightarrow g.\sigma u \; ; w(t) \rightarrow g.\sigma w$

$$F_{D,i,carac} = \frac{1}{2}.\rho.B.[C_D.\bar{U}^2 + C_D.2.g.\sigma u.\bar{U} + \tfrac{dC_D}{di})_{io}.\bar{U}.g.\sigma w]$$

VENT TURBULENT

Efforts considérés





valeurs caractéristiques

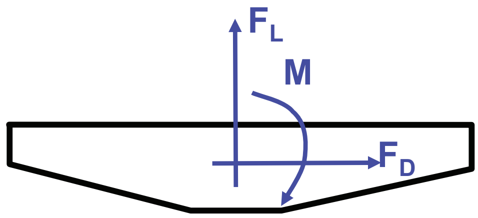
$$F_D = \frac{1}{2}.\rho.B.[C_D.\bar{U}^2 + C_D.2.g.\sigma u.\bar{U} + \tfrac{dC_D}{di})_{io}.\bar{U}.g.\sigma w]$$

$$= \frac{1}{2}.\rho.B.\bar{U}^2.[C_D + \underbrace{C_D.2.g.\frac{\sigma u}{\bar{U}}}_{\text{EC1: OK}} + \underbrace{\tfrac{dC_D}{di})_{io}.g.\frac{\sigma w}{\bar{U}}}_{\text{EC1: NO}}]$$

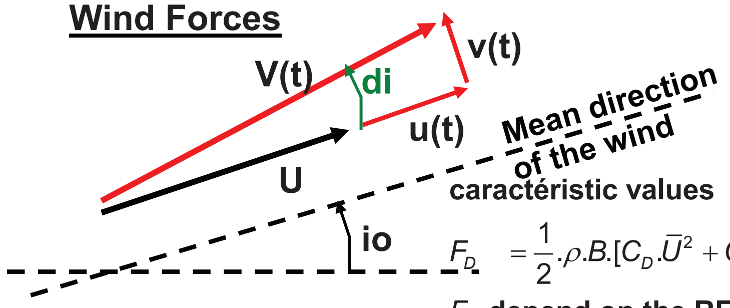
1rst conclusion: EC1 OK, if σw, vertucal turbulence is low

		mean	turbulent σu	turbulent σw
Millau	drag	1,10 t	1,40 t	0,260 t
	lift	0,20 t	0,25 t	3,43 t
Vesdre	drag			
	lift	0,46 t	0,35 t	1,52 t

TURBULENT WIND



Wind Forces



caractéristic values

$$F_D = \frac{1}{2}.\rho.B.[C_D.\bar{U}^2 + C_D.2.g.\sigma u.\bar{U} + (\tfrac{dC_D}{di})_{io}.\bar{U}.g.\sigma w]$$

F_D depend on the RELATIVE wind speed

versus the structure speed

$\Rightarrow F_D$ */* $(\bar{U} + u(t) - \dot{X}(t))^2$

in the relation of the wind forceweon change

$2.g.\sigma u$ by $2.(g.\sigma u - \dot{X})$

$$\Rightarrow F_D = \frac{1}{2}.\rho.B.[C_D.\bar{U}^2 + C_D.2.(g.\sigma u - \dot{X}).\bar{U} + (\tfrac{dC_D}{di})_{io}.\bar{U}.g.\sigma w]$$

$$F_D = \frac{1}{2}.\rho.B.[C_D.\bar{U}^2 + C_D.2.g.\sigma u.\bar{U} + (\tfrac{dC_D}{di})_{io}.\bar{U}.g.\sigma w] - (\rho.C_D.B.\bar{U}.\dot{X})$$

and the term

$$-\rho.C_D.B.\bar{U}.\dot{X}$$

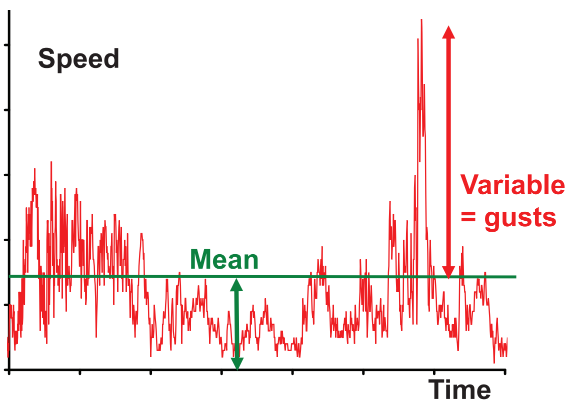
has the negative sign. It is the inverse of the wind forces and */* to $\dot{X}$

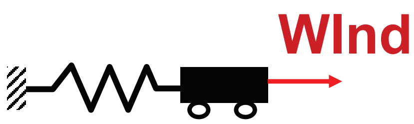
It can be considered as an aerodynamic damping

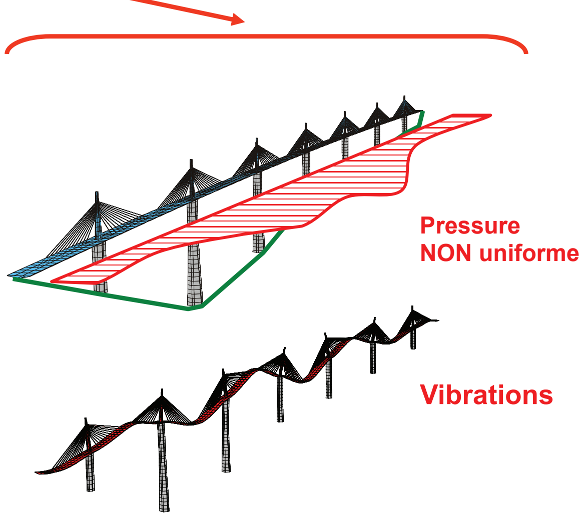
DYNAMICS

Nature
Wind

MILLAU

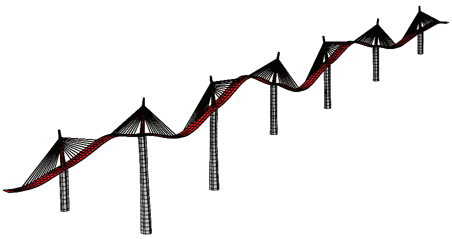


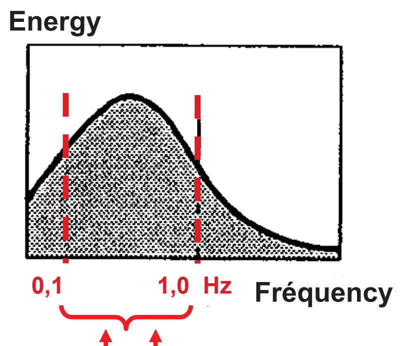




DYNAMICS

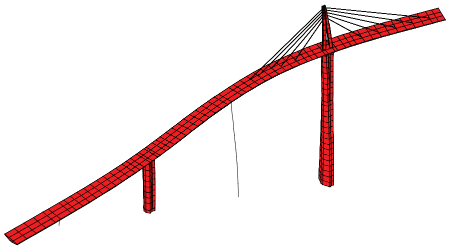
Nature
Wind





SERVICE

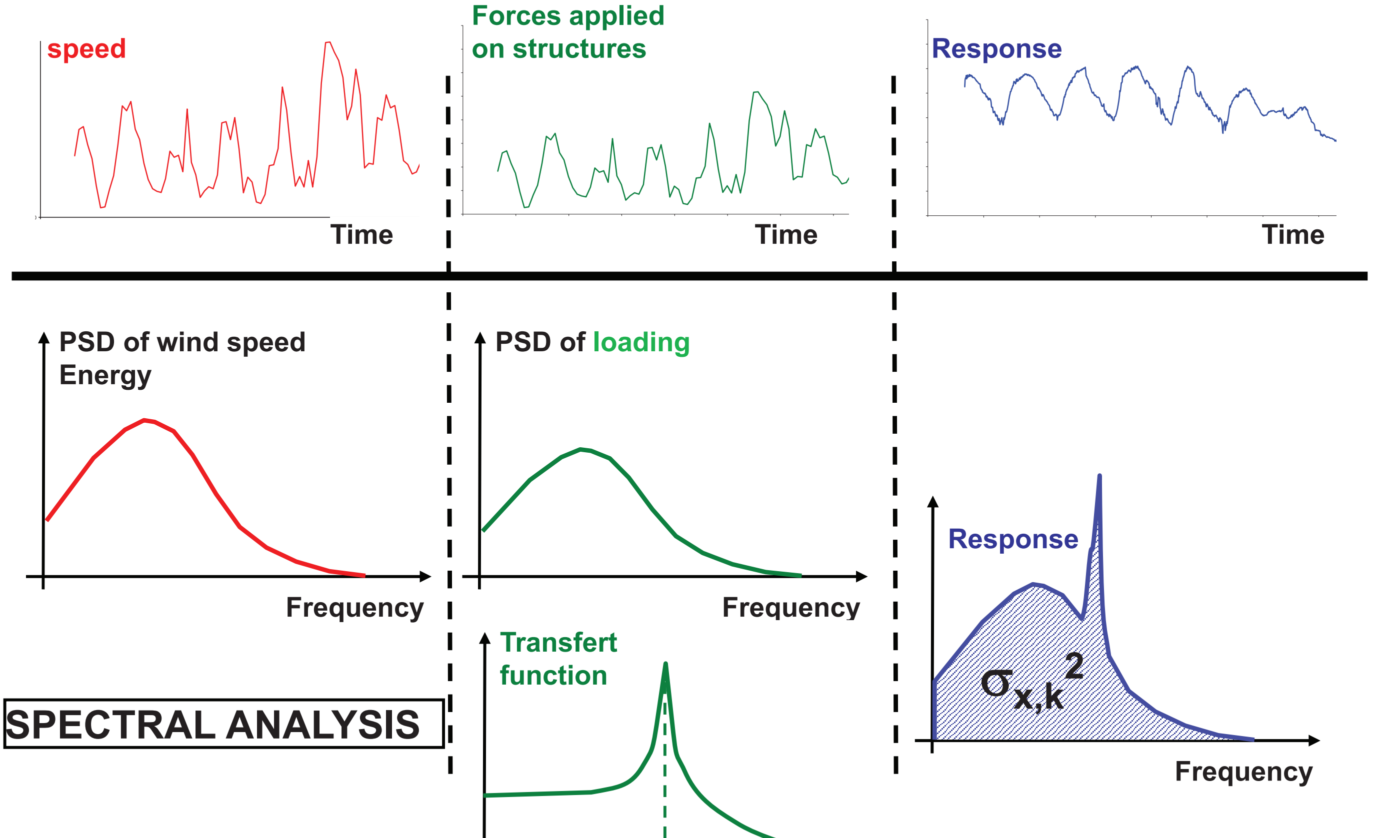
40^{rst} modes: 0,19 - 1,0 Hz
Transversal bending: 0,19 Hz
Vertical bending: 0,25 Hz



CONSTRUCTION STEPS

Transversal bending : 0,16 Hz
Vertical bending : 0,35 Hz

Turbulet wind



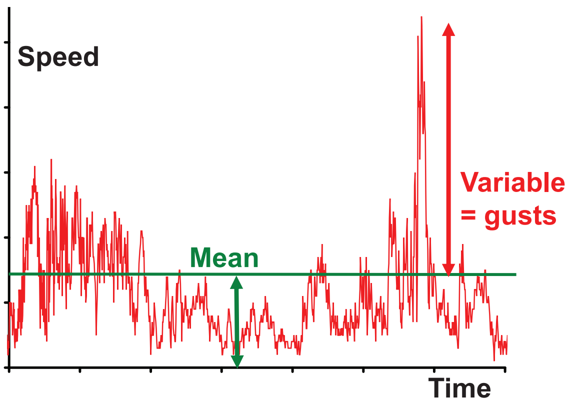
SPECTRAL ANALYSIS

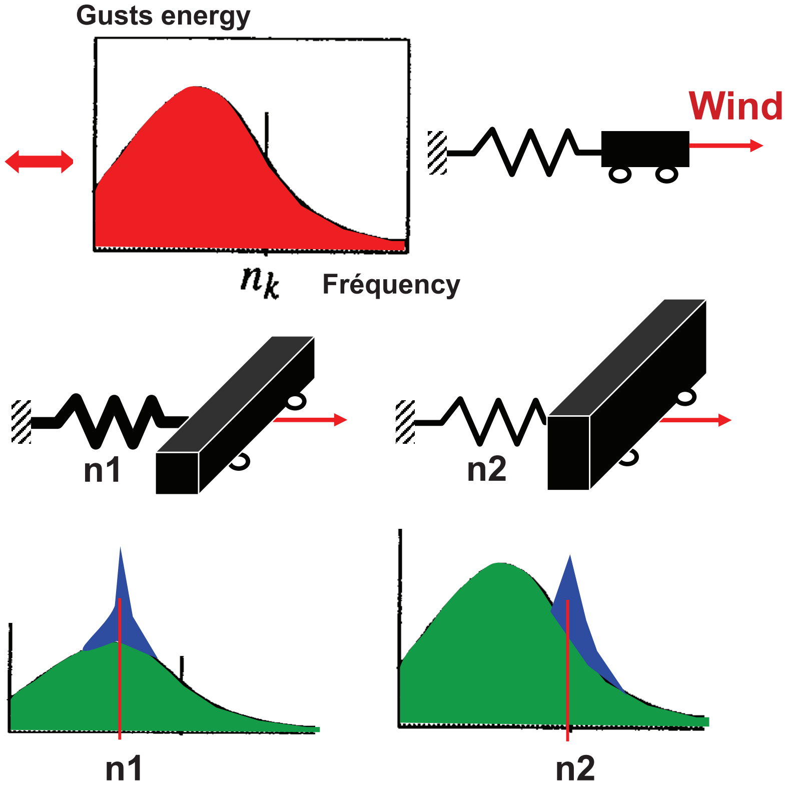
$$H_k(n) = \frac{1}{[16\pi^4 m_k(-n^2 + n_k^2)^2 + 4n^2 n_k^2 \xi_{tot}^2}$$

DYNAMICS

Nature
Wind

“Large” Structures

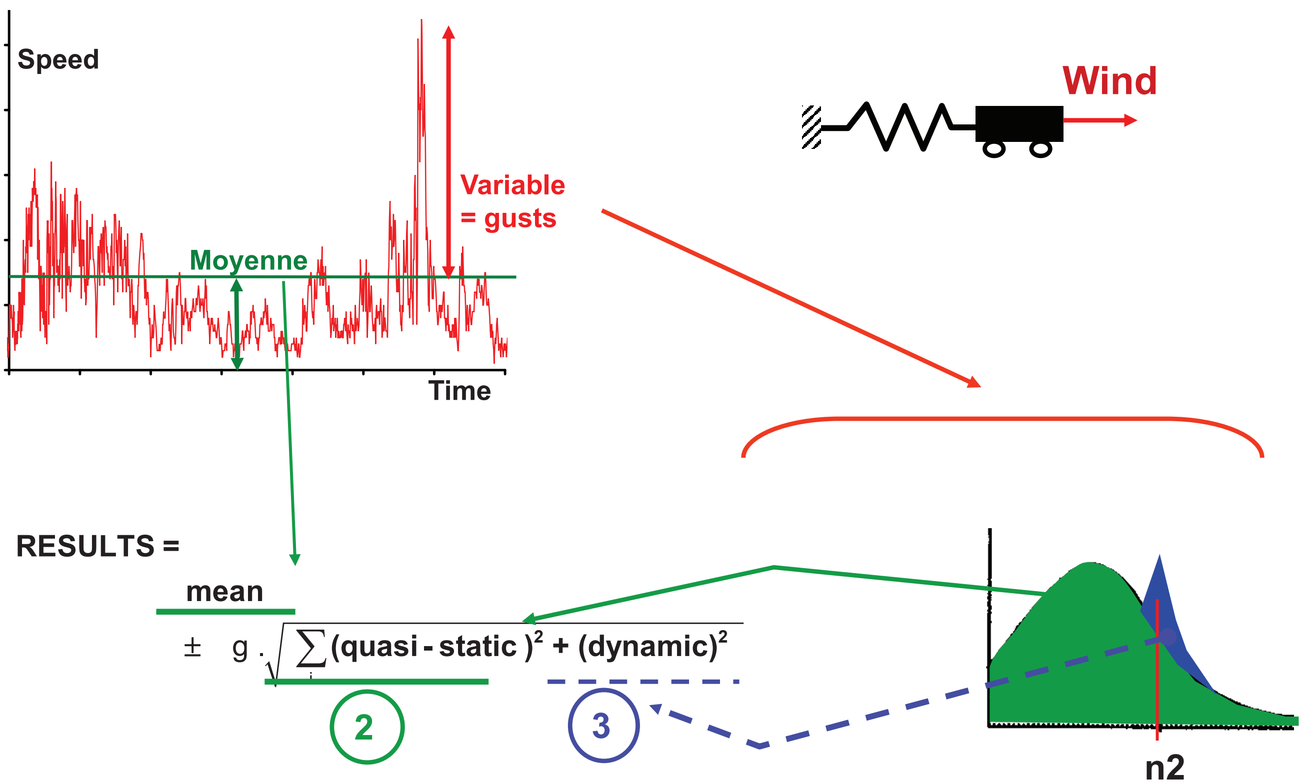




DYNAMICS

Nature
Wind

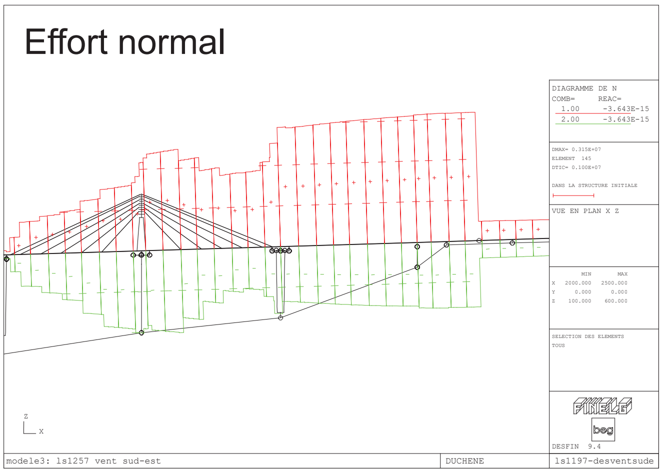
“Large” Structures

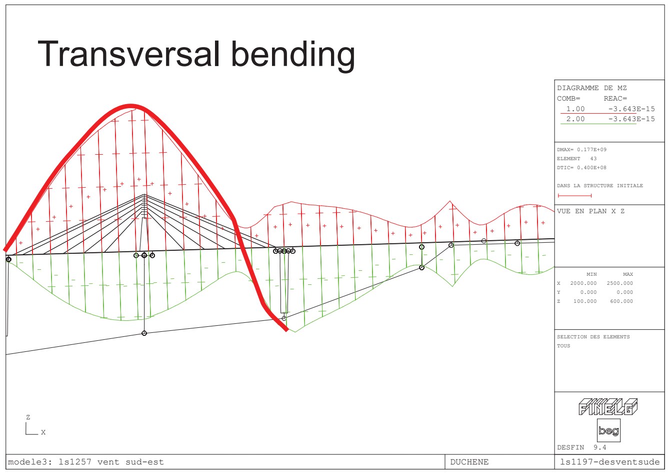


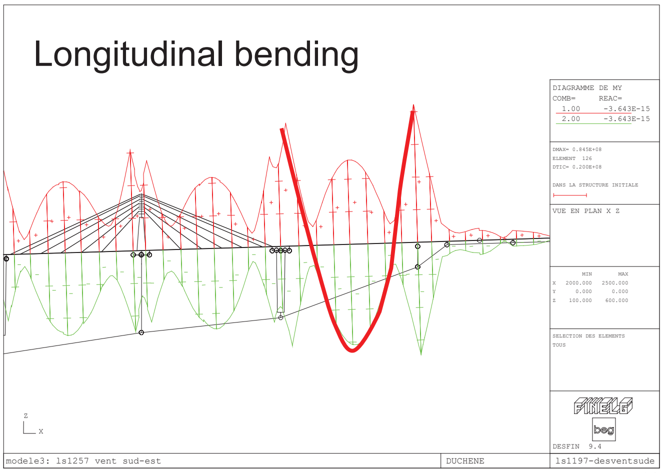
MILLAU viaduct

Results:

mean ± g.σ



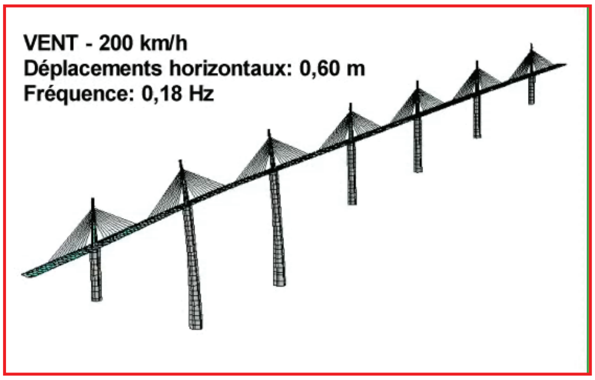


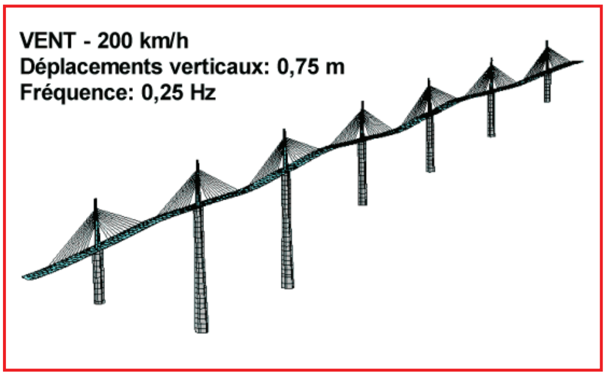


DYNAMICS

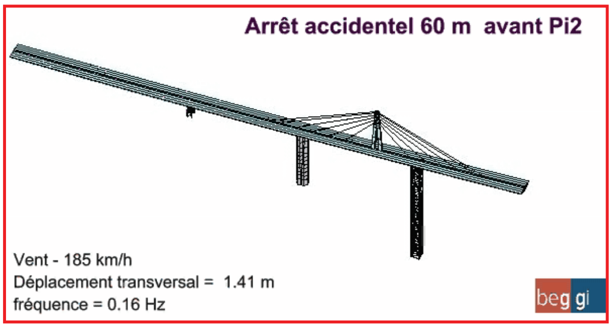
Nature
Wind

Caractéristics	**SERVICE**	**CONSTRUCTION**
Wind speed	**205 km/h**	**185 km/h**
return period	**50 years**	**10 yeras**
Life duration	**120 years**	**2 years**
Deck		***vertical loading***
Drag	**1,25 t/m**	**wind= 25 % total**
Lift	**3,50 t/m**	

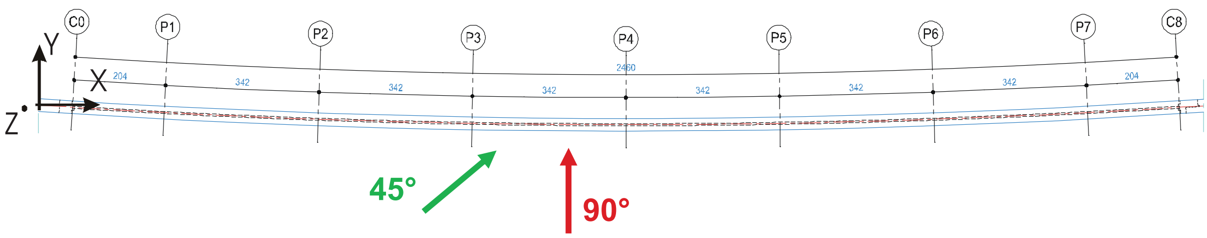




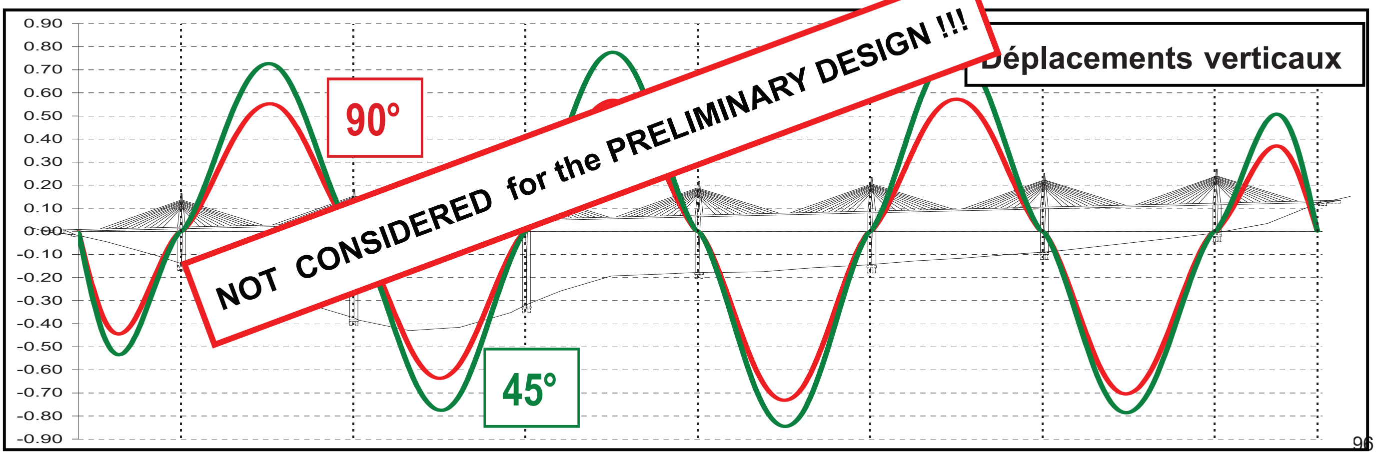
Displacements	SERVICE	CONSTRUCTION
transversal	60 cm	150 cm
Vertical	85 cm	90 cm



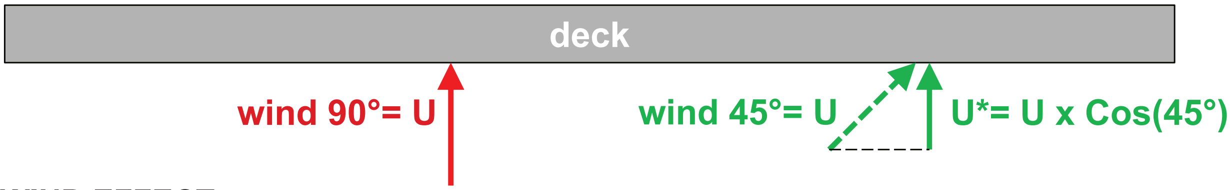
MILLAU: wind 45° > wind 90° !



- reactions on bearings: + 10 à 20 %
- bending moments : + 10 à 30 %



MILLAU: wind 45° > wind 90° !



WIND EFFECT

Wind 45° < 90° ?

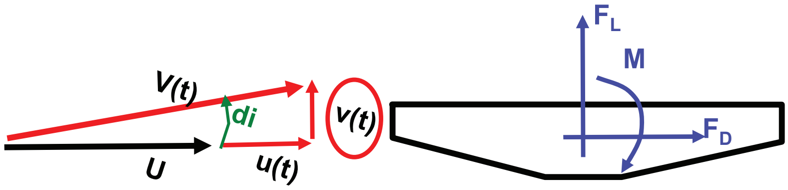
proportionnel:

- To the TRANSVERSAL wind speed): $U_{45} \times \cos(45°) < U_{90}$ ⇒ 45° < 90°
- to the vertical turbulence (Site of viaduct) $\sigma_{w,45} > \sigma_{w,90}$ ⇒ 45° > 90°

inversely proportionnel:

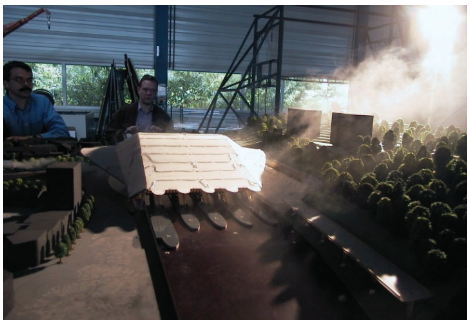
- To aerodynamic damping = fct($U_{transversal}$= U*<U) : $\xi_{45} < \xi_{90}$ ⇒ 45° > 90°

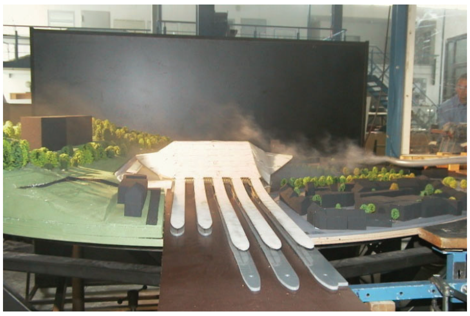
45° > 90°

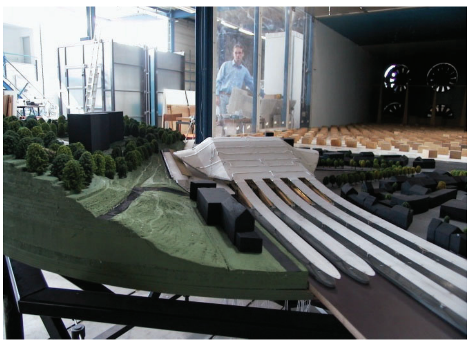


rappel

$$F_D = \frac{1}{2}.\rho.B.[C_D.\bar{U}^2 + C_D.2.g.\sigma u.\bar{U} + \frac{dC_D}{di})_{io}.\bar{U}.g.\sigma w] - (\rho.C_D.B.\bar{U}.\dot{X})$$







Wind loading

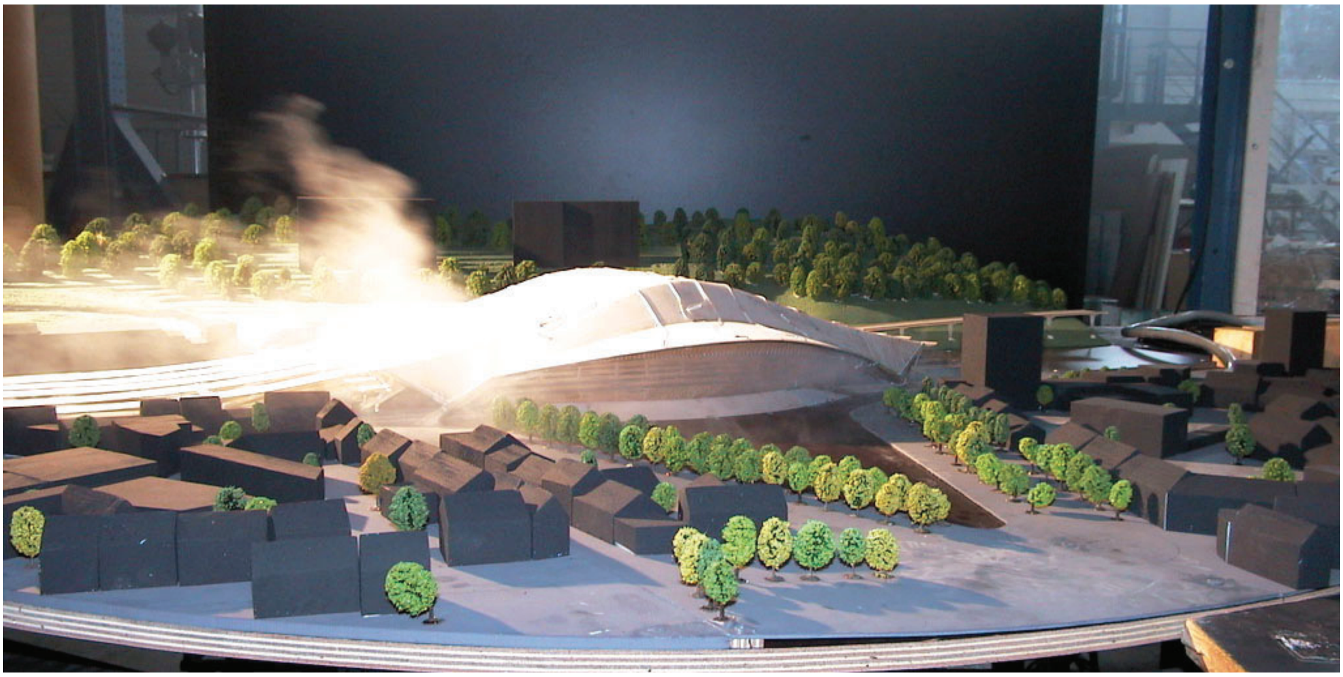
Tests in wind tunnel lab

1/200 – ϕ= 500 m

Wind loading

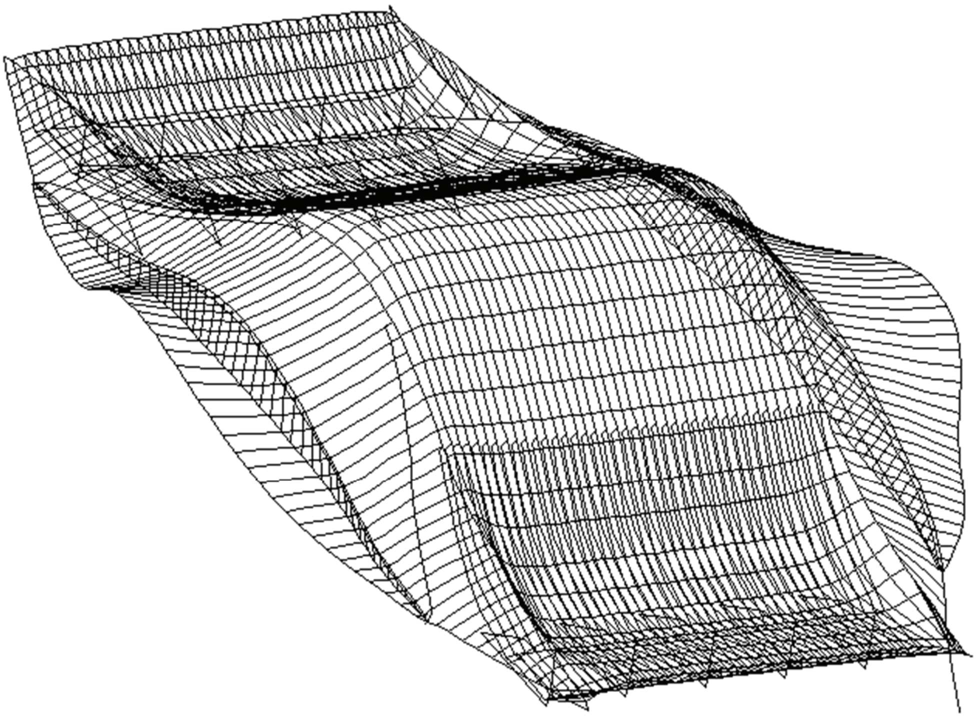
Tests in wind tunnel lab

1/200 – ϕ= 500 m



town

Wind loading



parking

Tests measurements + numerical simulations

TIV: Turbulence Induced Vibrations

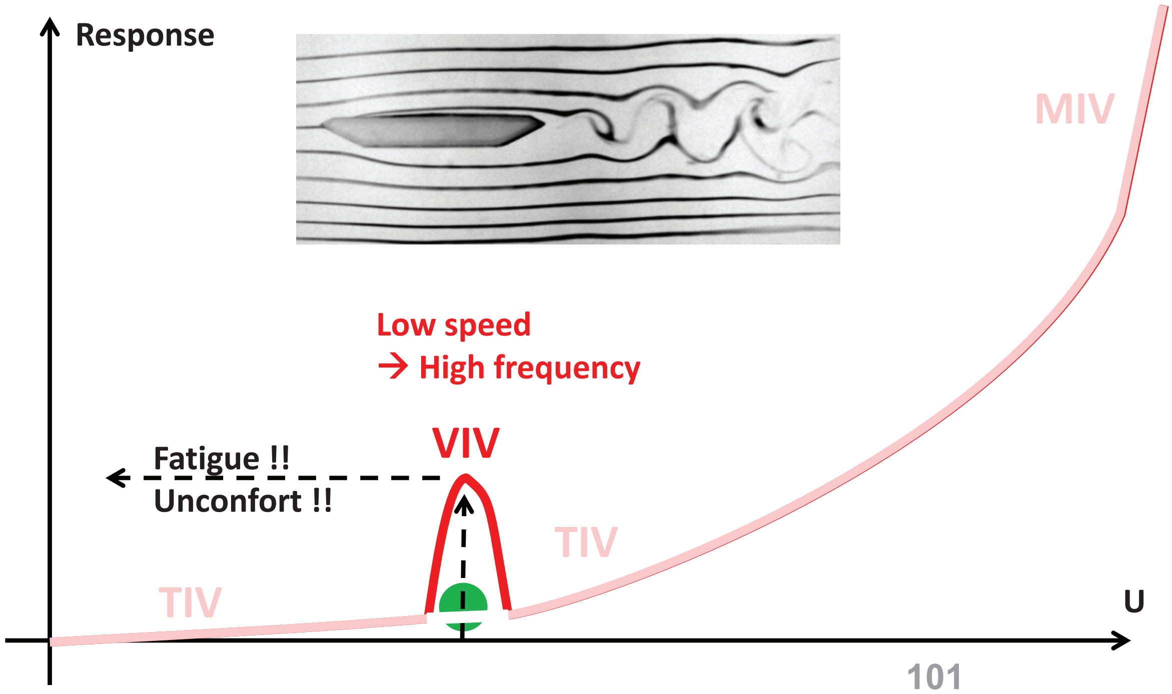
→ response % U^2

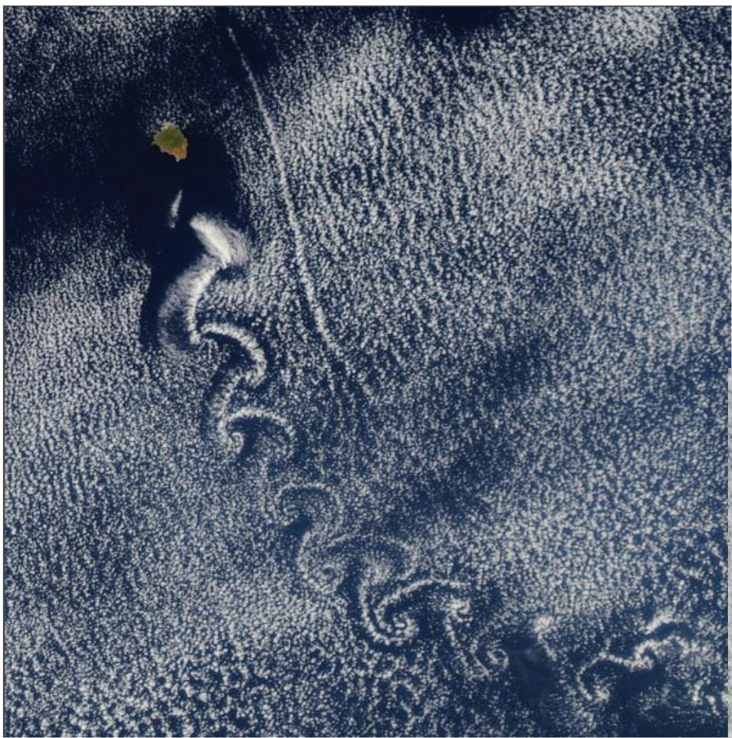
MIV: Movement Induced Vibrations

→ movement of structure modifies the wind flow (instability?)

VIV: Vortex Induced Vibrations

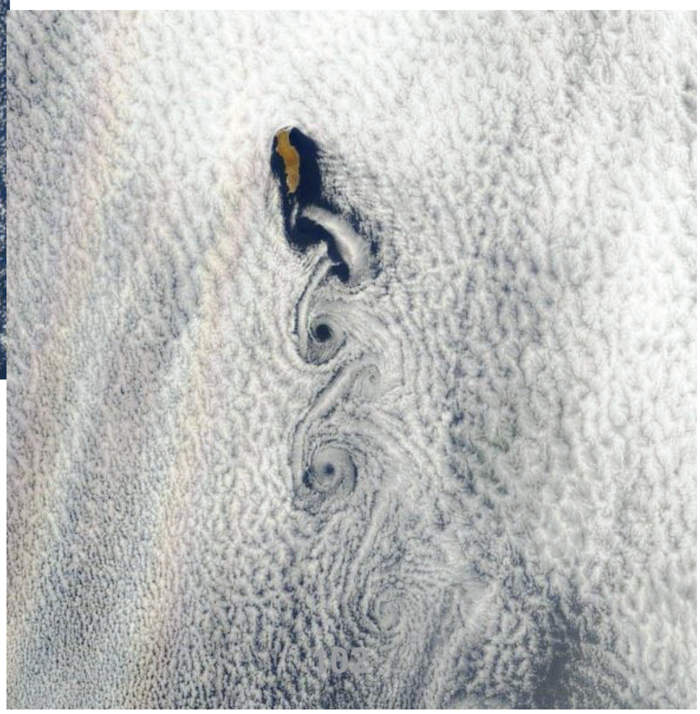
→ periodic movement induced by vortices



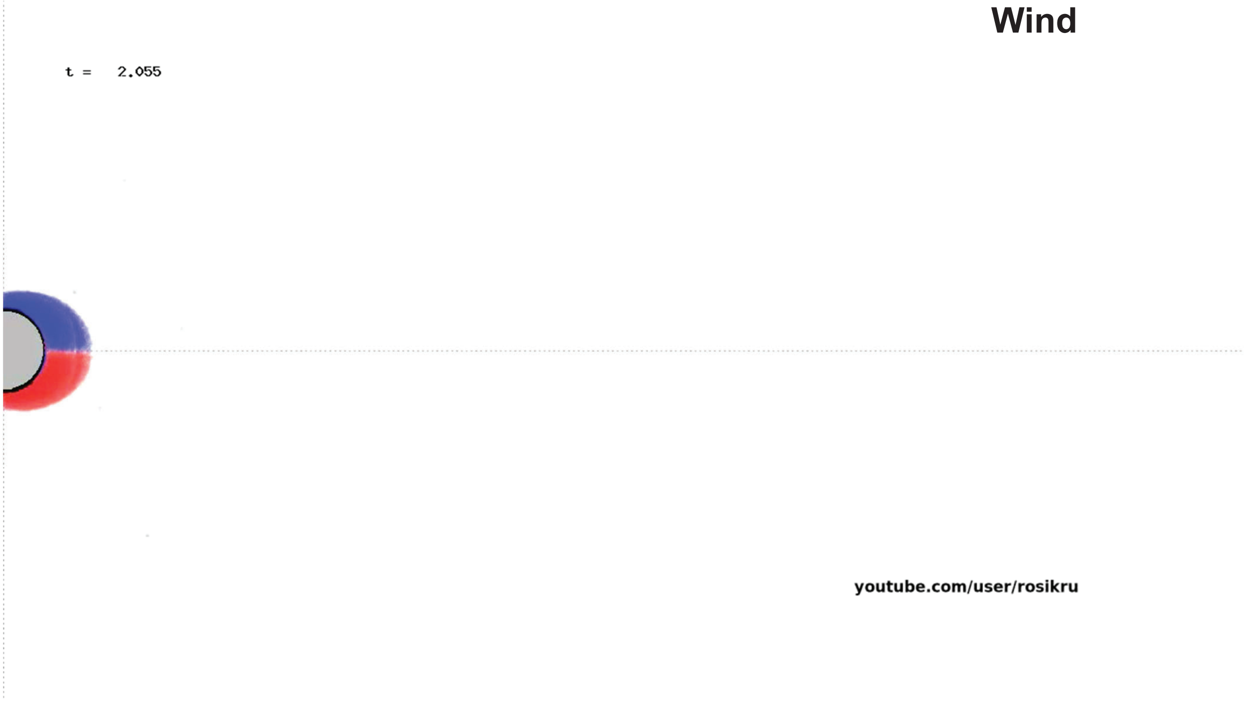


DYNAMICS

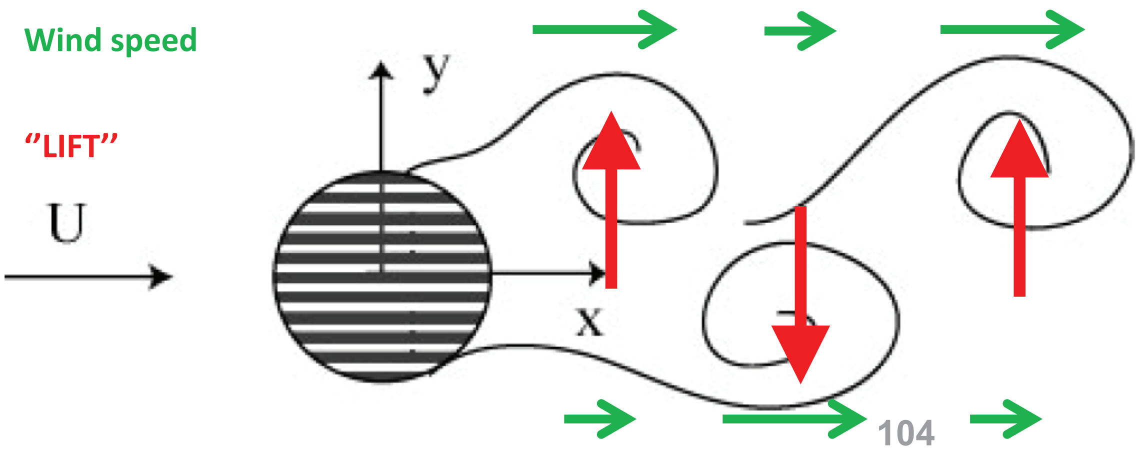
Nature
Wind



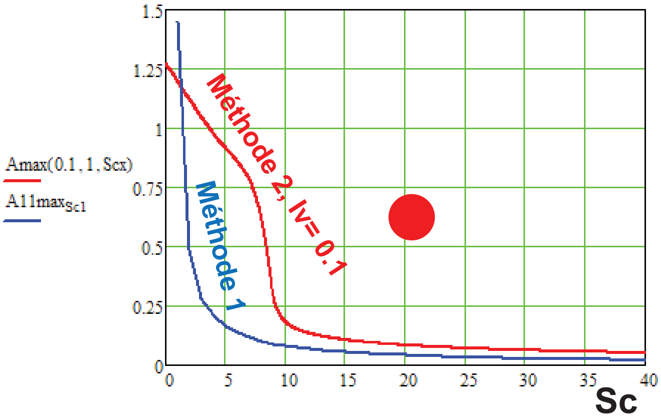
NATURE !!



Animation - VIV

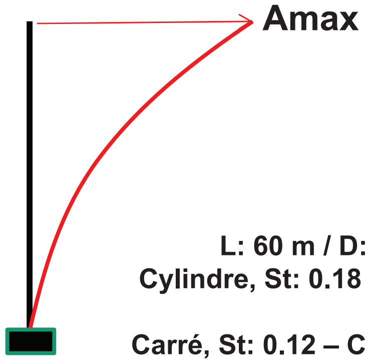


METHODE 1 et 2 - exemple



Méthode 1: bleu
Méthode 2, Iv= 0.1: rouge

$$Sc = \frac{2.\delta_s.m}{\rho.D^2}$$



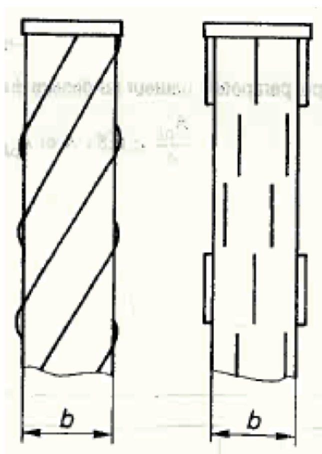
L: 60 m / D: 2.25m
Cylindre, St: 0.18 – Clat: 0.3
Carré, St: 0.12 – Clat: 1.1
Iv: 0, 0.1 , 0.2

DYNAMICS

Nature
Wind

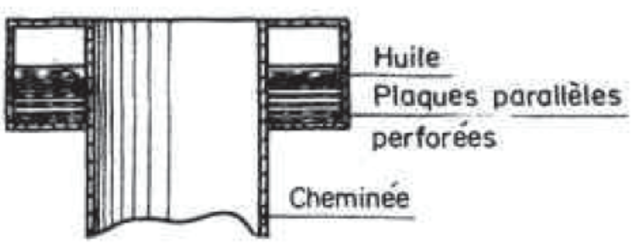
Decrease the effects of VIV

Modify the cross section shape



Modify the damping

LMD



TMD - pendule

$$f = \frac{1}{2\pi}\sqrt{\frac{g}{L}}$$

Masse pendule = 1..2% de ϕ.m.ϕ

Damper to increase $Sc = \frac{2.(\delta_s + \delta_a).m}{\rho.D^2}$

DYNAMICS

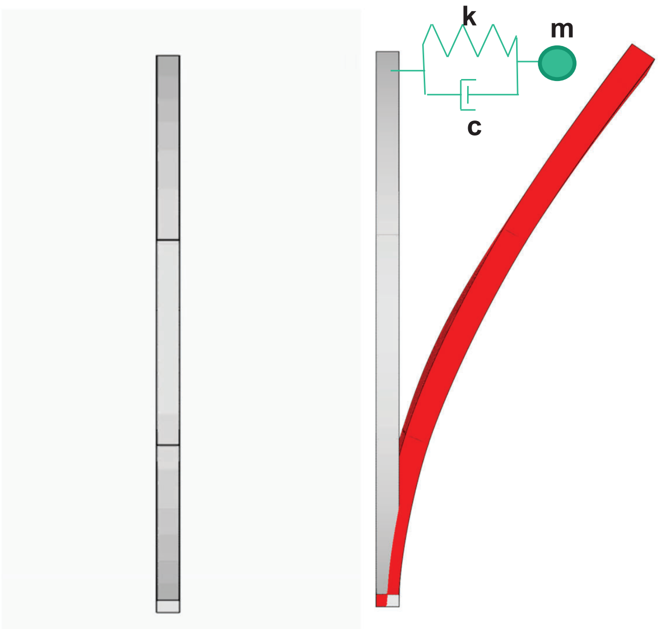
Nature
Wind

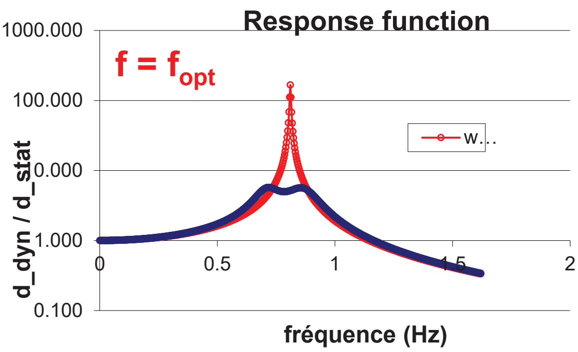
Arc Majeur – Damper Design

Freq. = 0.8 Hz
M = ϕ.M.ϕ = 25 tons
ξ = 0.3 %

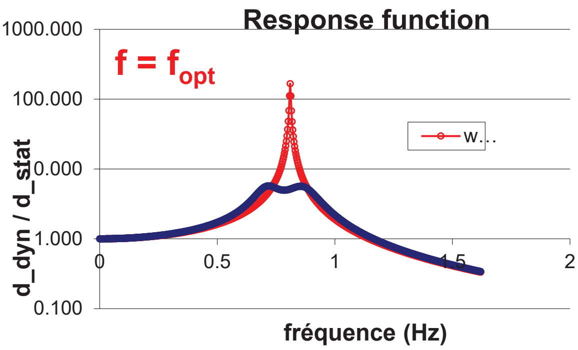
k = 1,50 tons
μ = m/M
f_{opt} = Freq/(1+μ)

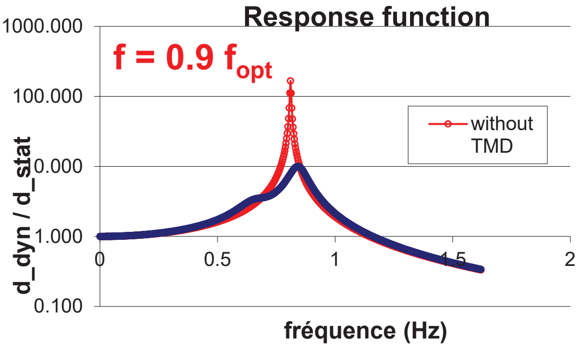
$$\zeta_{opt} = \sqrt{\frac{3\mu}{8(1+\mu)}}$$

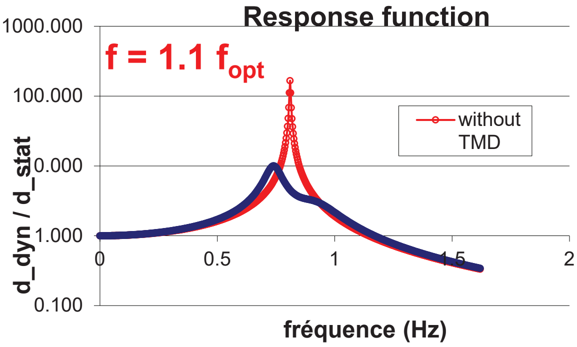


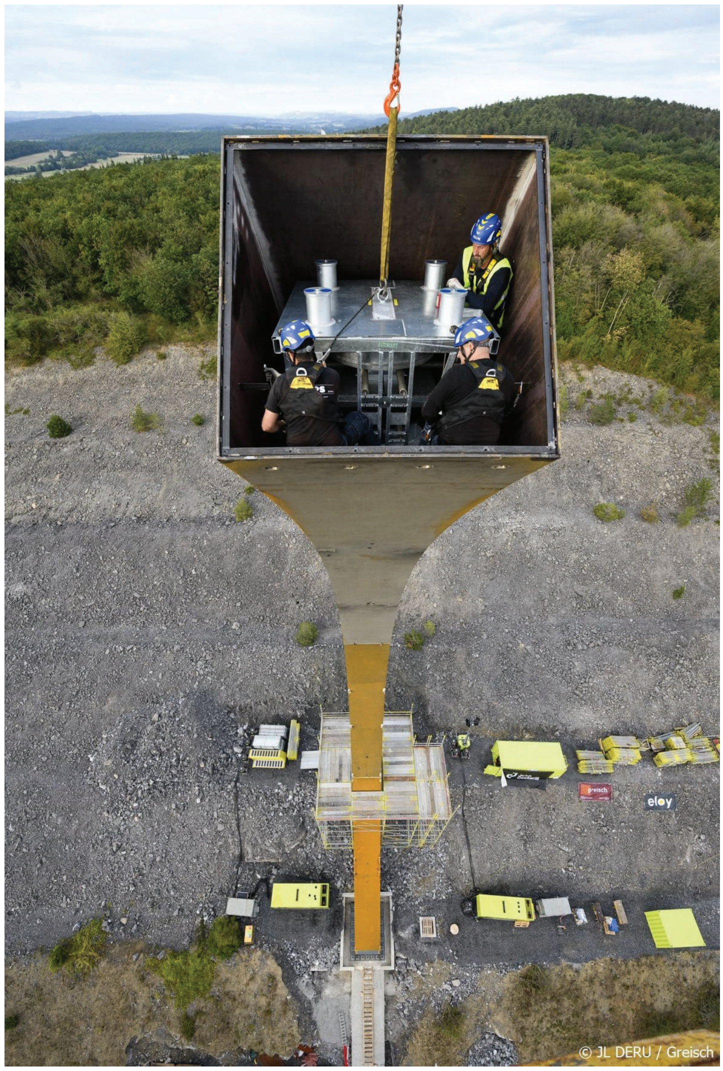


Arc Majeur – Damper Design

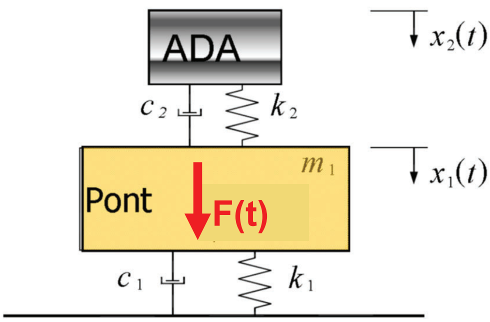


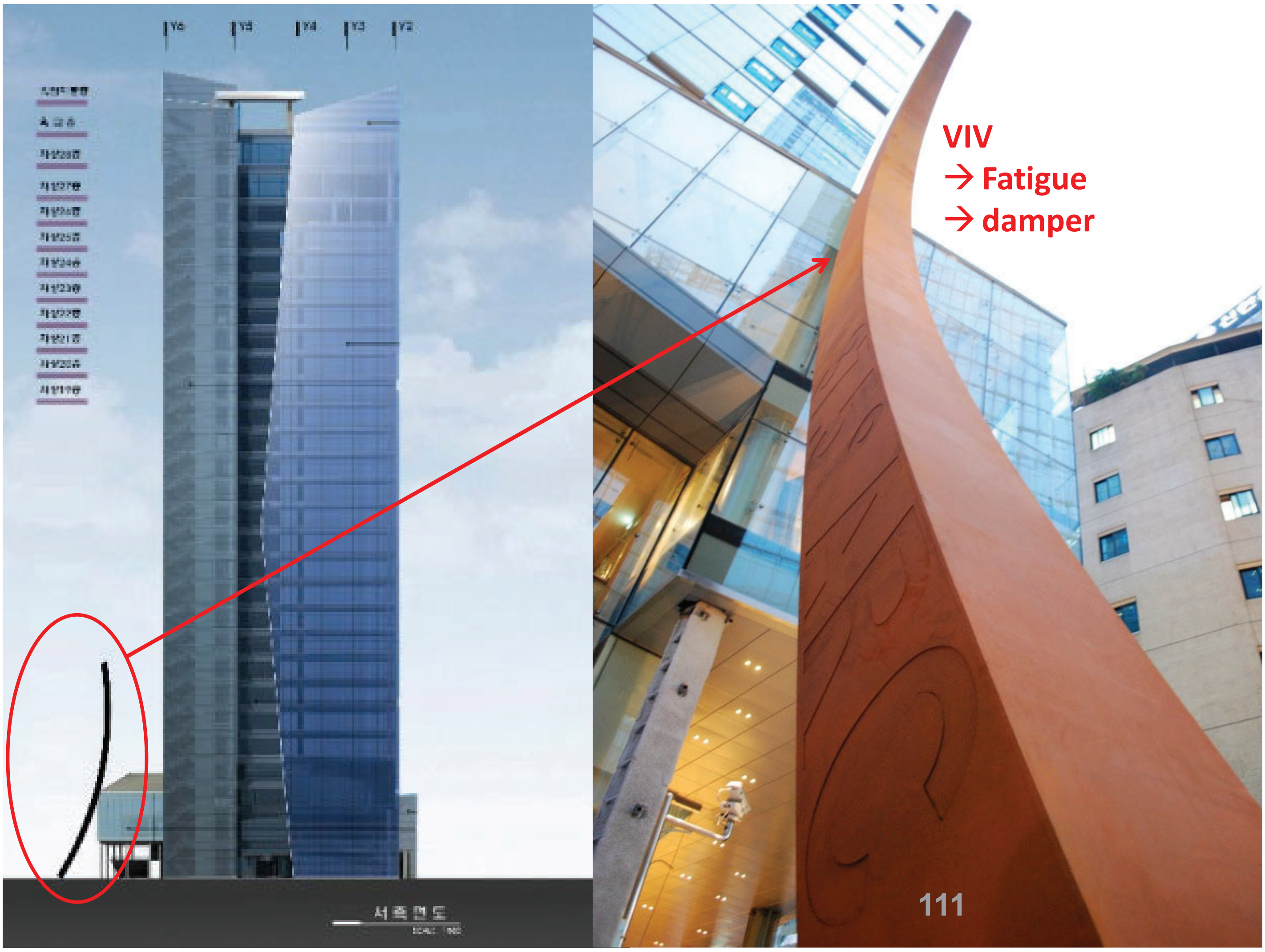






With TMD,
Depmax / 6



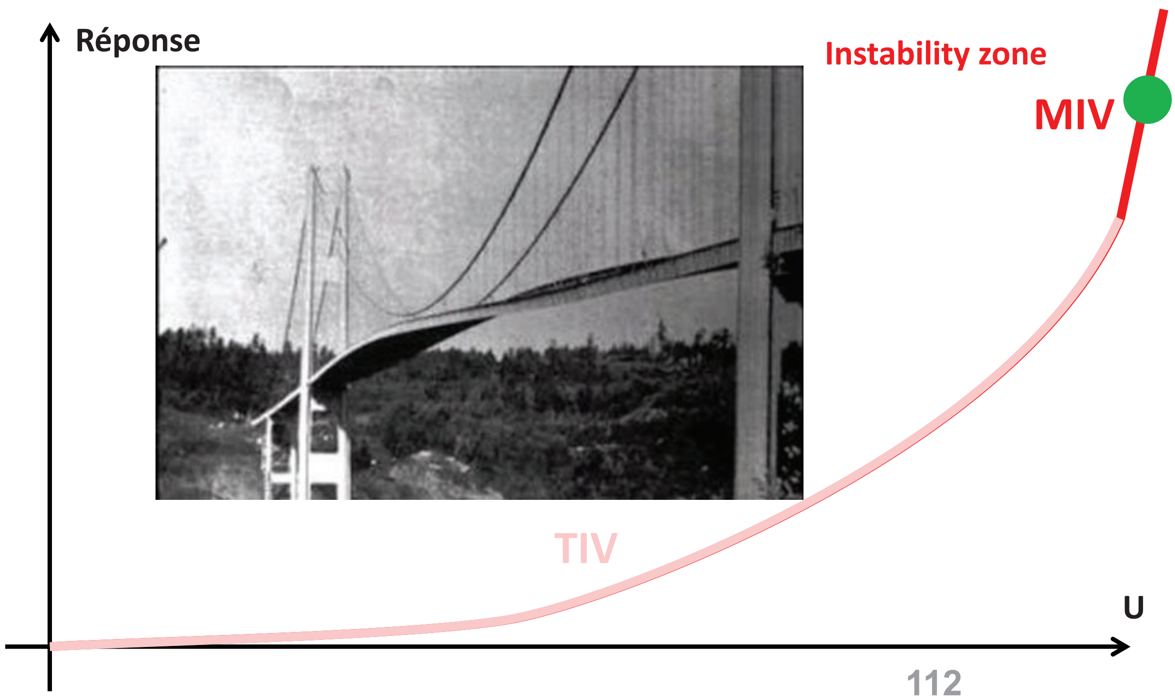


TIV: Turbulence Induced Vibrations

→ response % U^2

MIV: Movement Induced Vibrations

→ movement of structure modifies the wind flow (instability?)

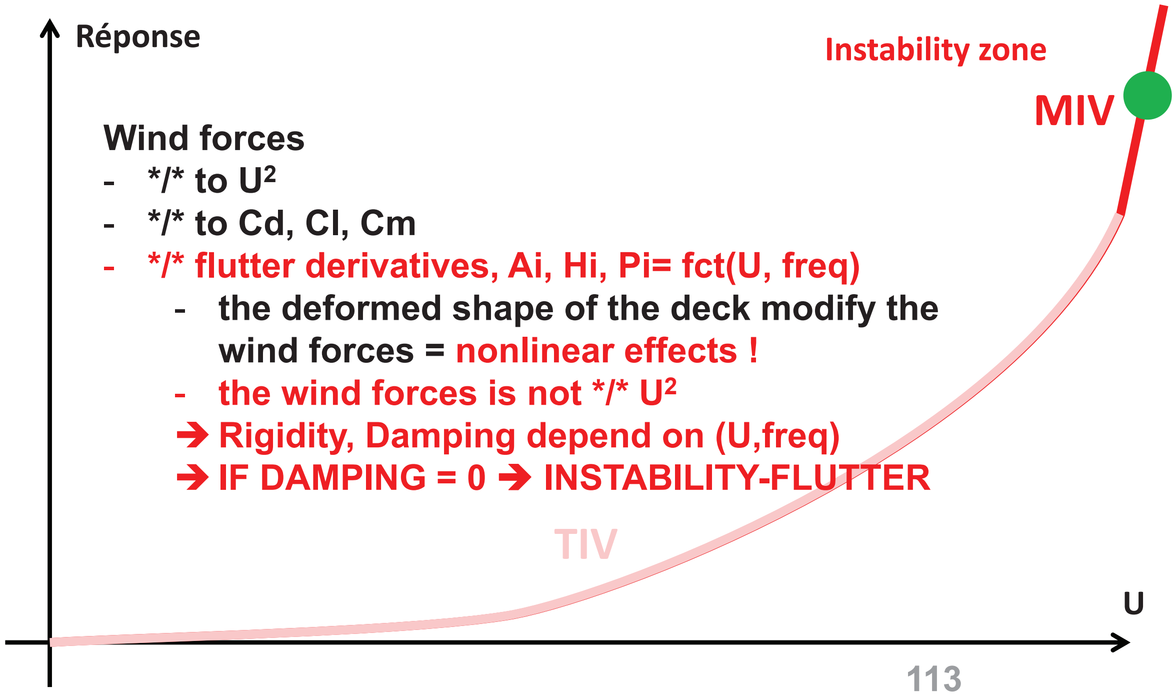


TIV: Turbulence Induced Vibrations

→ response % U^2

MIV: Movement Induced Vibrations

→ **movement of structure modifies the wind flow (instability?)**



CLASSICAL APPROACH

PSD de von Karman

$$\frac{f\cdot S_u(f)}{\sigma_u^2}=\frac{4\left(\frac{f\ {}^xL_u}{U}\right)}{\left[1+70.8\left(\frac{f\ {}^xL_u}{U}\right)^2\right]^{5/6}}\qquad \frac{f\cdot S_w(f)}{\sigma_w^2}=\frac{4\left(\frac{f\ {}^xL_w}{U}\right)\left(1+755.2\left(\frac{f\ {}^xL_w}{U}\right)^2\right)}{\left[1+283.2\left(\frac{f\ {}^xL_w}{U}\right)^2\right]^{11/6}}$$

Stationnary forces */* u, w

$$F_{buf}=\frac{1}{2}\rho U^2 B\begin{bmatrix}2Cd & (\frac{dC_D}{d\alpha}-Cl)\\ 2Cl & (\frac{dC_L}{d\alpha}-Cd)\\ 2BCm & B\frac{dC_M}{d\alpha}\end{bmatrix}\begin{bmatrix}\frac{u}{U}\\ \frac{w}{U}\end{bmatrix}$$

Coherence between 2 points of the deck

$$\Lambda_{ii}=\exp\left(-\frac{2\sqrt{(C_{iz}\Delta_x)^2+(C_{iz}\Delta z)^2}\ f}{\overline{U_P}+\overline{U_Q}}\right)$$

where $i=u$ or w, $C_{ux}=10$, $C_{uz}=10$, $C_{wx}=6.50$, $C_{wz}=3$, $\Delta z=z_P-z_Q$ and $\Delta x=x_P-x_Q$.

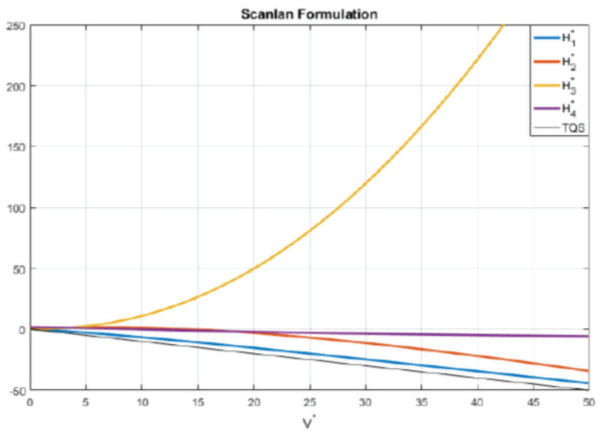
AERO-ELASTIC APPROACH - SCANLAN

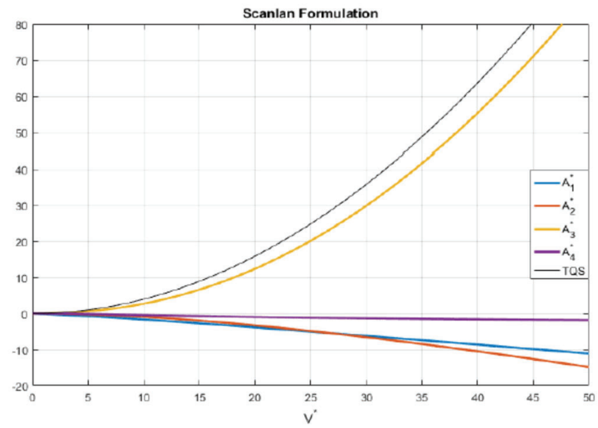
$$F = F_{moy} + F_{buff} + F_{aer}$$

$$\begin{bmatrix} F_{y,aer} \\ F_{z,aer} \\ F_{\alpha,aer} \end{bmatrix} = \begin{bmatrix} \rho U^2 B/2 & 0 & 0 \\ 0 & \rho U^2 B/2 & 0 \\ 0 & 0 & \rho U^2 B/2 \end{bmatrix} \cdot \begin{bmatrix} KP_1^* \frac{1}{U} & KP_5^* \frac{1}{U} & KP_2^* \frac{B}{U} & K^2 P_4^* \frac{1}{B} & K^2 P_6^* \frac{1}{B} & K^2 P_3^* \\ KH_5^* \frac{1}{U} & KH_1^* \frac{1}{U} & KH_2^* \frac{B}{U} & K^2 H_6^* \frac{1}{B} & K^2 H_4^* \frac{1}{B} & K^2 H_3^* \\ KA_5^* \frac{\dot{x}}{U} & KA_1^* \frac{1}{U} & KA_2^* \frac{B}{U} & K^2 A_6^* \frac{1}{B} & K^2 A_4^* \frac{1}{B} & K^2 A_3^* \end{bmatrix} \cdot \begin{bmatrix} \dot{y} \\ \dot{z} \\ \dot{\alpha} \\ y \\ z \\ \alpha \end{bmatrix}$$

/ y, z, α → K_{aero}
rigidity

/ $\dot{y}, \dot{z}, \dot{\alpha}$ → C_{aero}
damping





BENCHMARK 1.2.A.

No	Mode	Modal	mass	Freq [Hz]	Damping
1	horizontal	1	1.7424E+07	0.0521	0.0030
2	vertical	1	1.8231E+07	0.0839	0.0030
3	vertical	2	1.6682E+07	0.0998	0.0030
4	horizontal	2	1.8981E+07	0.1179	0.0030
5	vertical	3	1.2559E+07	0.1317	0.0030
6	vertical	4	2.1215E+07	0.1345	0.0030
7	vertical	5	1.7402E+07	0.1827	0.0030
8	horizontal	3	2.4313E+07	0.1866	0.0030
9	torsional	1	1.6827E+09	0.2784	0.0030
10	vertical	6	1.6538E+07	0.2815	0.0030
11	torsional	2	1.9232E+09	0.3833	0.0030
12	vertical	7	1.7269E+07	0.3975	0.0030

Possible coupling
- Of torsional mode, f_{tor}
- With bending mode, f_{ben}

IF same shape

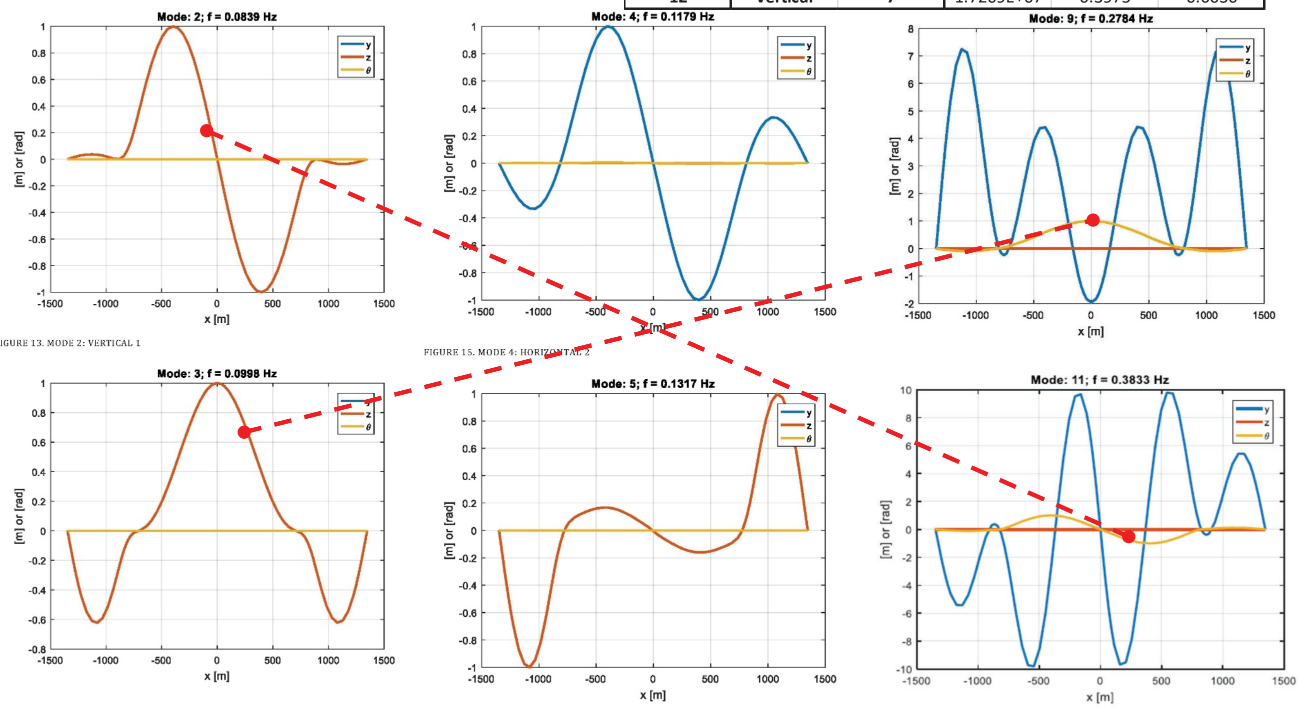


FIGURE 13. MODE 2: VERTICAL 1

FIGURE 15. MODE 4: HORIZONTAL 2

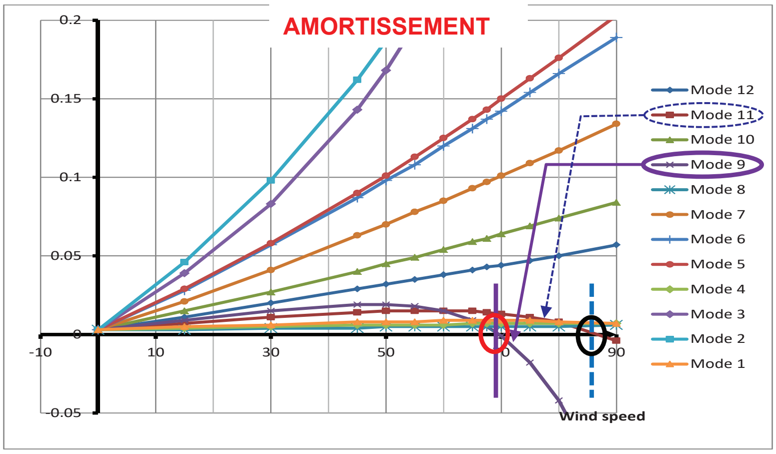
BENCHMARK 1.2.A.

Damping nul

➔ FLUTTER WIND SPEED

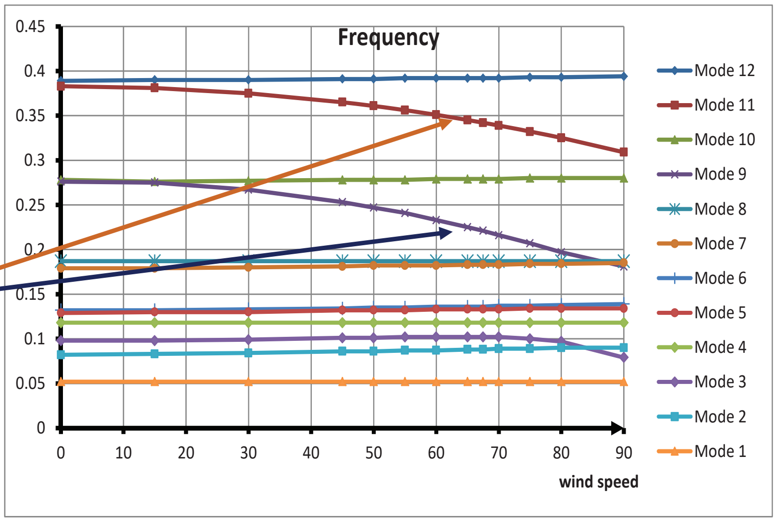
Ucr1= 69.47 m/sec

Ucr2= 86,66 m/sec



Frequencies of the torsional modes

is decreasing versus the wind speed



118

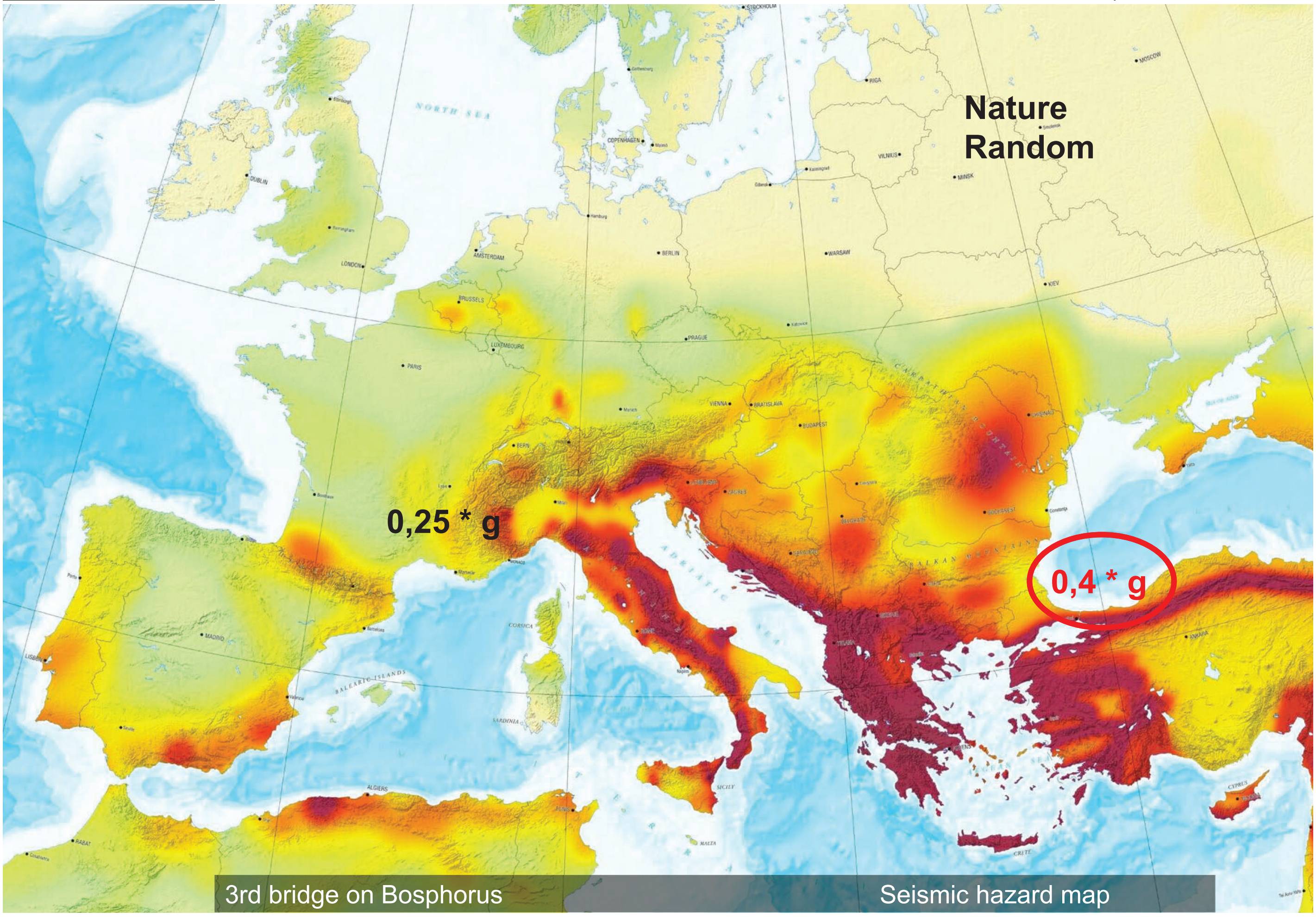
MAN | **NATURE**

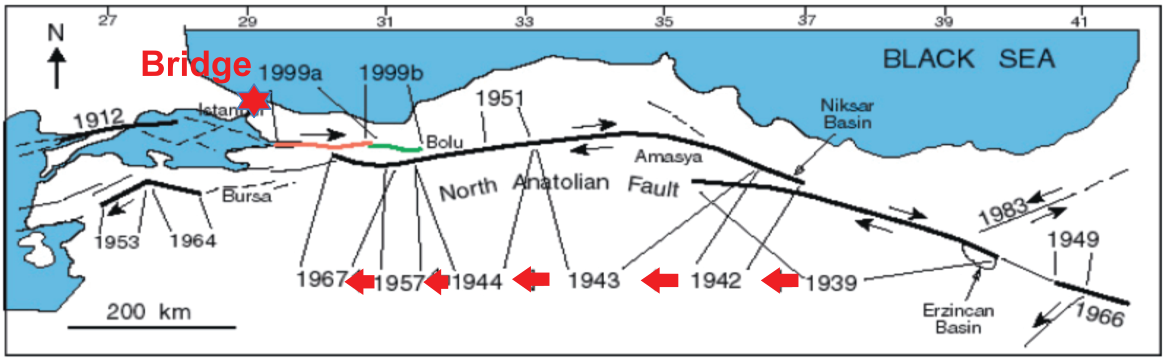
trains cars | **pedestrians** | **wind** | **earthquake** | **wave**

Earthquakes …

greisch

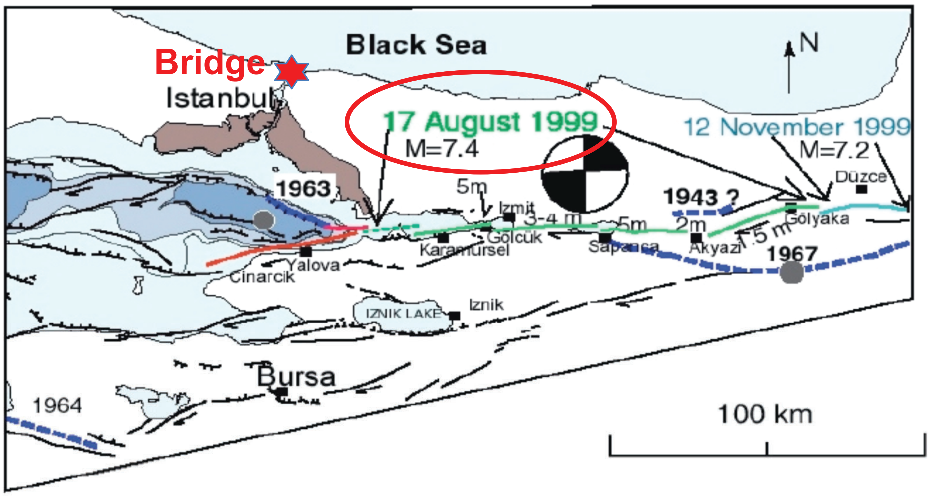
EARTHQUAKE





From Barka et al., 2002

Progression of 20th century earthquakes along the North Anatolian fault



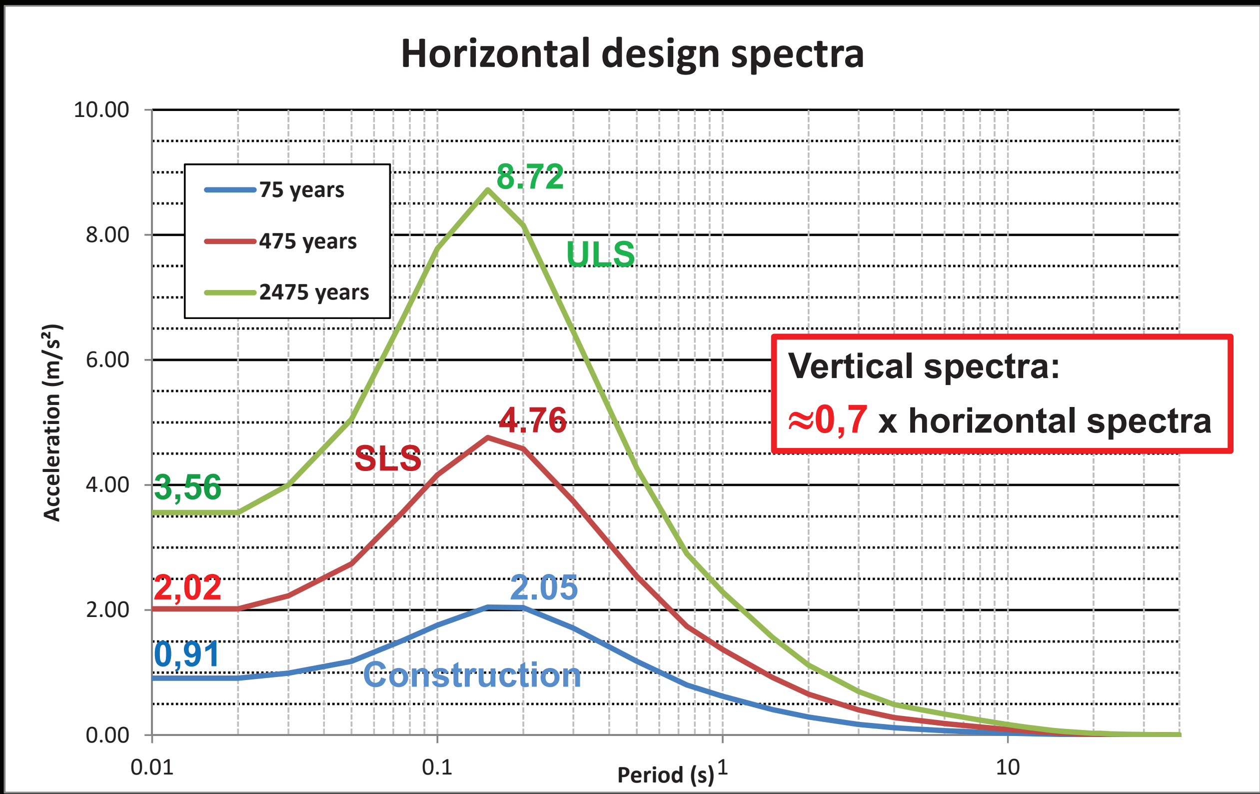
From Barka et al., 2002

1999 earthquake surface ruptures map

LOADING: - Traffic (cars, trains)

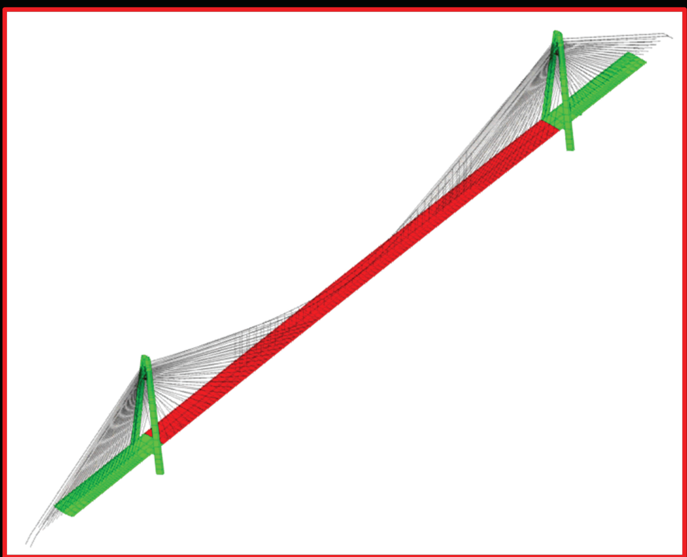
- Wind

- Earthquake



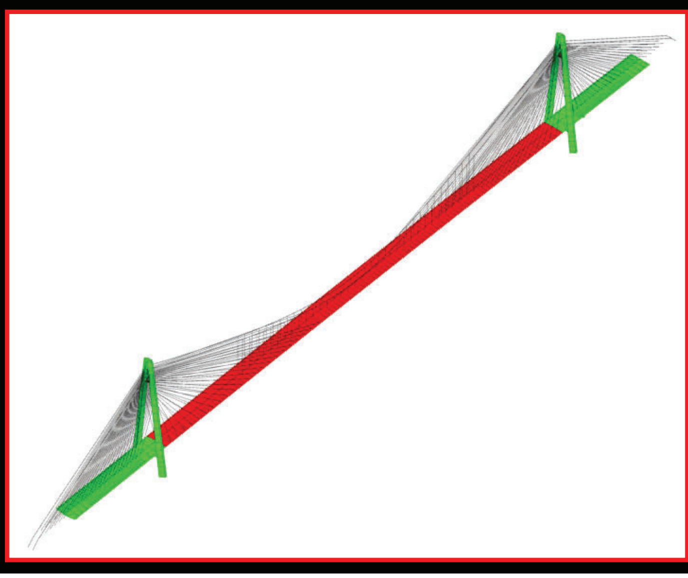
BRIDGE - Service

- Eigen modes



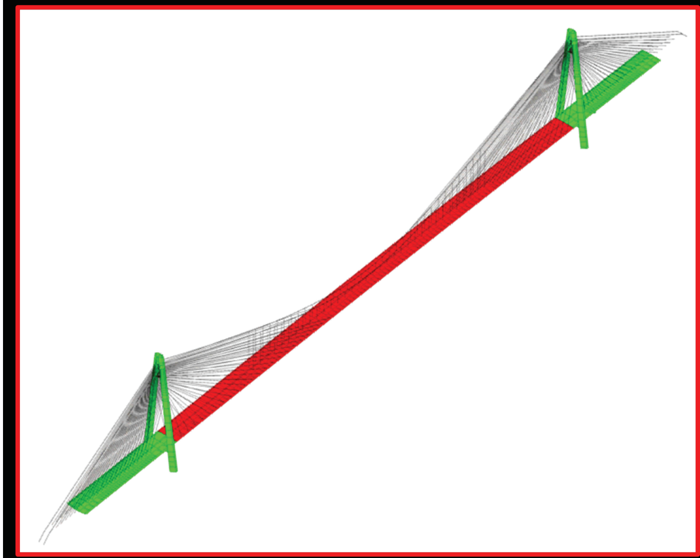
0,094 Hz - (mode 1)
Transversal

0,170 Hz (mode 3)
Longitudinal + vertical -2 ondes



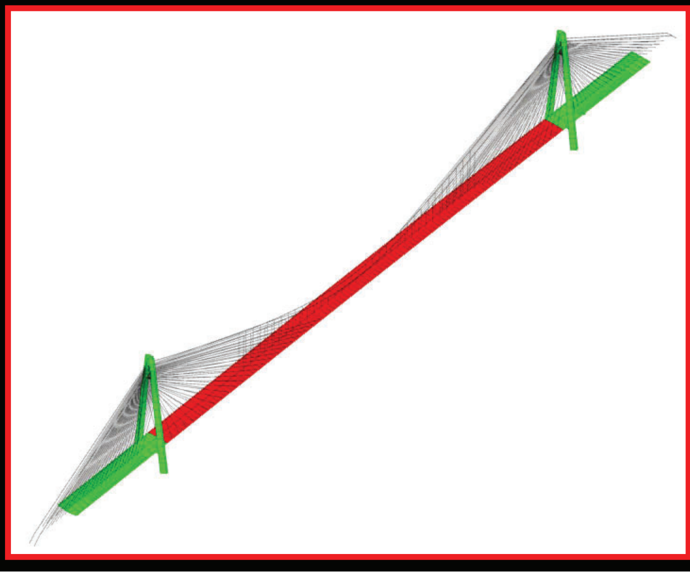
BRIDGE - Service

- Eigen modes



0,166 Hz (mode 2)
Vertical - 1 onde

0,300 Hz (mode 11)
Torsion



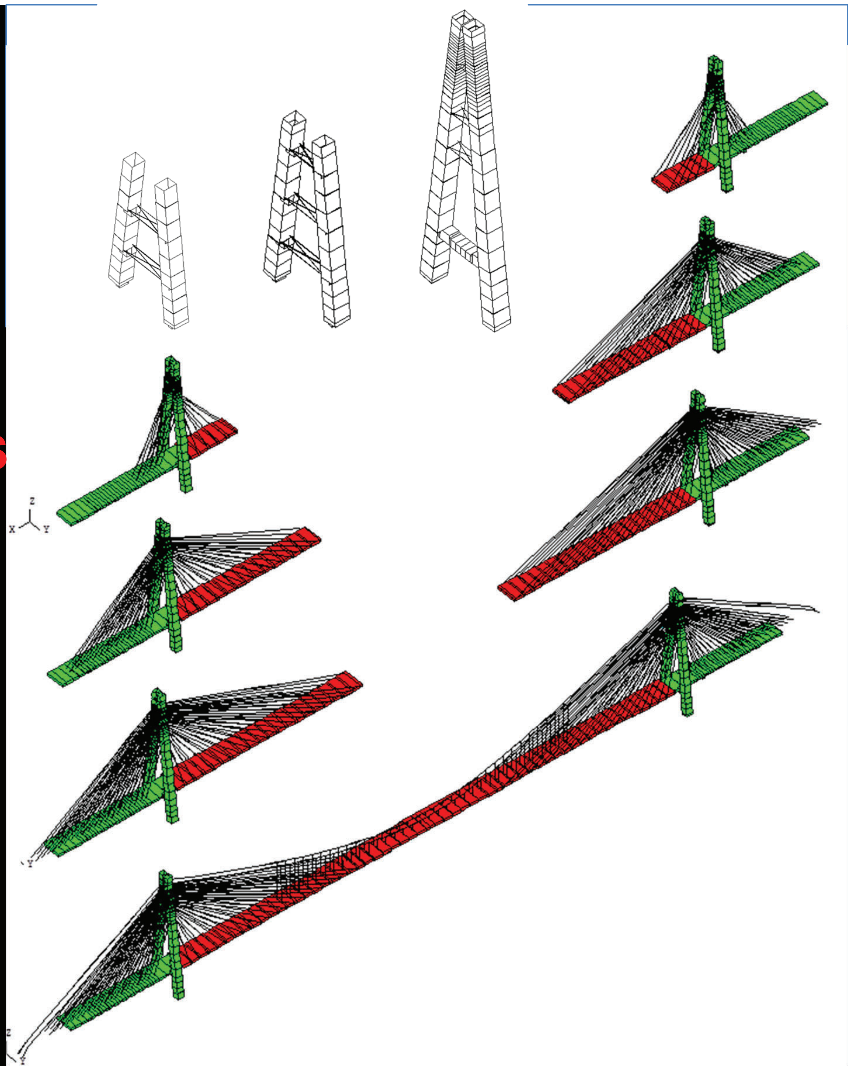
SEISMIC design

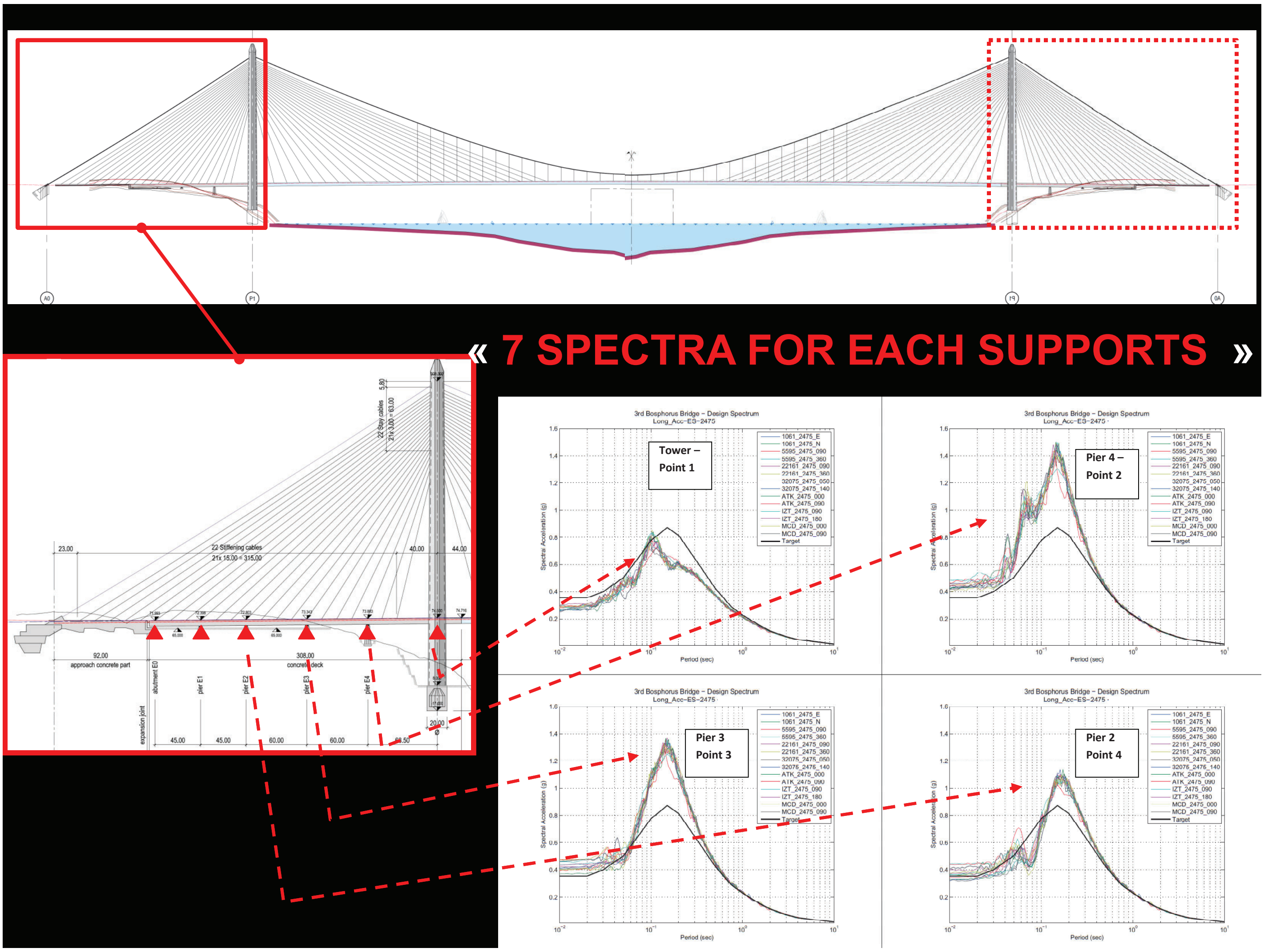
Configurations

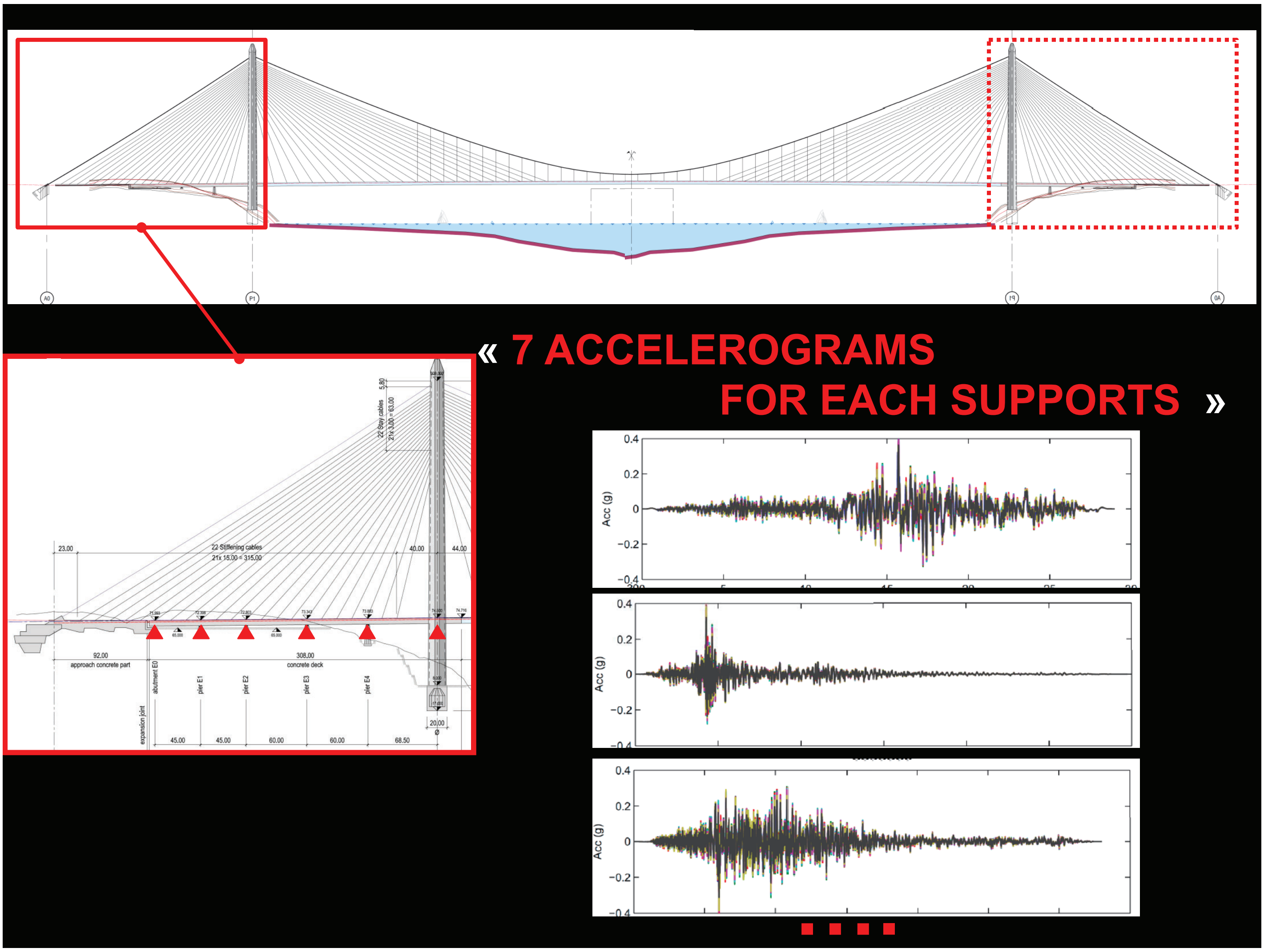
- Construction
- Service

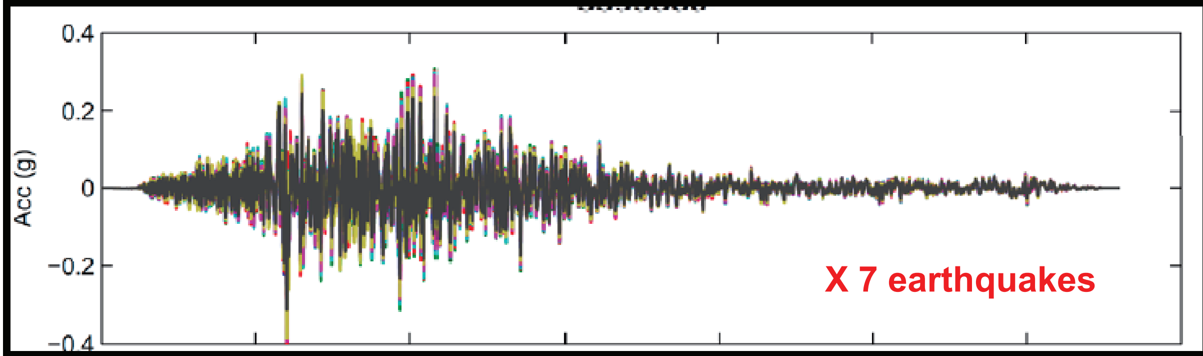
SPECTRAL ANALYSES

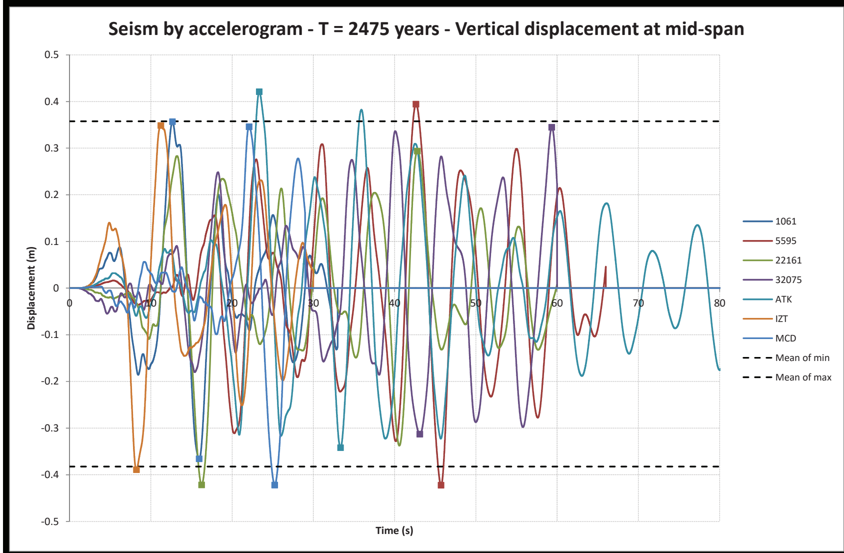
- 1.0 Ex +/- 0.3 Ey +/- 0.3 Ez
- 0.3 Ex +/- 1.0 Ey +/- 0.3 Ez
- 0.3 Ex +/- 0.3 Ey +/- 1.0 Ez




« 7 SPECTRA FOR EACH SUPPORTS »
22 Stiffening cables
21x 15,00 = 315,00
92,00
approach concrete part
308,00
concrete deck
45,00
60,00
68,50
20,00
3rd Bosphorus Bridge – Design Spectrum
Tower – Point 1
Pier 4 – Point 2
Pier 3 Point 3
Pier 2 Point 4
Period (sec)
Target


« 7 ACCELEROGRAMS FOR EACH SUPPORTS »
22 Stiffening cables
21x 15,00 = 315,00
92,00
approach concrete part
308,00
concrete deck
Acc (g)





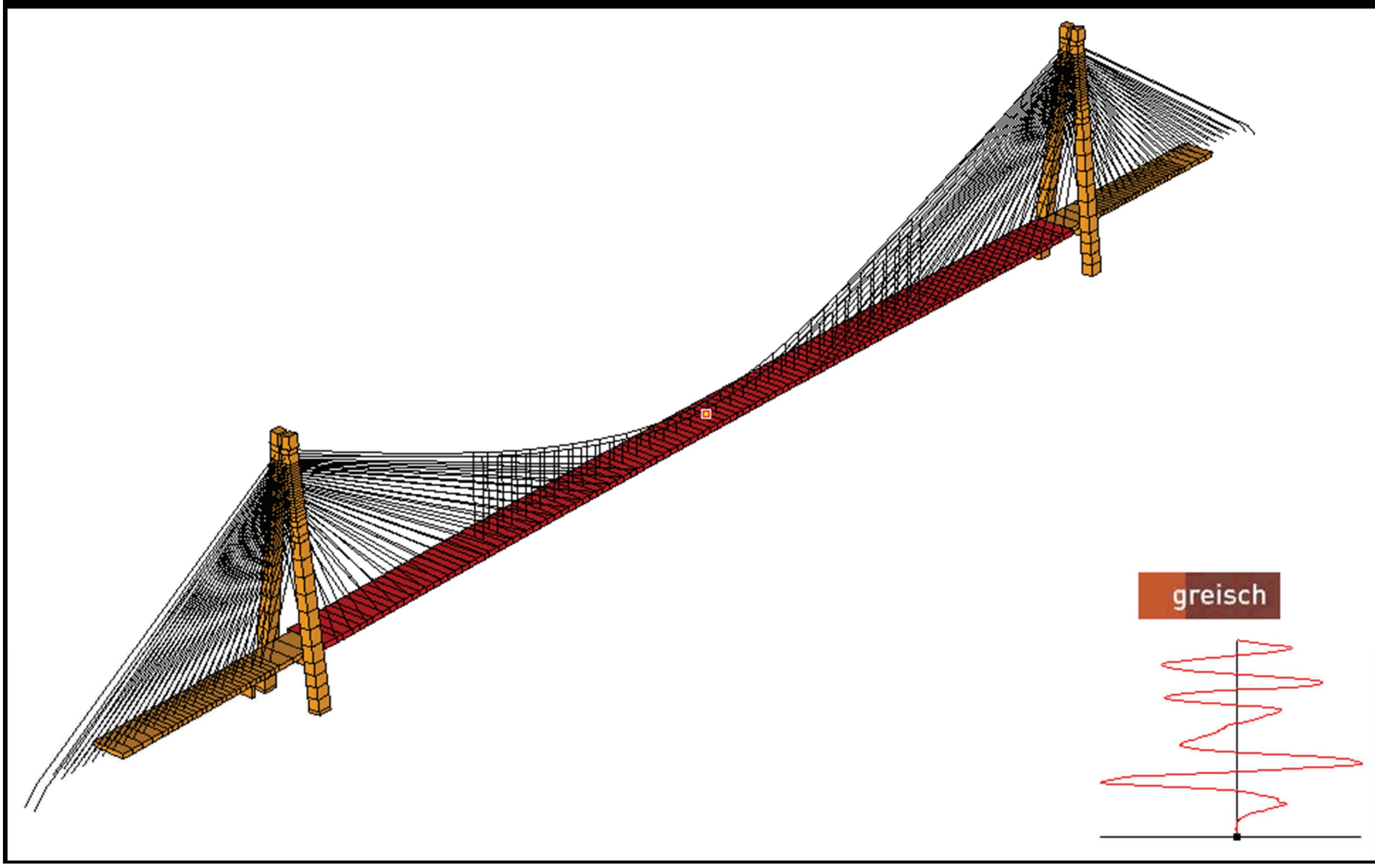
Design=

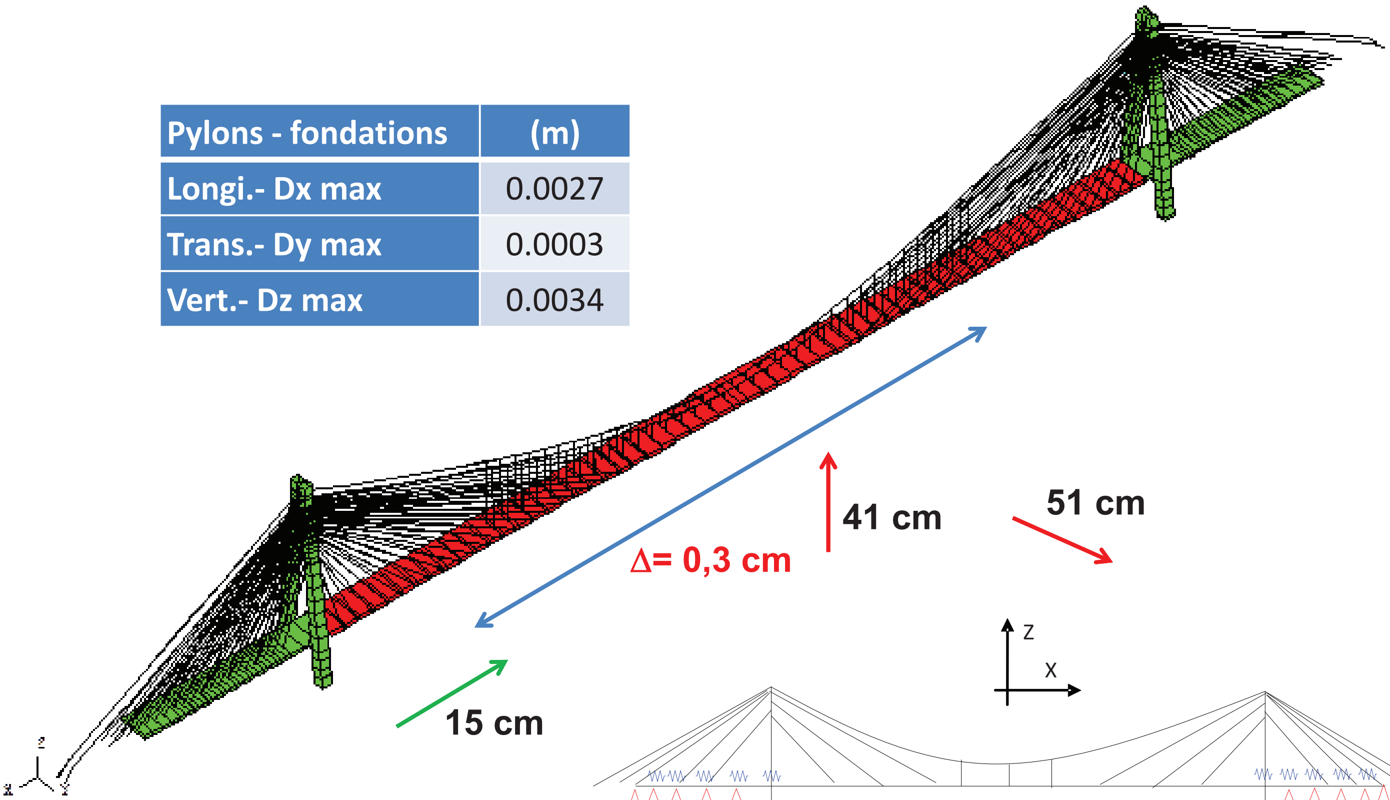
mean of MAX(result$_i$)
for i= 1 to 7 earthquakes

+ concomitant efforts

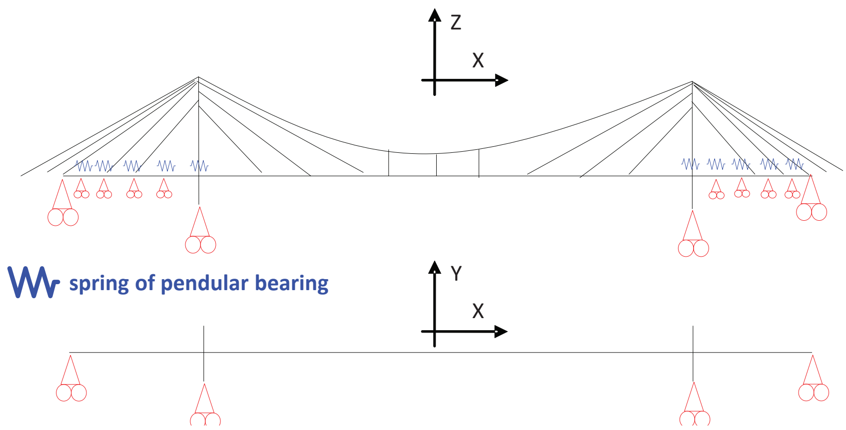
EARTHQUAKE

- Behaviour





Pylons - fondations	(m)
Longi.- Dx max	0.0027
Trans.- Dy max	0.0003
Vert.- Dz max	0.0034

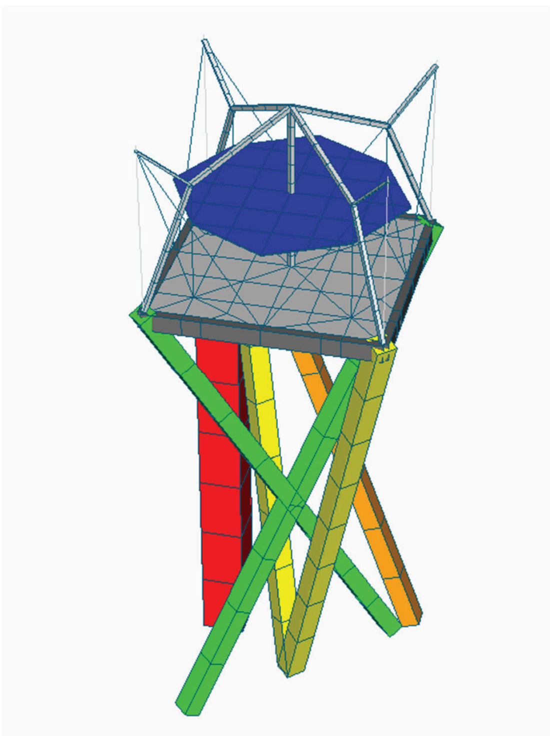


[redacted]

EARTHQUAKE

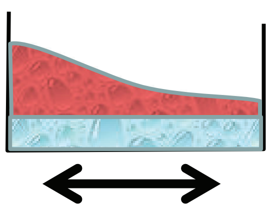
WATER TANK - GHLIN

Nature
Random



$f_{structure} = 0.6$ Hz
$f_{mobile} = 0.2$ Hz

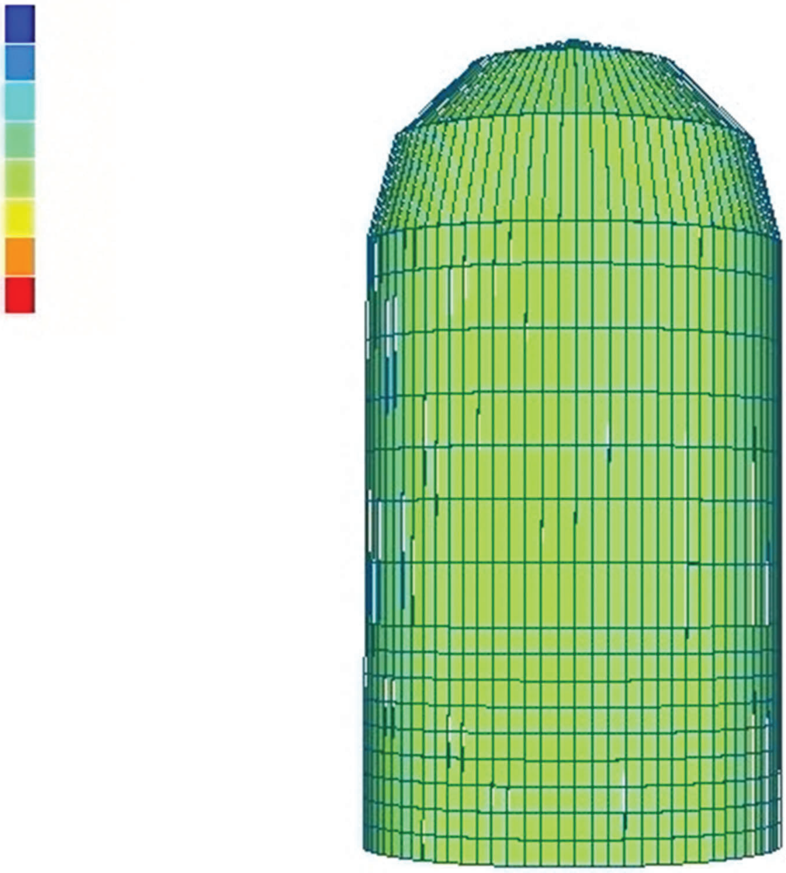
$M_{fixed} = 1200$ tons
$M_{mobile} = 800$ tons



Housner

EARTHQUAKE

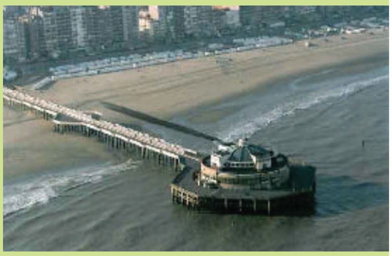
Nature
Random



MAN | NATURE

trains cars | pedestrians | wind | earthquake | wave

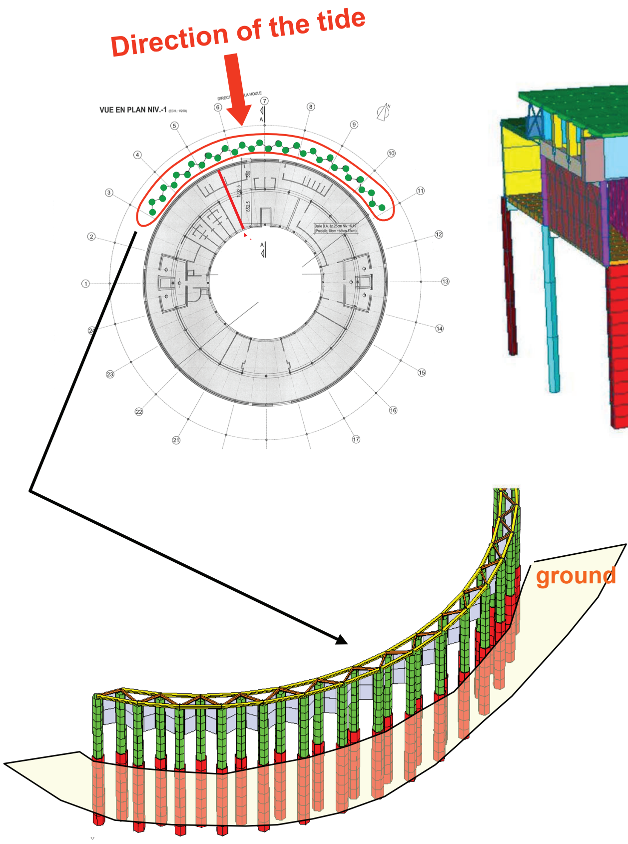
Wave, Impulse, explosion

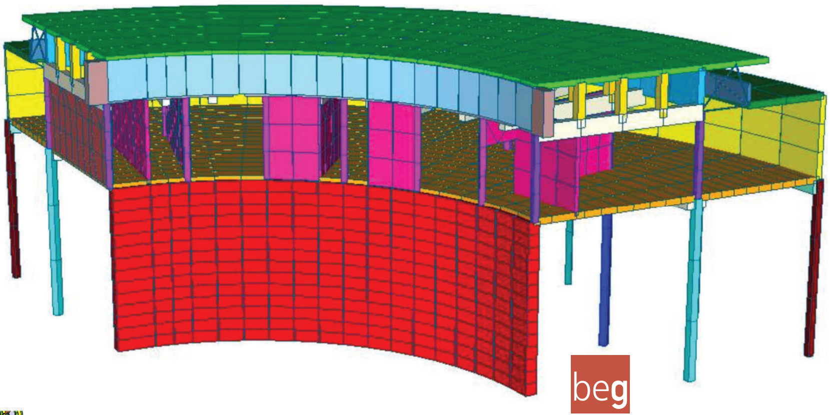


IMPACT

Nature
Waves

PIER BLANKENBERGE



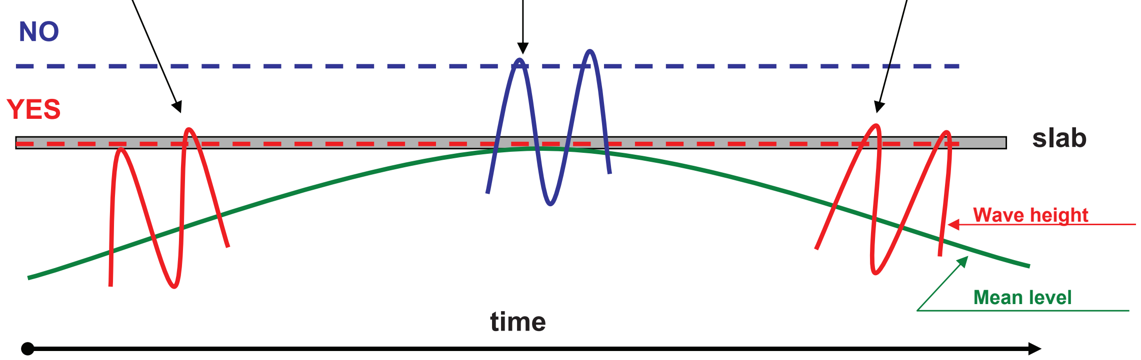


Measurements on site

Storm: 8 february 2004

⇒ Measurements at 2 h pm | at 4h pm

Rising tide | ⇒ High tide = nothing | Failing tide

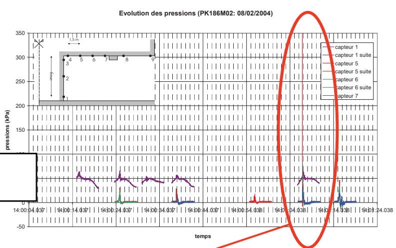


When the wave level is high ⇒ NO IMPACTS

Measurements

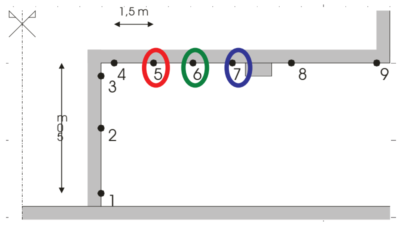
Prof. De Rouck

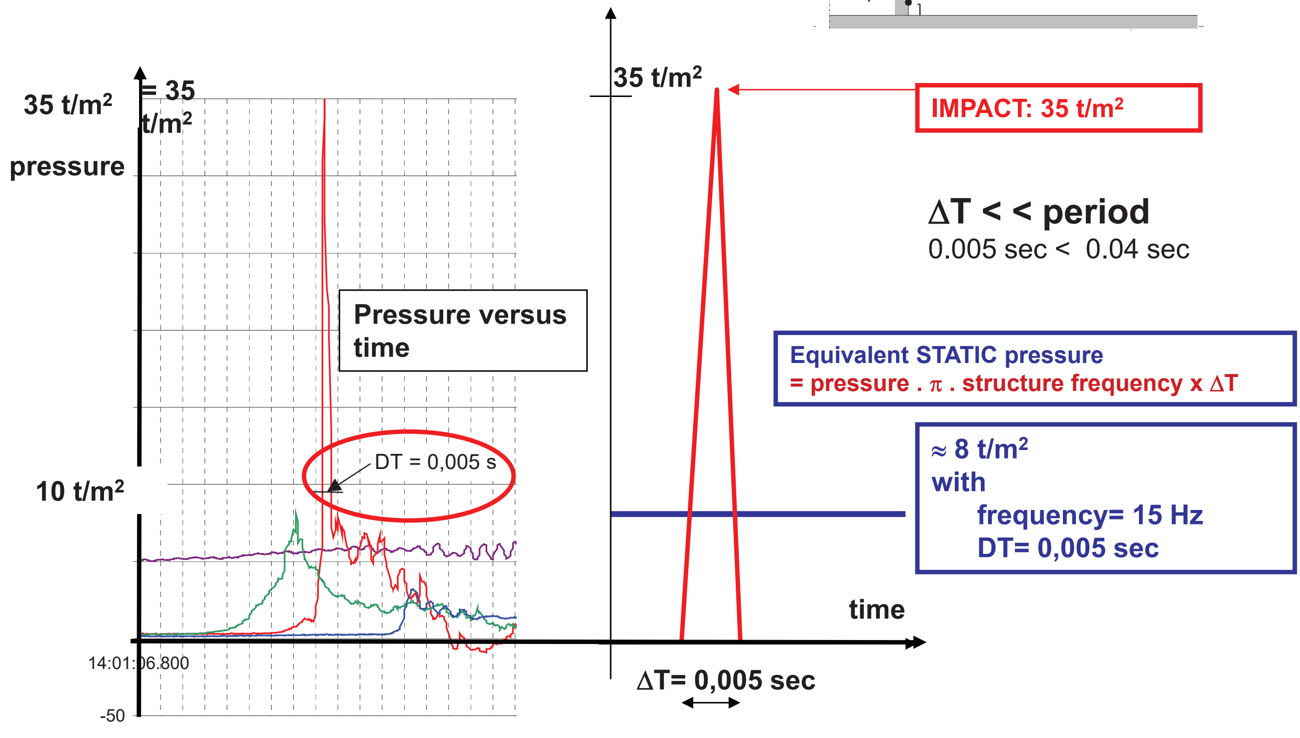
Storm - 8 february 2004 - measurementss at 2 h pm



1°) Meaning of the mx pressure ?

Consider in perspective !!!





IMPACT

Nature Waves

2 events :

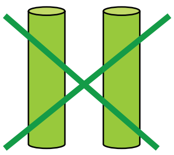
1° : stopped horizontal movement

- vertical movement
- vertical kinetic energy
  → pressure

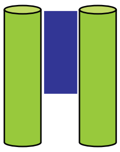
2° : horizontal + vertical movement

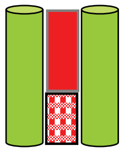
➔ air blocked

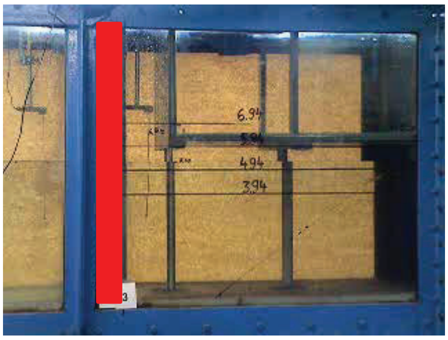
➔ large pressure on little surface



2D TESTS



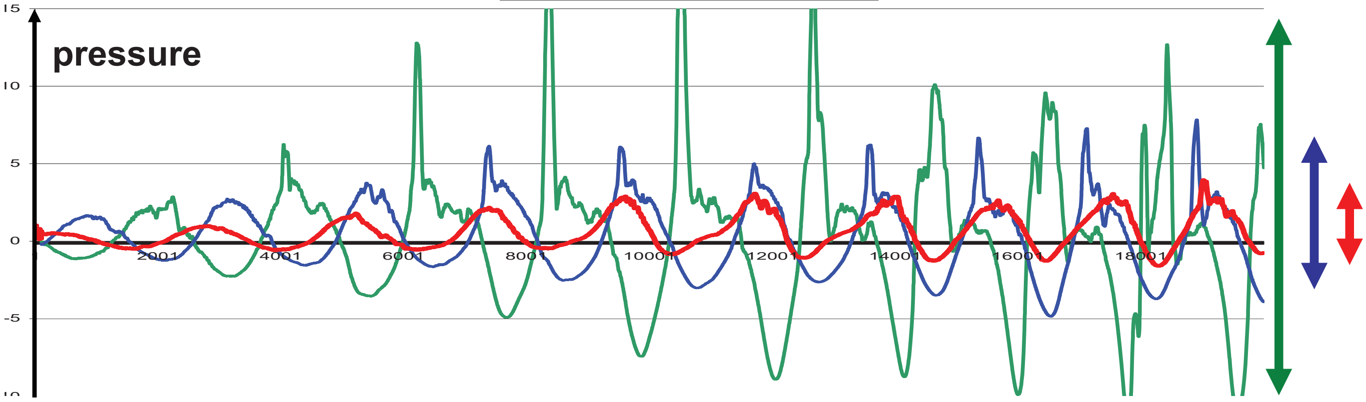


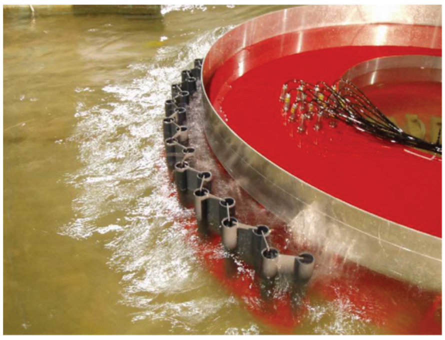


WITHOUT protection
Eff.= 0 %

Mur 1rst
Eff.= 55 %

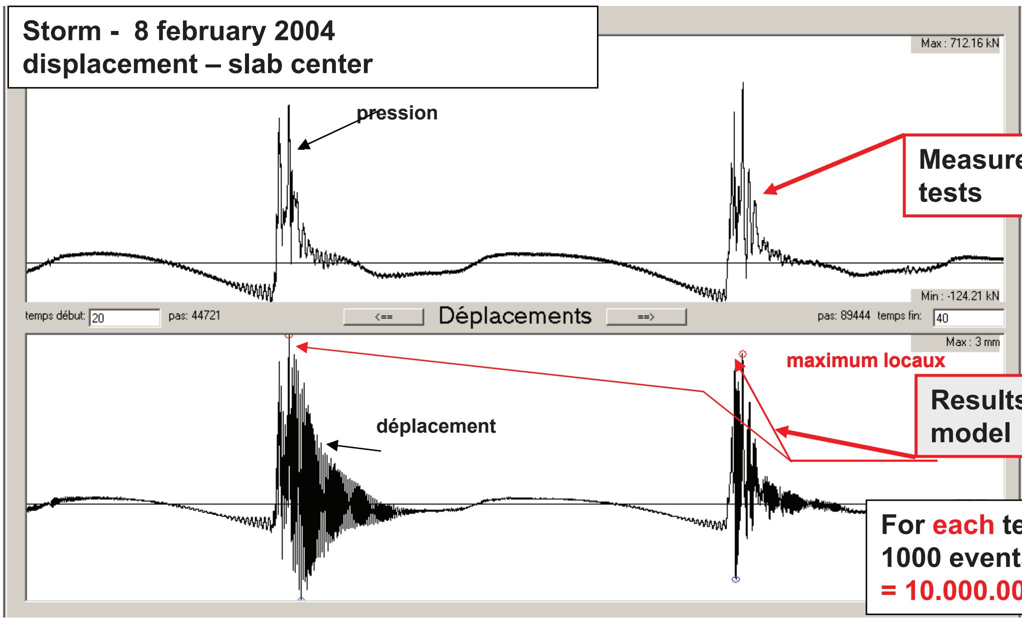
Mur 2nd
Eff.= 81 %





IMPACT

Nature Waves

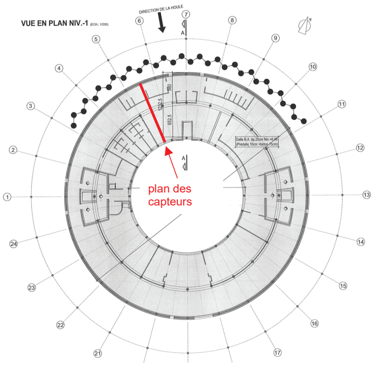


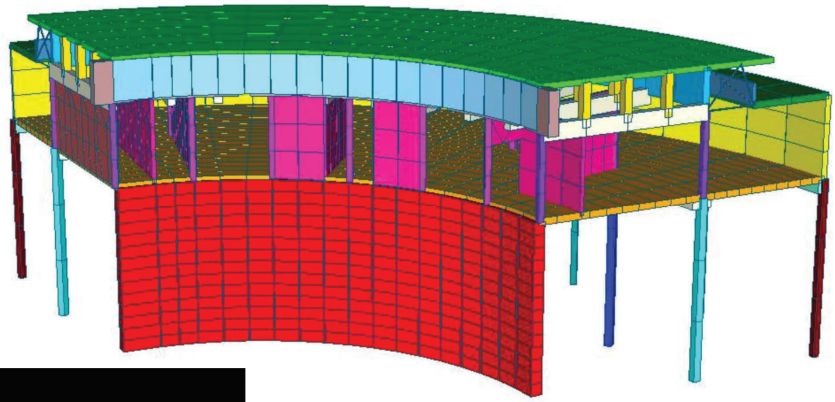
Measurements of pressure tests

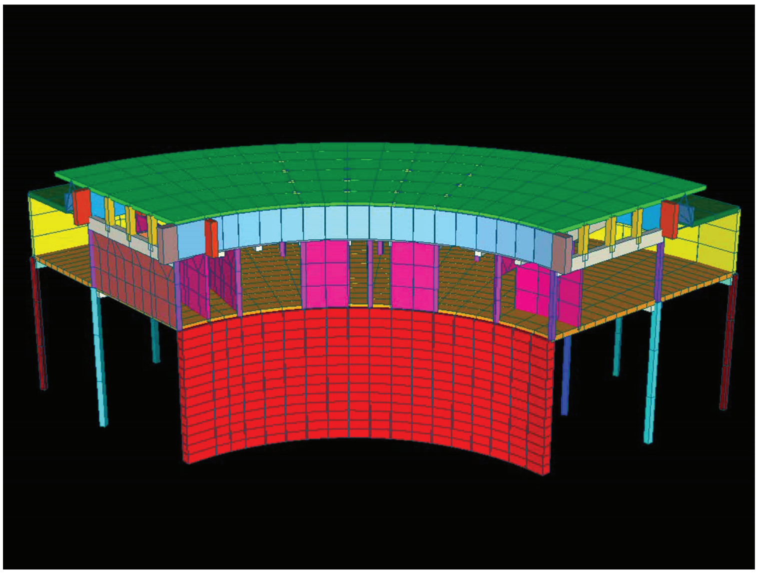
Results obtained with model beg

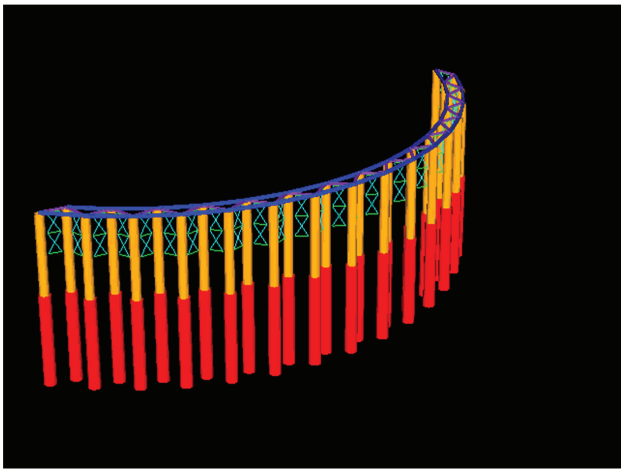
For each test:
1000 events= 1000 waves
= 10.000.000 de measures

Computation model



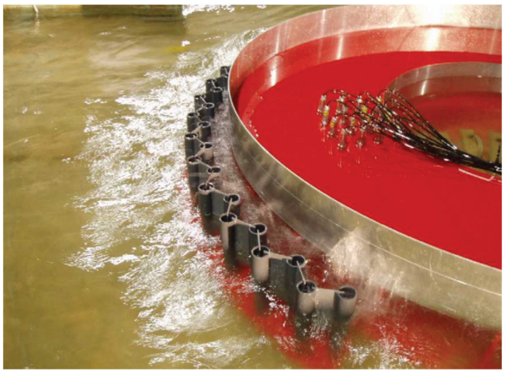


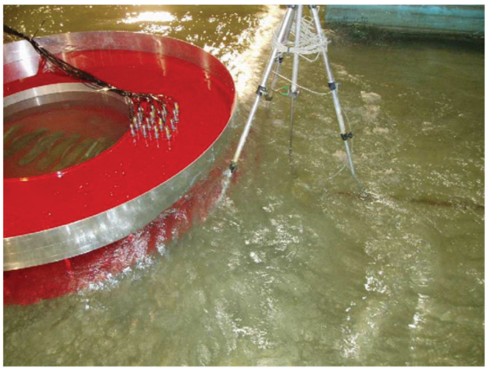




IMPACT

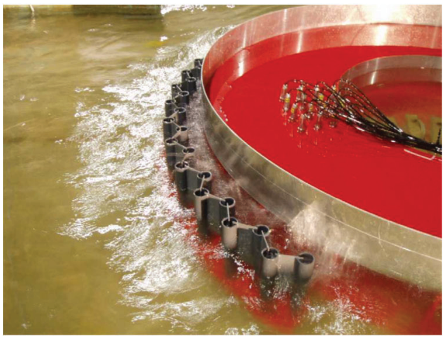
Nature Waves



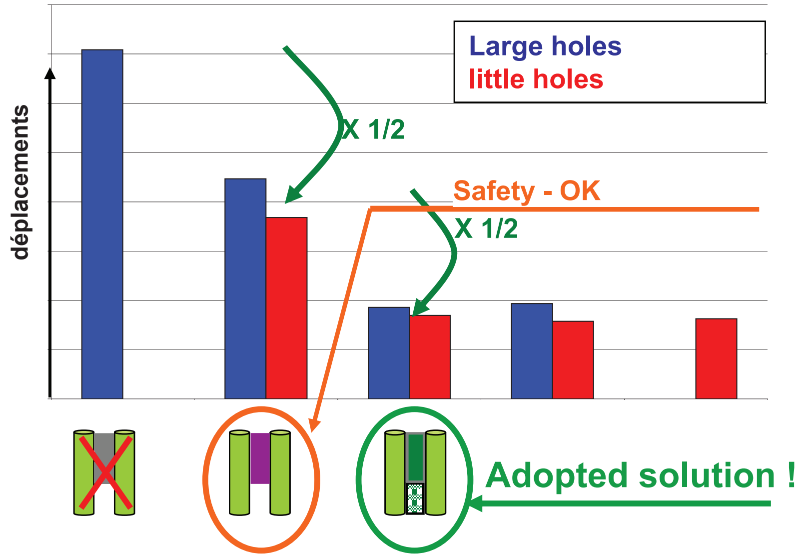


IMPACT

Nature
Waves



Storm - 8 february 2004
displacement – slab center

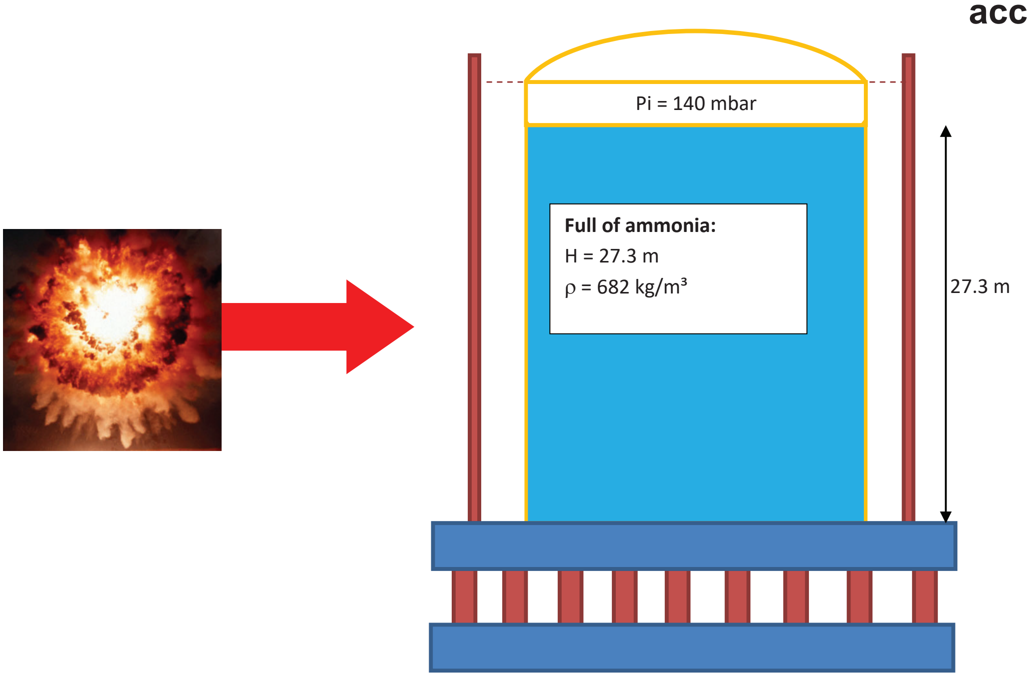


Amonium storage in Tertre (15 000 tonnes)

M.O. : **Yara**
Concrete tank design

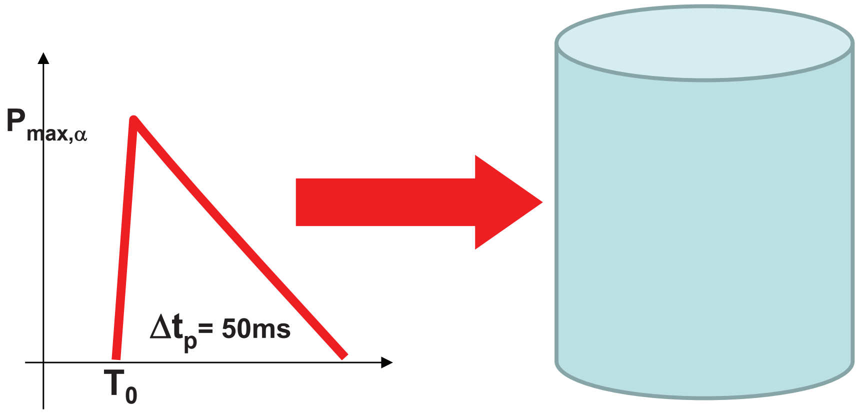
IMPACT

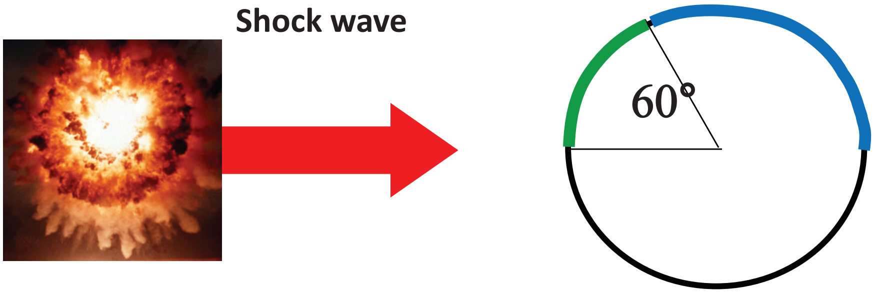
Blast
accidental



IMPACT

Blast accidental





α= [0, 60°] → P_{max}= **45 000** N/m2, $T_{0,60°}$= 0.035 sec
α= [60°, 180°] → P_{max}= **20 000** N/m2, $T_{0,180°}$= 0.095 sec

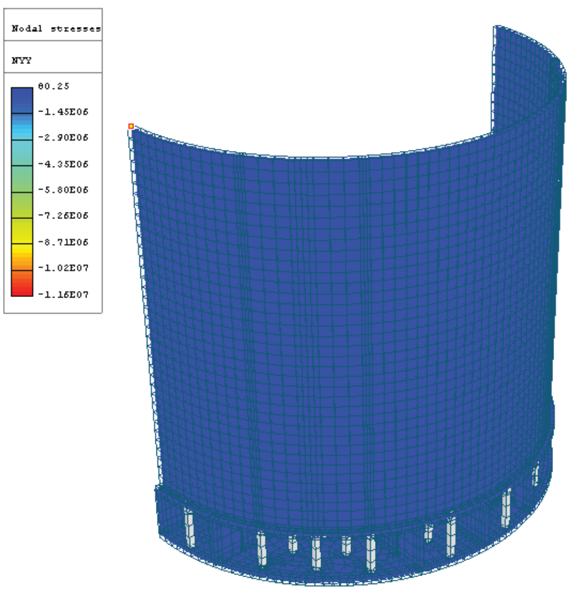
Amonium storage in Tertre (15 000 tonnes)

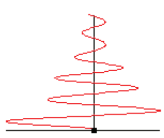
M.O. : **Yara**
Concrete tank design

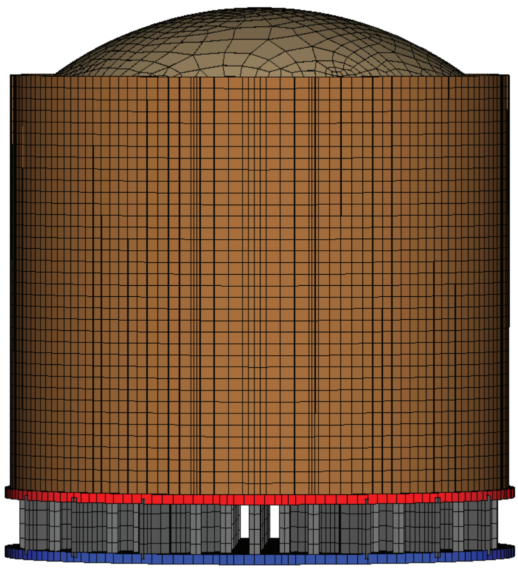
IMPACT

Blast accidental

Explosion simulation







45000 N/m2
4,5 t/m2
DT= 50 msec

Statics – Dynamics

Civil Engineering

Fixed structures

1) larges loads
2) permanent loads
3) **variables laods**

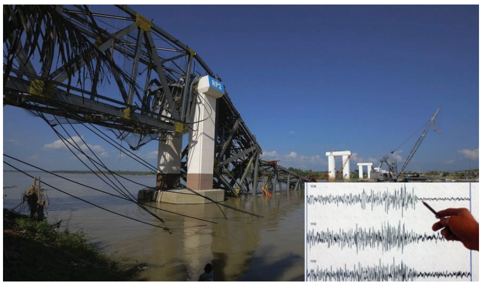
YESTERDAYS
- **rigid structures**

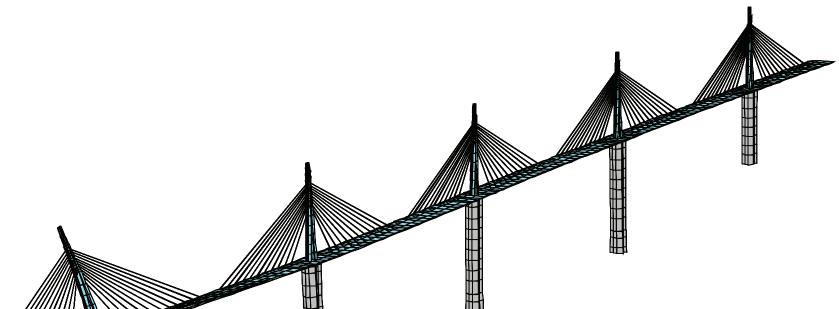
➔ **static…**

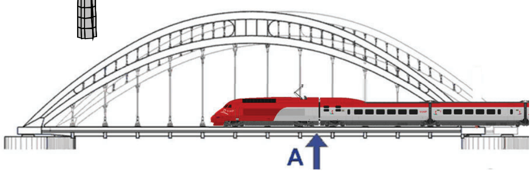
TODAY
- **slender structures**

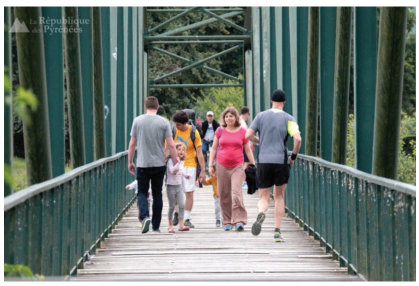
➔ **dynamic**

MORE AND MORE







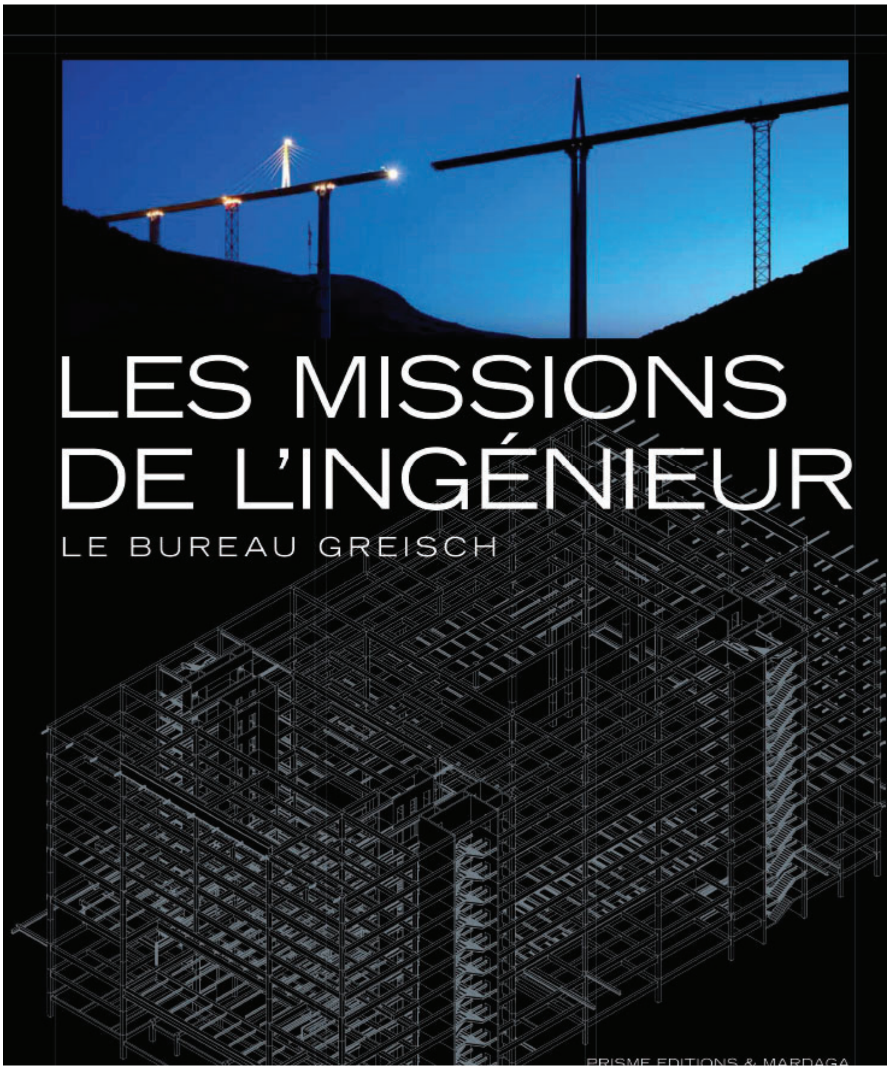


11 may 2022

The dynamics of structures
Civil Engineering

V. de VILLE de GOYET, dr.ir.
Scientific Director, Greisch
Prof. ULG, CHEC

greisch



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- Ingénieur en infrastructures, espaces publics et environnement (h/f)
- Ingénieur en ouvrages du génie civil (h/f)
- Dessinateur – Projeteur en infrastructures, espaces publics et environnement (h/f)
- Dessinateur – Projeteur en ouvrages du génie civil (h/f)
- Ingénieur – chef de projet (h/f)
- Ingénieur en stabilité (h/f)
- Dessinateur – Projeteur en stabilité (h/f)
- Chef de projet en techniques spéciales, orienté HVAC/Sanitaire (h/f)
- Ingénieur en techniques spéciales, orienté HVAC/Sanitaire (h/f)
- Dessinateur – Projeteur en techniques spéciales (h/f)
- Coordinateur BIM (h/f)

VACANCIES – JOB's

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- Nederlandstalige tekenaar – modeller (m/v)
- Dessinateur – Projeteur (h/f)

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- Ingénieur en stabilité (h/f)
- Dessinateur – Projeteur en stabilité (h/f)
- Chef de projet en techniques spéciales, orienté HVAC/Sanitaire (h/f)
- Dessinateur – Projeteur BIM en techniques spéciales (h/f)