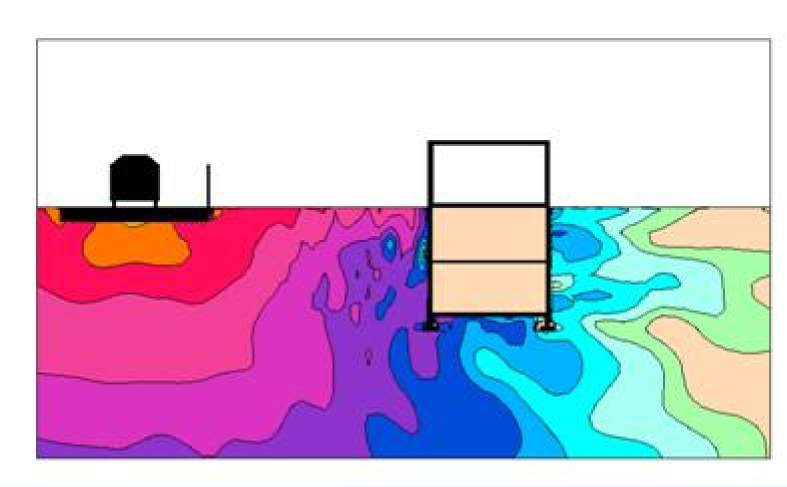
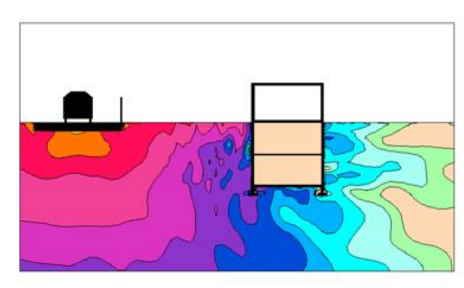
Numerical tools to model ground/structure interaction
(+ Track system modeling and testing)

Philippe JEAN, Michel VILLOT



Introduction



Problem

source : model calibration from ground vibration

Propagation: ground models

Transfer to structure: type of contact, 2D, 3D

Propagation through structures

Acoustic radiation in rooms

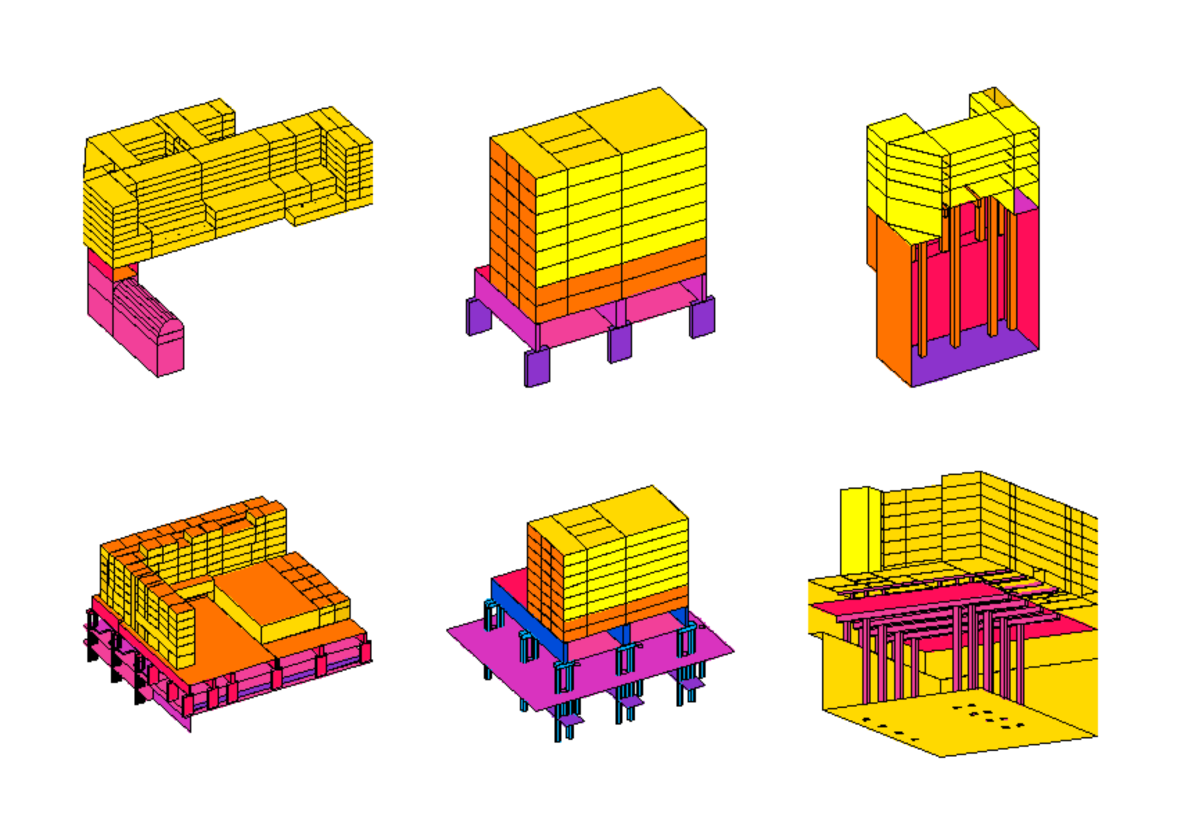
Perception : vibration, ground borne noise

Exposure descriptors

Modèles: Energetic, FEM/BEM, hybrid, mobilities,..

(SEA) Statistical Energy Analysis

Linked to other models for underground structures



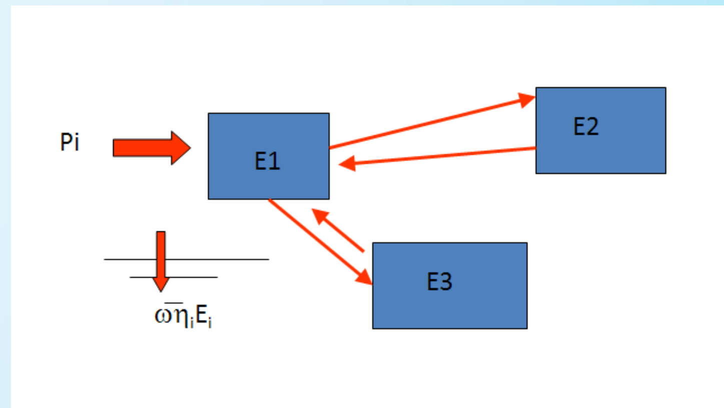
SEA : Principles

Decomposition of the problem into systems: plates/ beams/ columns

Average Energies (F,L,T) per system & per bandwidth (1/3 octave)

Power balance

$$P_i = \omega\eta_i E_i + \Sigma\, \omega\eta_{ij}\,(E_i / ni - E_j / n_j)$$



$$\begin{pmatrix} \eta_1+\eta_{12}+\eta_{13} & -\eta_{21} & -\eta_{31} \\ -\eta_{12} & \eta_2+\eta_{21} & 0 \\ -\eta_{13} & 0 & \eta_3+\eta_{31} \end{pmatrix} \begin{Bmatrix} E1 \\ E2 \\ E3 \end{Bmatrix} = \begin{Bmatrix} P_i/\omega \\ 0 \\ 0 \end{Bmatrix}$$

SEA : limitations

Minimum of modes per bandwidth required

Problem in Low Freq for longitudinal waves:
In practice:
- OK for bending excitation down to 50 Hz
- NO for in plane excitation

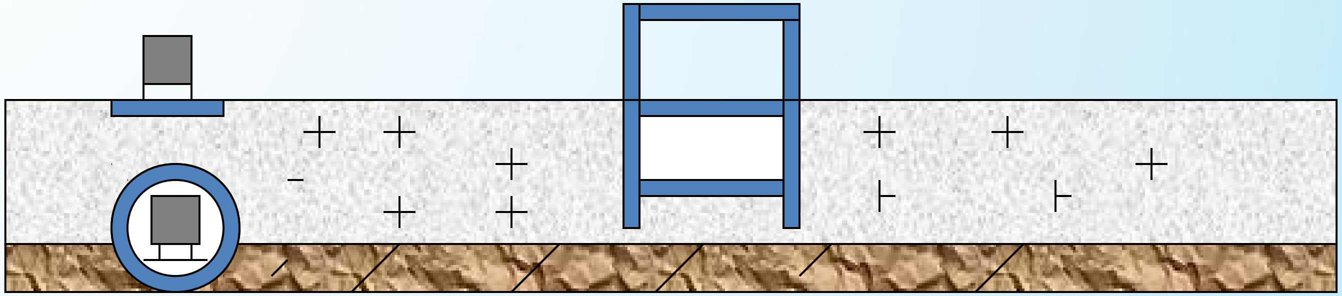
$\Rightarrow$ Hybrid Models SEA/ modal / waves

Models adapted to Low Frequencies: FEM / BEM

FEM/BEM methods Software MEFISSTO

FEM : Finite Element Method
BEM : Boundary Element method

Interaction Grounds/Structures (2D & 2.5D)

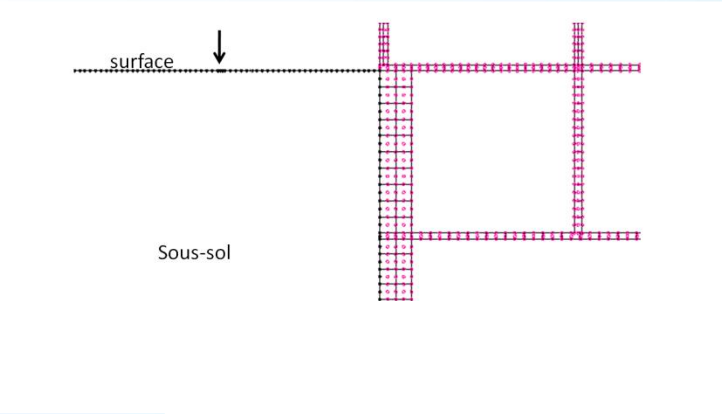


$$\bar{u}(M).\bar{I}(M) = \int_S [\bar{\bar{T}}(Q,M).\bar{u}(Q) - \bar{\bar{G}}(Q,M).\bar{t}(Q)]dS + \bar{h}(M)$$

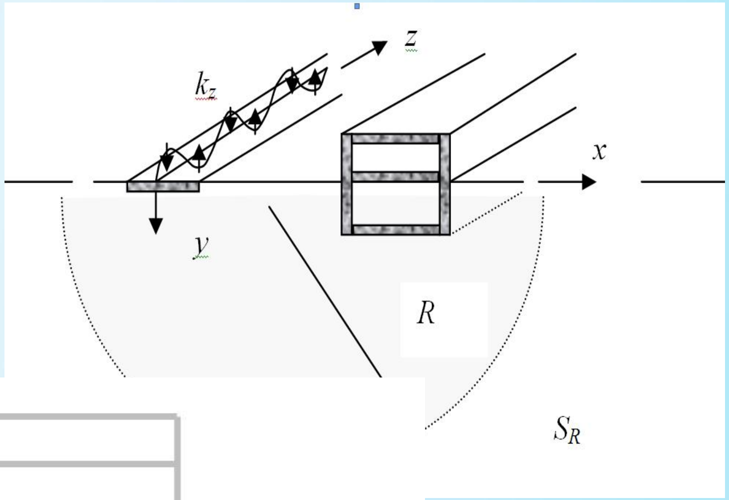
- Separation into sub-domains
- Integral Representation BEM (collocation) (ground or thick structures)
- or FEM: condensation at boundaries (structure or portions of ground)
- Continuity of displacements and/or stresses at interfaces

FEM/BEM methods

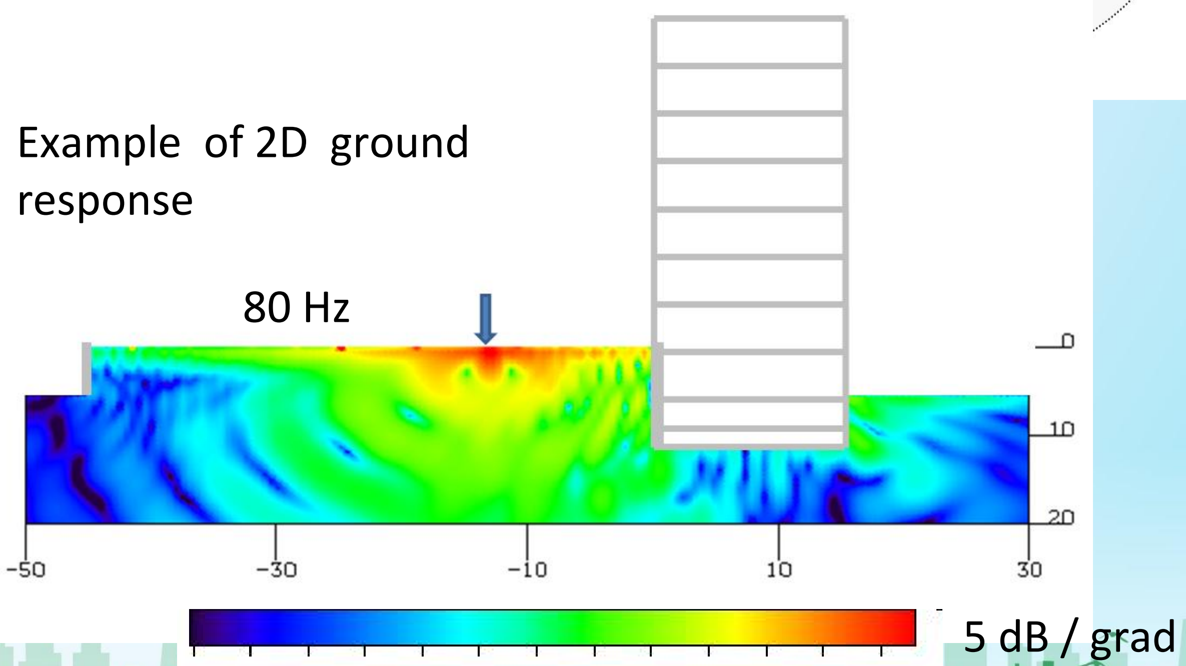
Example of 2D meshing



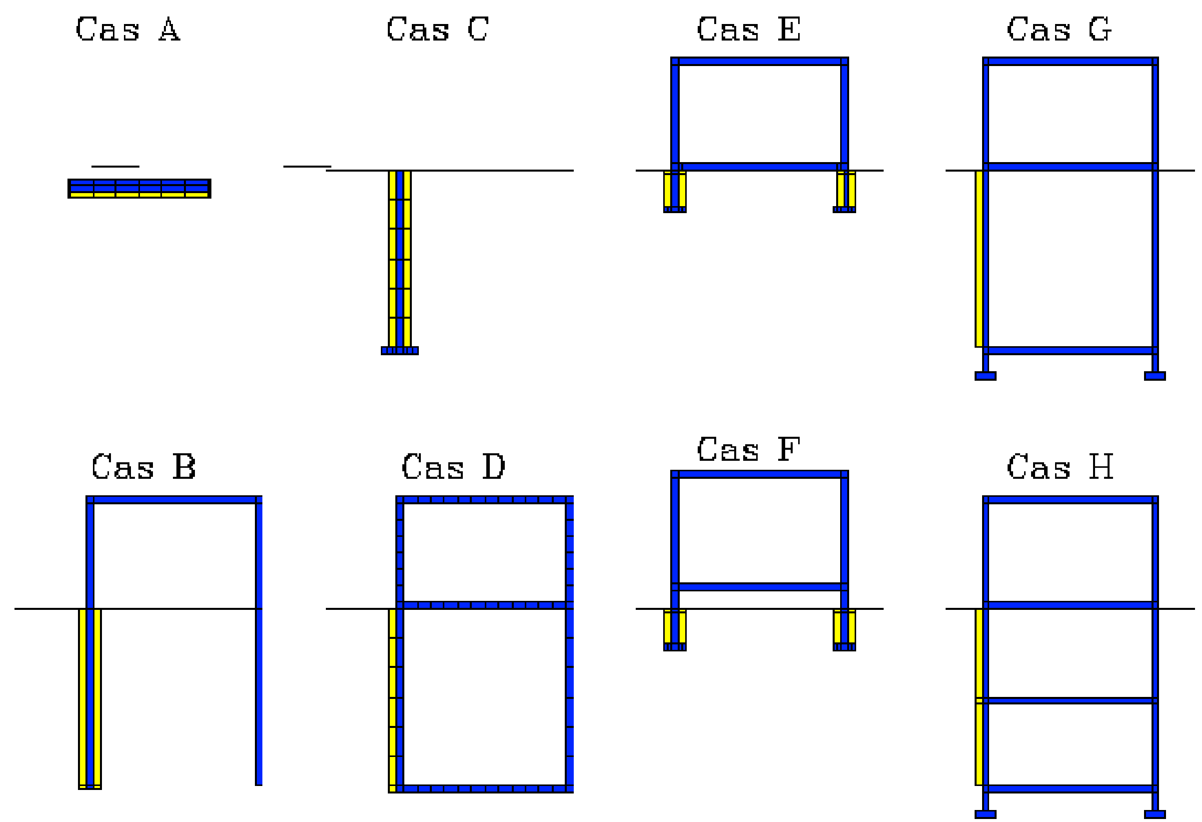
2.5D approach



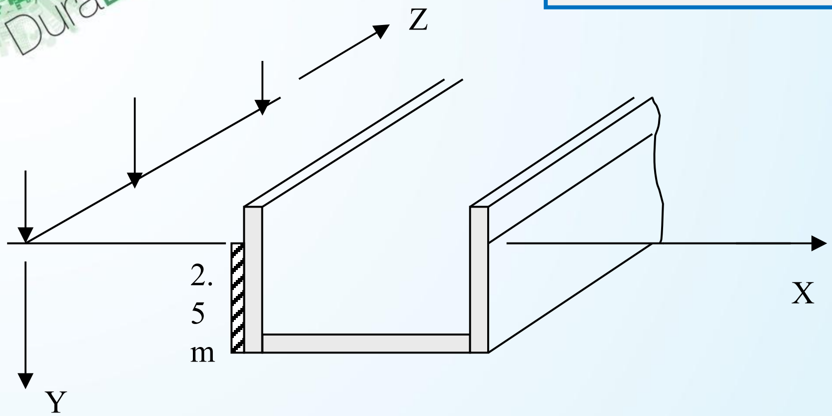
Example of 2D ground response



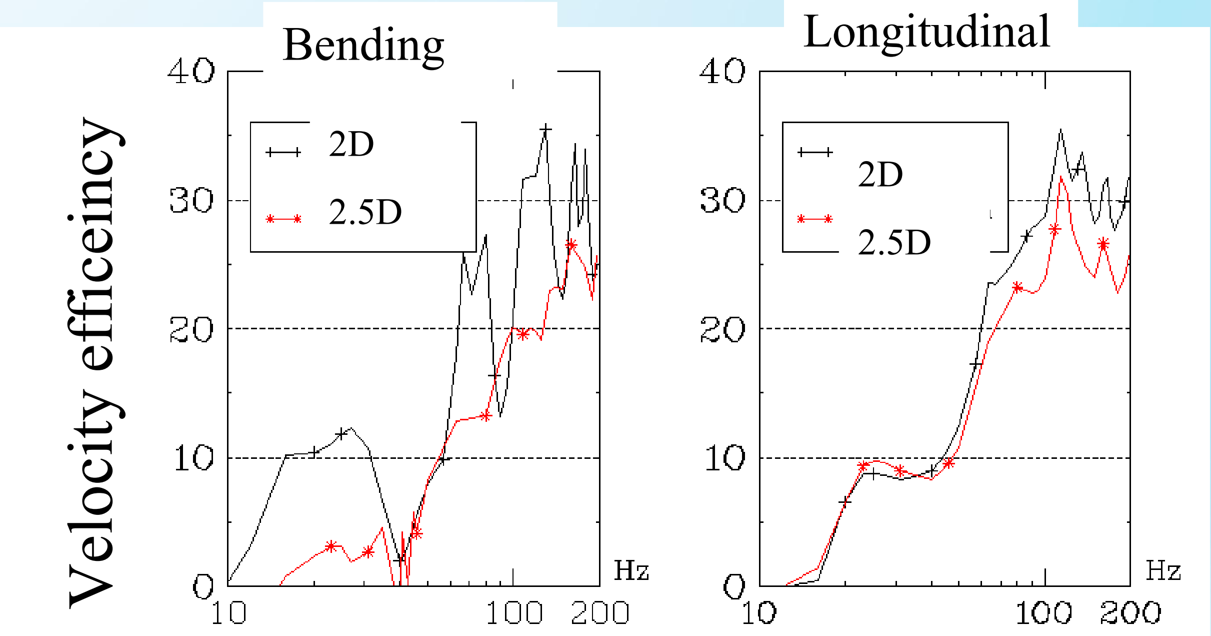
Foundation ground lining *(ADEME)*



BEM 2.5D

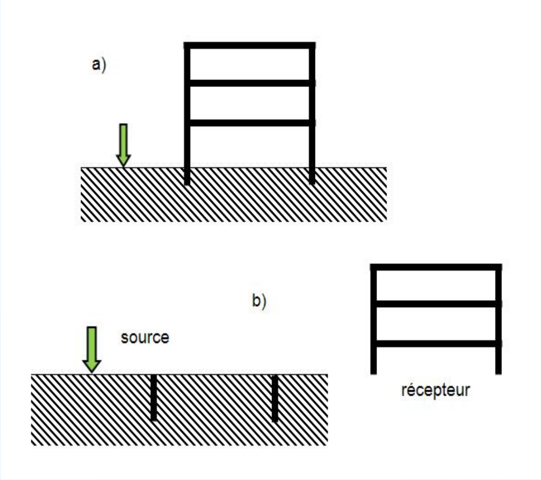


Example of calculated efficiency 2D /2D ½



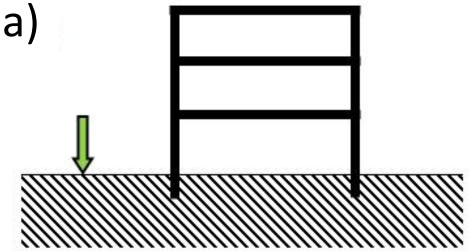
Source Receiver Mobility Approach

PhD Pierre ROPARS (2009-2011)
CSTB/ Univ Paris Est



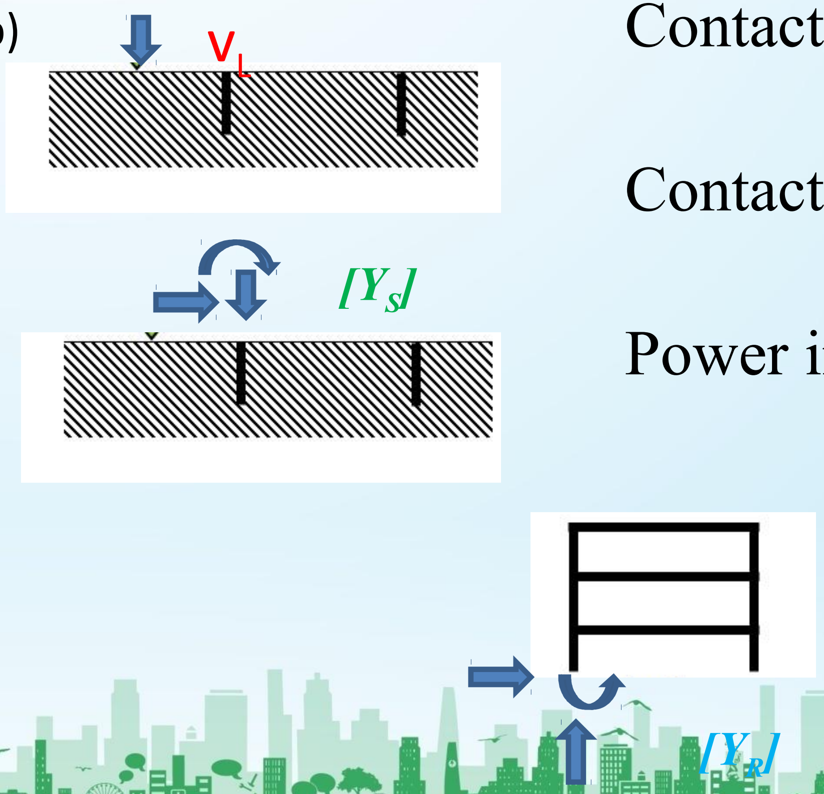
PRINCIPLE

a)



Separation of a problem into 2 parts
(a) / (b) : source/receiver

b)



Contact force $(f_c) = ([Y_S] + [Y_R])^{-1}\,(v_L)$

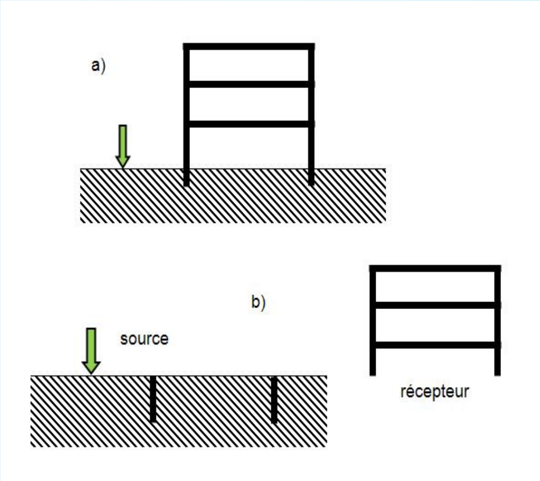
Contact velocity $(v_c) = [Y_R]([Y_S] + [Y_R])^{-1}(v_L)$

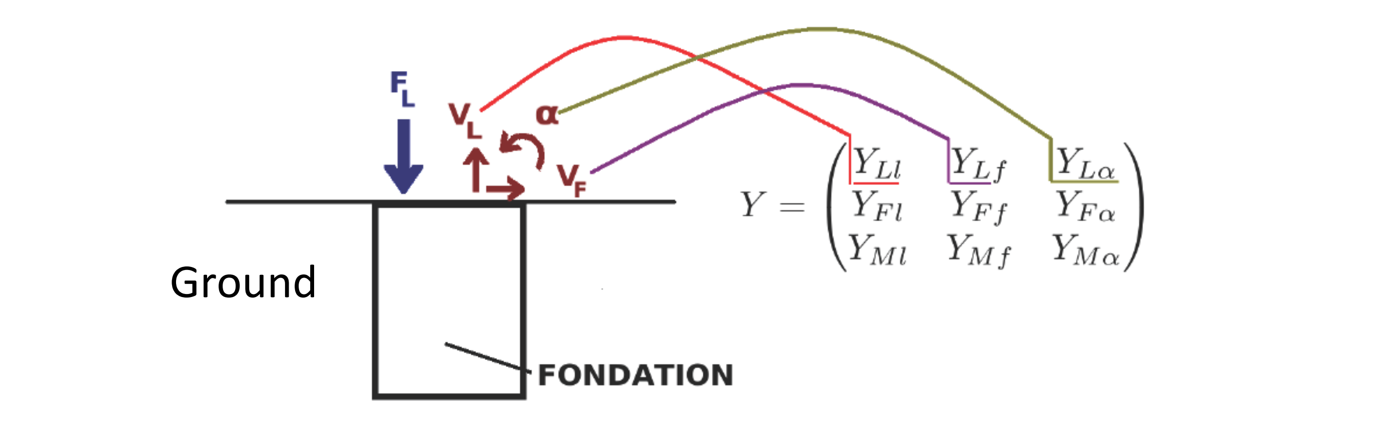
Power into building $\Pi = 1/2\ Re\{\,(f_c)^T(vc)^*\}$

Models used:

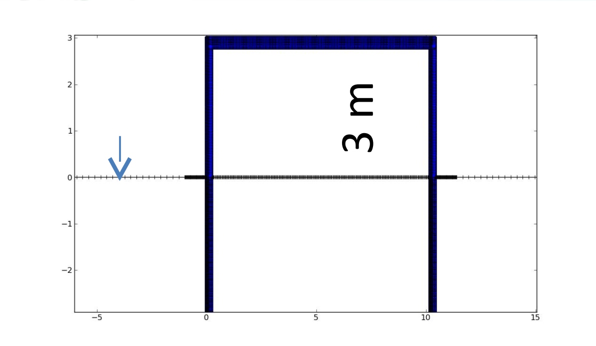
BEM/FEM (Mefissto) : ground + foundations

FEM (NASTRAN) : Buildings

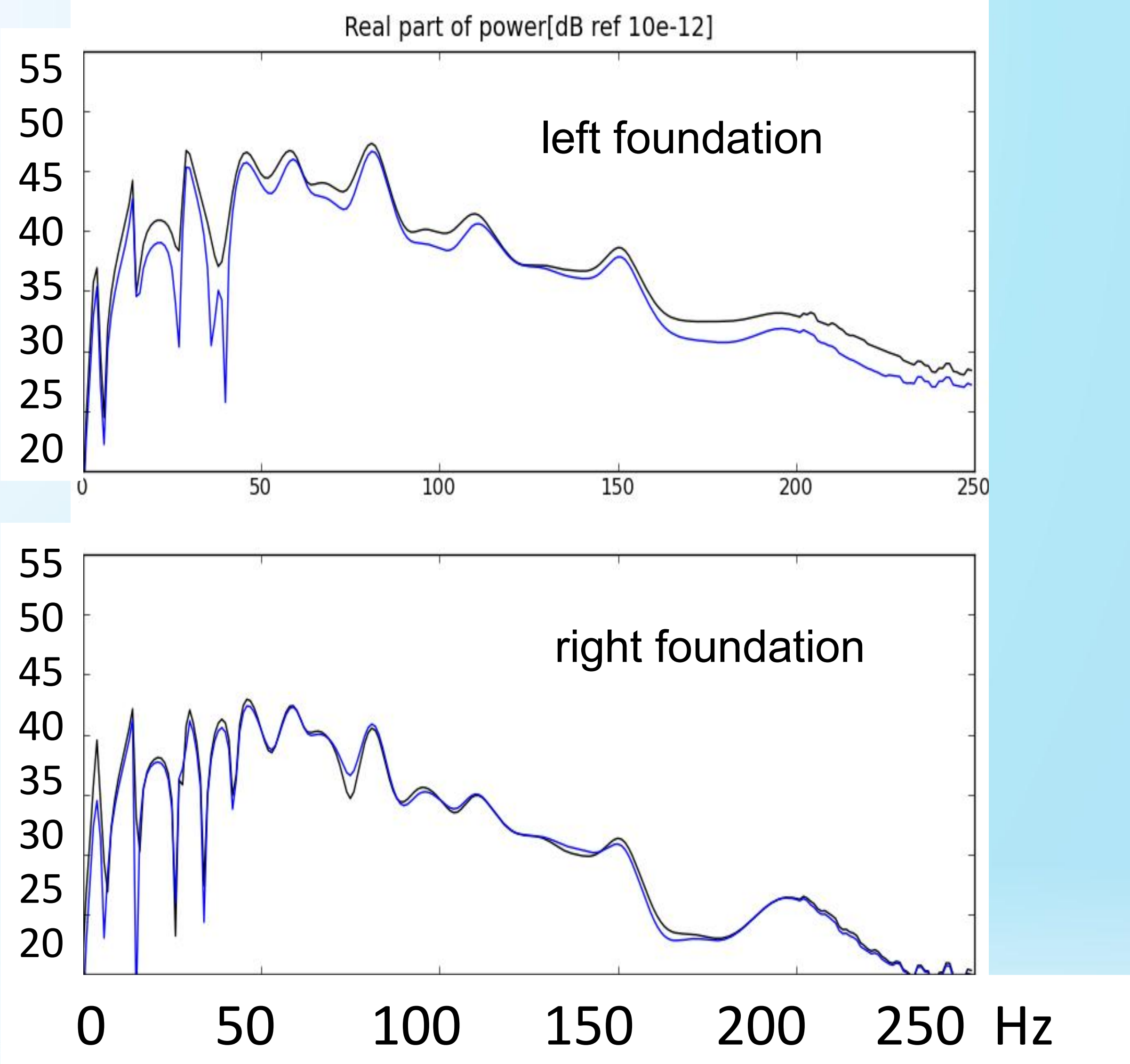




Mobility Technique: VALIDATION



10 m

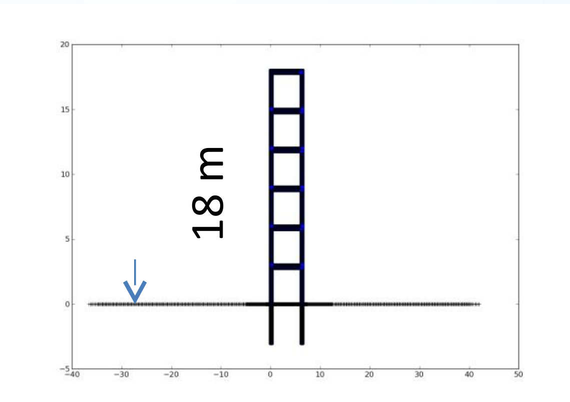


Total injected Power:

Mobility Approach

MEFISSTO

Mobility Technique: VALIDATION

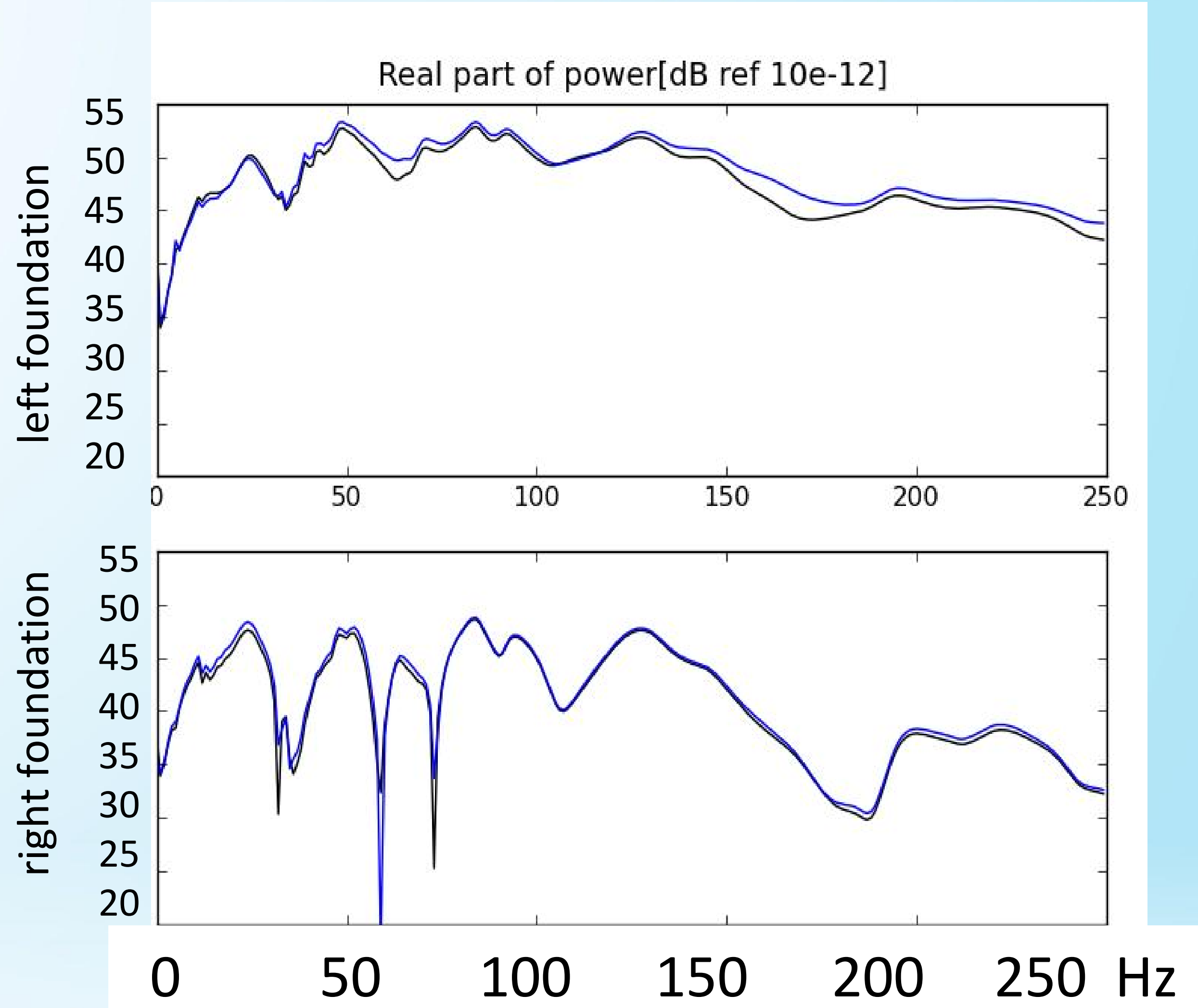


10 m

Total injected Power:

Mobility Approach

MEFISSTO



Buildings close to
Railway Tracks
Validation + influence of
structural modifications

VIBSOLFRET
SNCF/CSTB/SATEBA

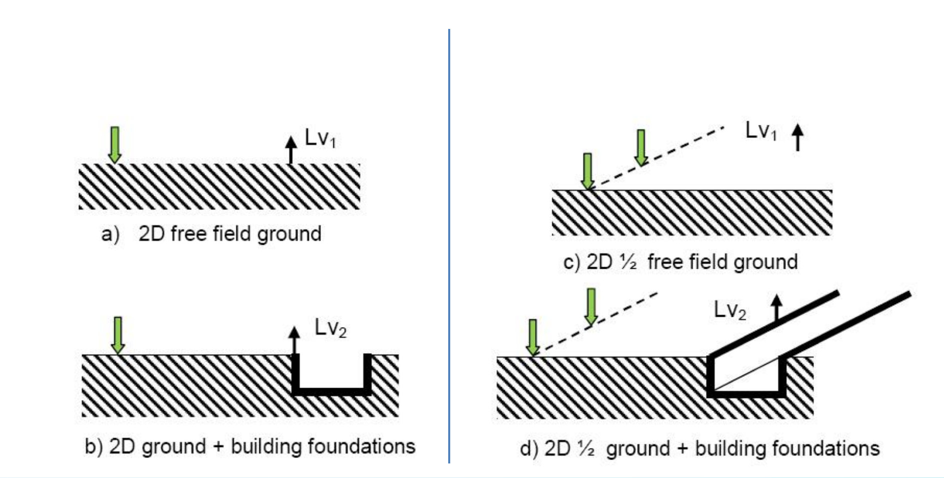
VIBSOLFRET ; source calibration

SNCF/CSTB/SATEBA

1. Source calibrated from measured ground vibration

2. Transfer Function : H = LV(ground only) – LV(ground+foundation)

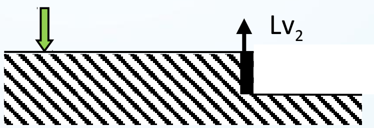
computed in 2D and 2D ½



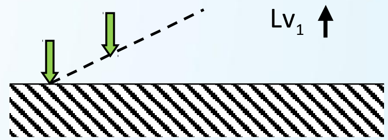
3. Extrapolation to other situations: BEM2D computations:
   Calibration of 2D BEM computations corrected by : H(2D) / H(2.5D)

Calibration correction factor 2.5D / 2D

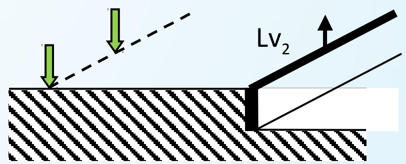
a) 2D free field ground



b) 2D ground + building foundations

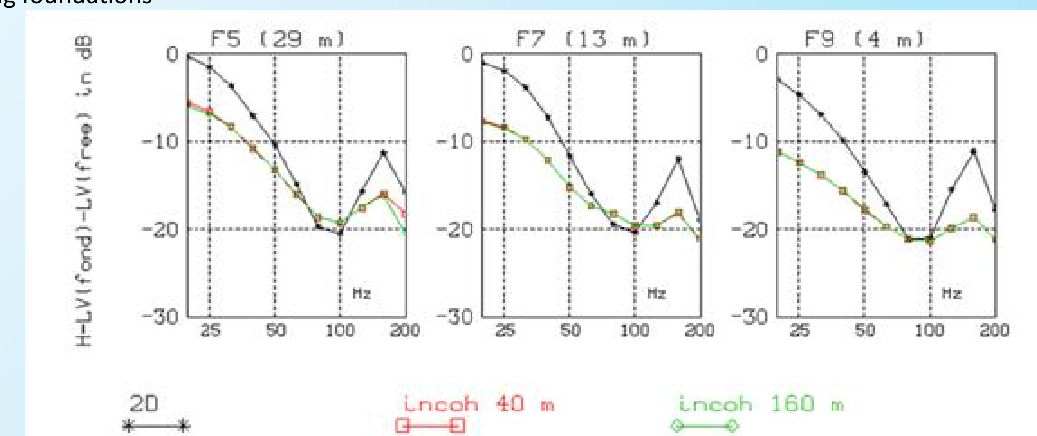


c) 2D ½ free field ground

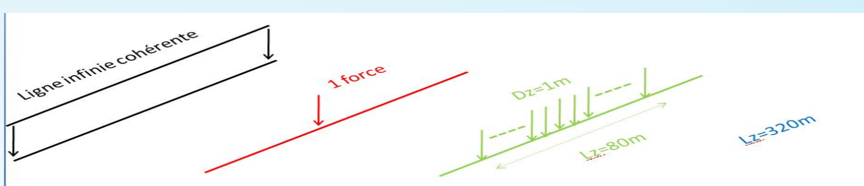


d) 2D ½ ground + building foundations

H=LV(ground)-LV(foundation)



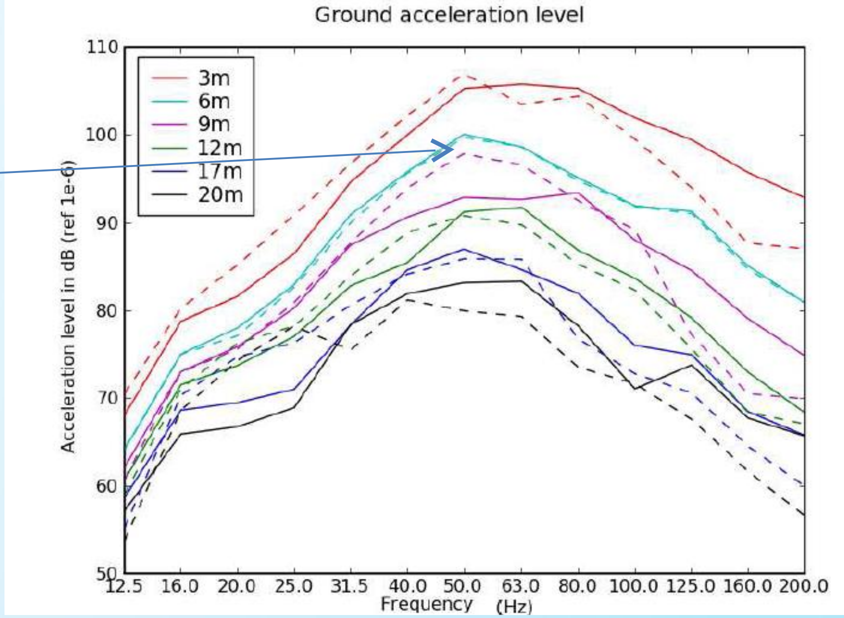
Coherent line, point source forces every meter along 80 m, along 320 m



VIBSOLFRET ; ground calibration

SNCF/CSTB/SATEBA

Surface Acceleration at d m to the track
BEM2.5D referenced to d=6 m



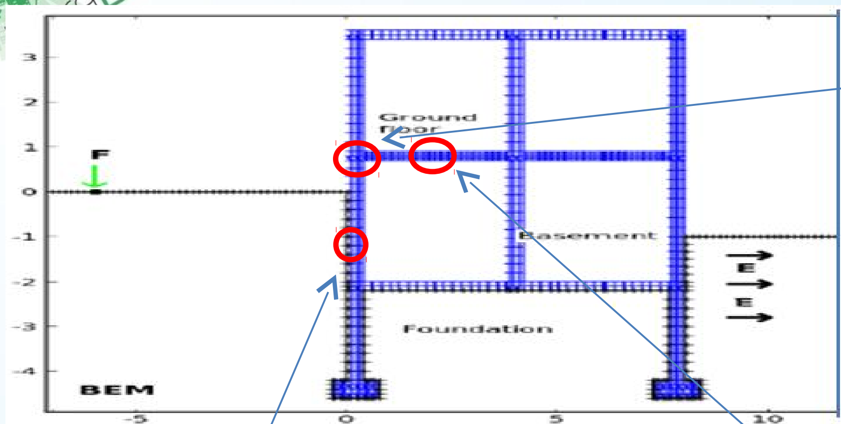
Use of 3 types of homogeneous ground
- standard
- rather hard
- rather soft

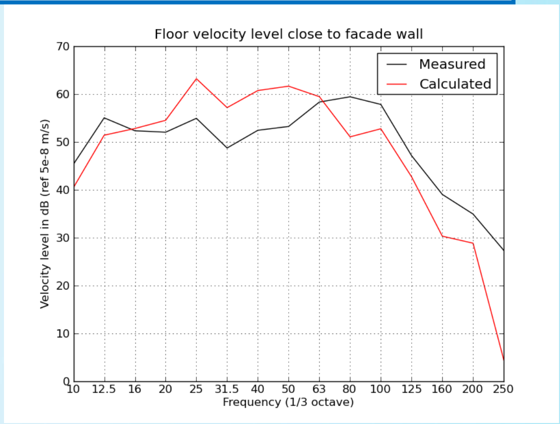
Ground evaluated by comparing calculated and measured attenuation spectra

Attenuation with distance:
MEFISSTO 2.5D (__) measured (- - -)

VIBSOLFRET ; experimental validation

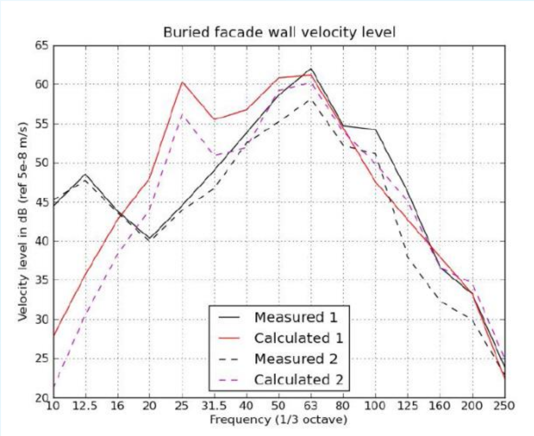
SNCF/CSTB/SATEBA

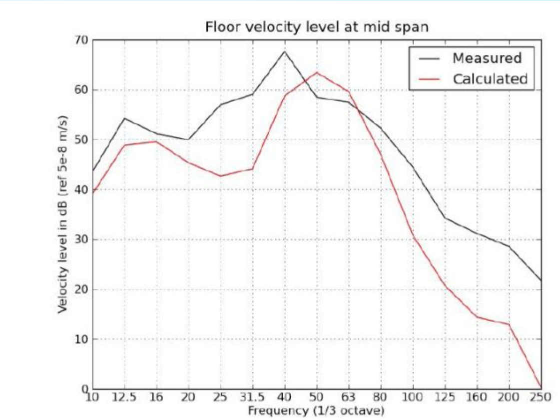




Vertical velocity on the facade

Measured
Computed



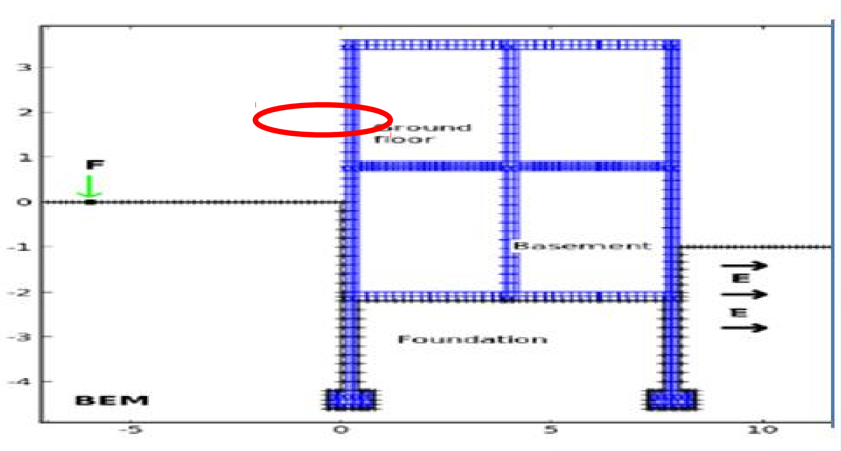


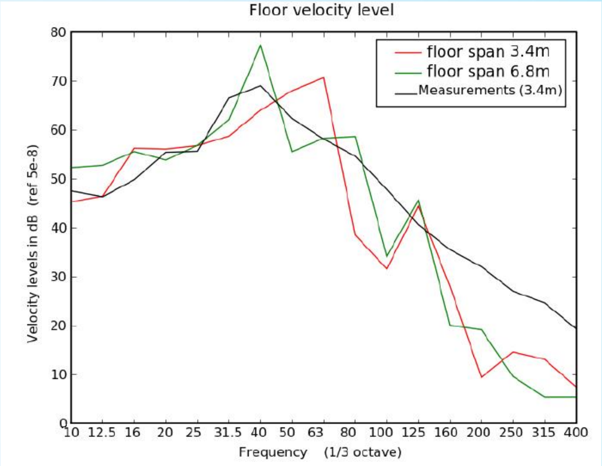
Horizontal Velocity: burried front wall

Bending Velocity on floor (Centre)

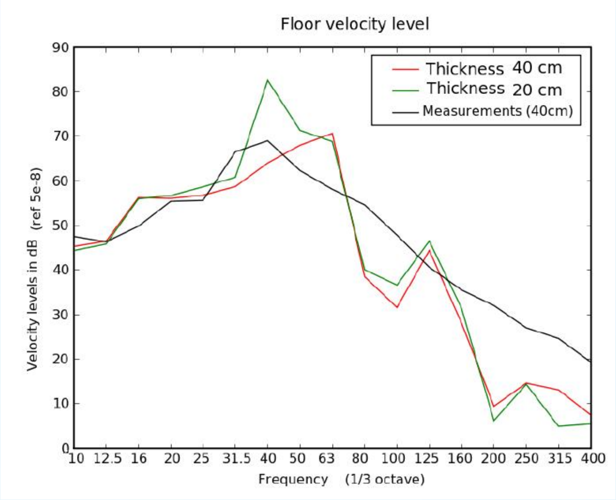
VIBSOLFRET ; influence of structural modifications

SNCF/CSTB/SATEBA

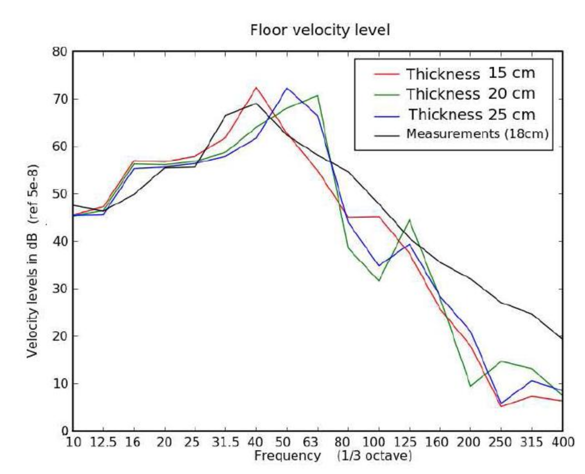




Influence of floor dimension



Influence of facade thickness



Influence de floor thickness

VIBSOLFRET ; vibration descriptors

SNCF/CSTB/SATEBA

Descriptors for annoyance (e.g. Norwegian standard NS 8176) integrated into the numerical model

Measured situation:

dist to tracks=6m, h facade=40cm, h floor=20cm, floor length=3.4 m

Indicator $V_{w,95}$ for simulated situations

	Measured (6 m)	Same Building at 20 m	h facade 20 cm	h floor 15 cm	h floor 25 cm	Floor length= 6.80m
$v_{w,95}$ mm/s	0.11	0.04	0.89	0.26	0.11	0.56

Class A ($v_{w,95}$ < 0.1): vibrations non percieved

Class B (0.1< $v_{w,95}$ < 0.15): low % of annoyance (<10%) likely to occur

Class C (0.15< $v_{w,95}$ < 0.3): about 15% of people annoyed (recommended for new buildings)

Class D (0.3< $v_{w,95}$ < 0.6): about 25% of annoyance likely to occur (recommended for existing buildings if upgrading costs to reach class C are too high)

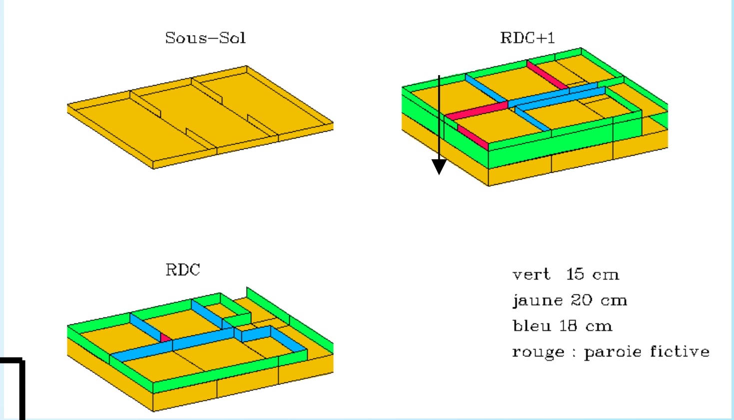
Sources inside buildings:

Drills, impact hammer... (bending excitation)

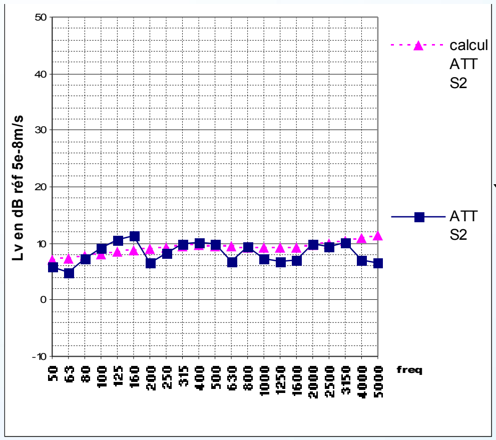
BOUYGUES/CSTB

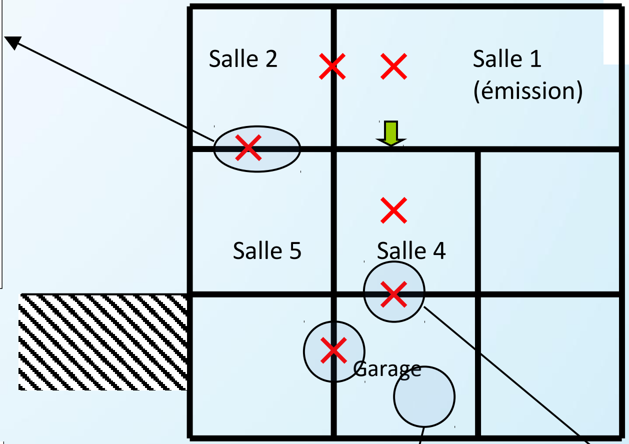
Vibration Transfers : SEA

Buildings under construction

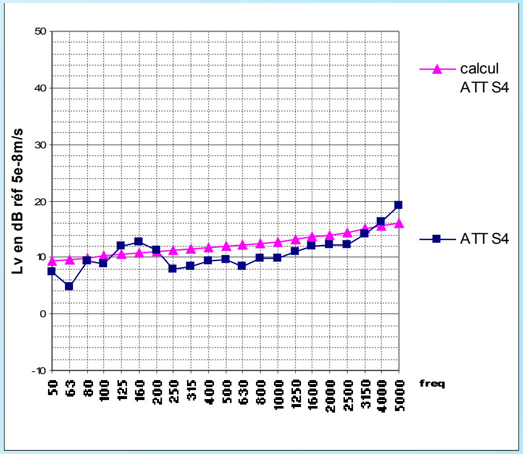


Velocity Levels

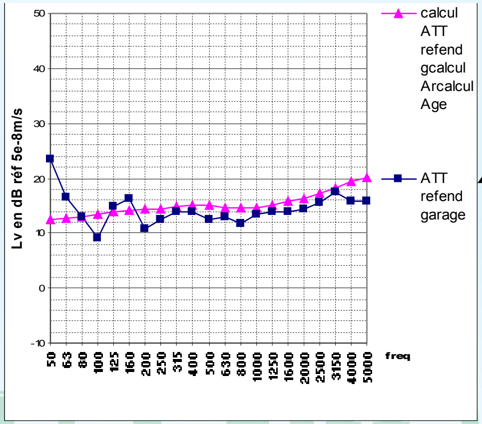


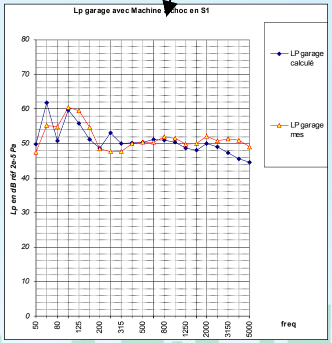


Velocity Levels



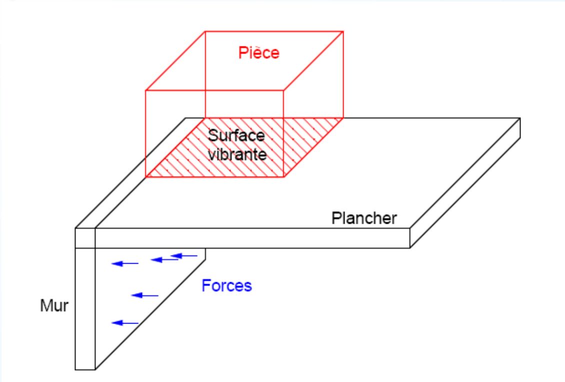
Velocity Levels





Sound Levels

Acoustic Radiation into rooms
Computations
PhD Guillaume COCQUEL (2005-2008) RATP/CSTB



$$\sigma = \frac{\Pi_{rad}}{\rho_0 c_0 S < v^2 >} \quad \text{where} \quad \Pi_{rad} = \frac{< p^2 > A}{4 \rho_0 c_0}$$

Modelisation of Acoustic Radiation

Analytical model => floor velocity V

Acoustic Radiation: V, G (room response) => P

$$p(M) = \int_{S_v} j\omega\rho_0 \times v(Q) \times G_v(M,Q) \times dS(Q)$$

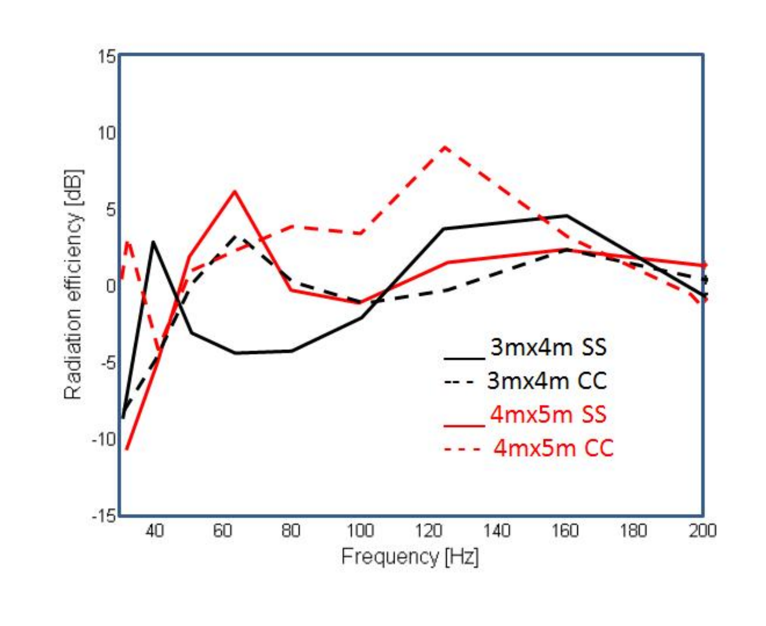
Tr => A A et P^2 => Π_{rad} => σ

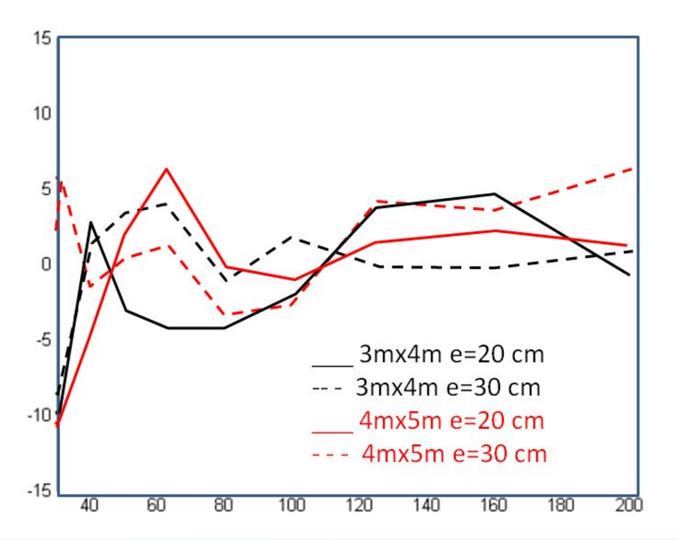
Guillaume COCQUEL RATP/CSTB

Effect of characteristics on the radiation factor

2 dimensions 3x4 m2 & 4x5 m2
2 boundary conditions: simply supported (SS) & clamped (CC)
2 thicknesses : 20 cm & 30 cm

Example of calculated radiation efficiency

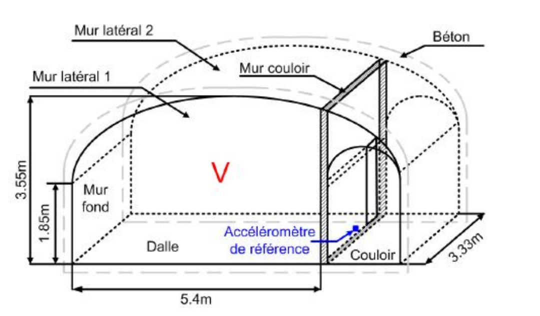




=> Estimation of uncertainty range

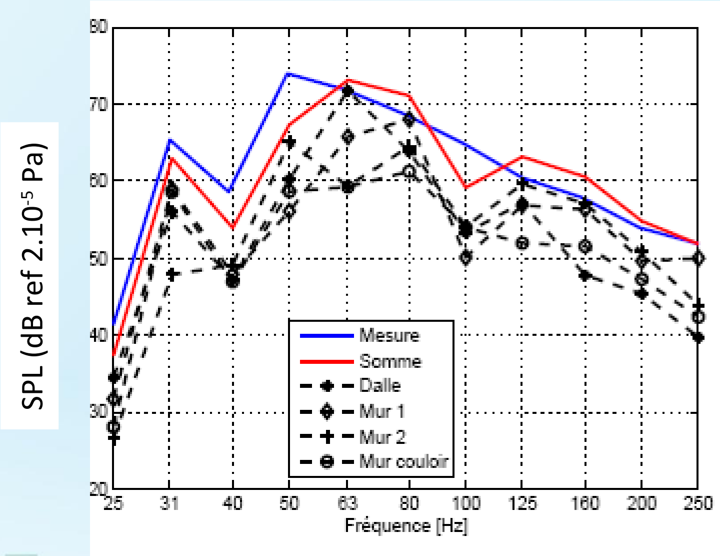
Acoustic Radiation into volumes: measurements

Technical Room at RATP



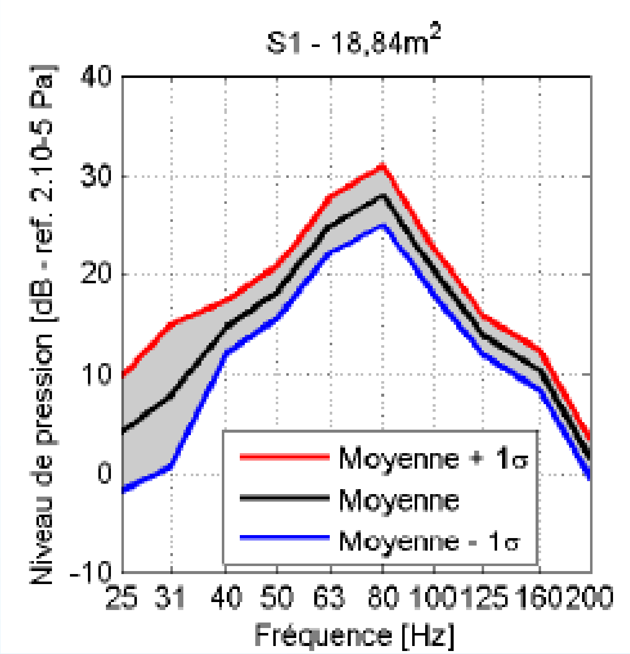
Measurement of Lv (floor and walls)

Estimation of sound from Lv and calculated radiation efficiency
σ et Tr => Π_{rad} => LP

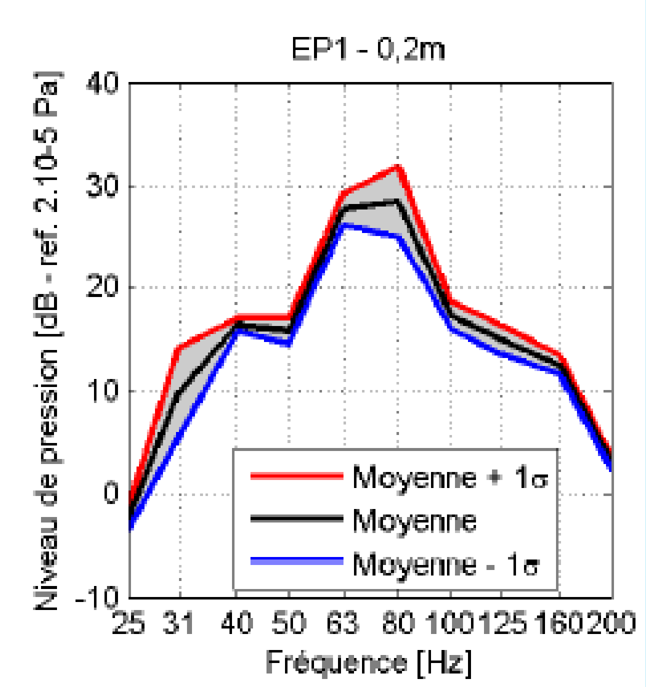


Acoustic Radiation into volumes: variability

Computed variability : mean value and standard deviation



Blocked floor dimensions



Blocked floor thickness

- Salle de séjour : S1 = 18,24m^2, S2 = 19,11m^2, S3 = 20,00m^2, S4 = 20,91m^2, S5 = 21,84m^2,
- Hauteur : H1 = 2,5m, H2 = 2,6m, H3 = 2,7m, H4 = 2,8m, H5 = 2,9m, H6 = 3m,
- Epaisseur de la dalle : EP1 = 0,200m, EP2 = 0,225m, EP3 = 0,250m, EP4 = 0,275m, EP5 = 0,300m,
- Conditions aux limites : Encastré (CC), Appuis Simples (SS).

Track work: model

Track system modeling:

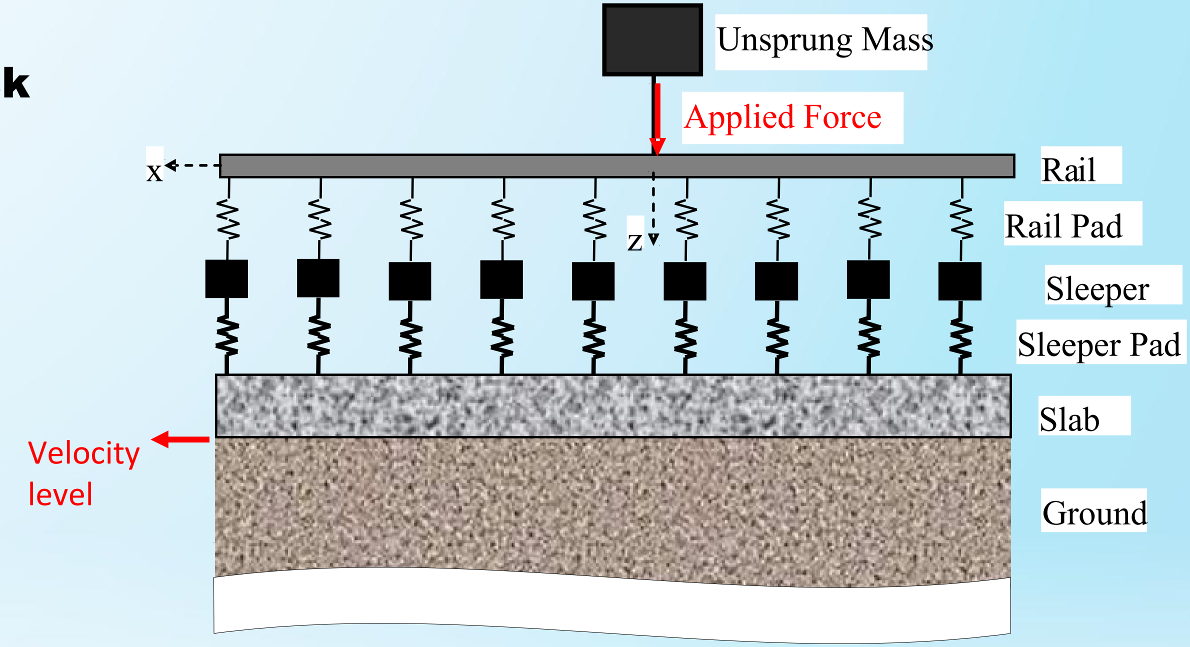
- CASC software based on wave approach on infinite beam structures

- comparison between track systems (insertion gain)

- **laboratory test rig optimization**

Output: transfer mobility between velocity level at ground / track system interface and applied force

Model main parameters



Track work: test rig

Laboratory test rig:

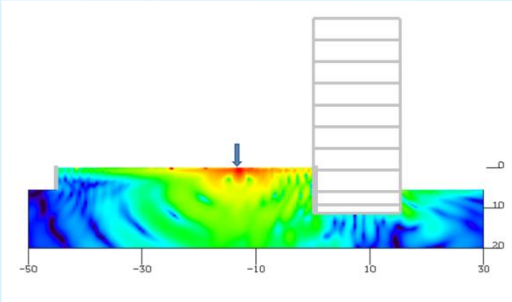
- **NF ISO EN 10846-2 implemented on whole tie (performance of resilient layer)**

- **setup for insertion loss measurements**

CASC software and test rig used for Eurostar track work in London (SATEBA / CSTB); ongoing work for tramway tracks

- CSTB / SNCF track department (2008)
- SNCF / RFF / CSTB / SATEBA on freight trains (VIBSOLFRET 2007-2008)

Conclusions & perspectives



•SEA: valid for bending excitation above 50 Hz

•BEM/FEM approaches

•Source /receiver approach using mobilities: ground/foundation: BEM2.5D, (3D under way)
building (upper structure) : commercial software (Nastran,...)

•Superstructure in 2D: results are sufficient for a parametric study

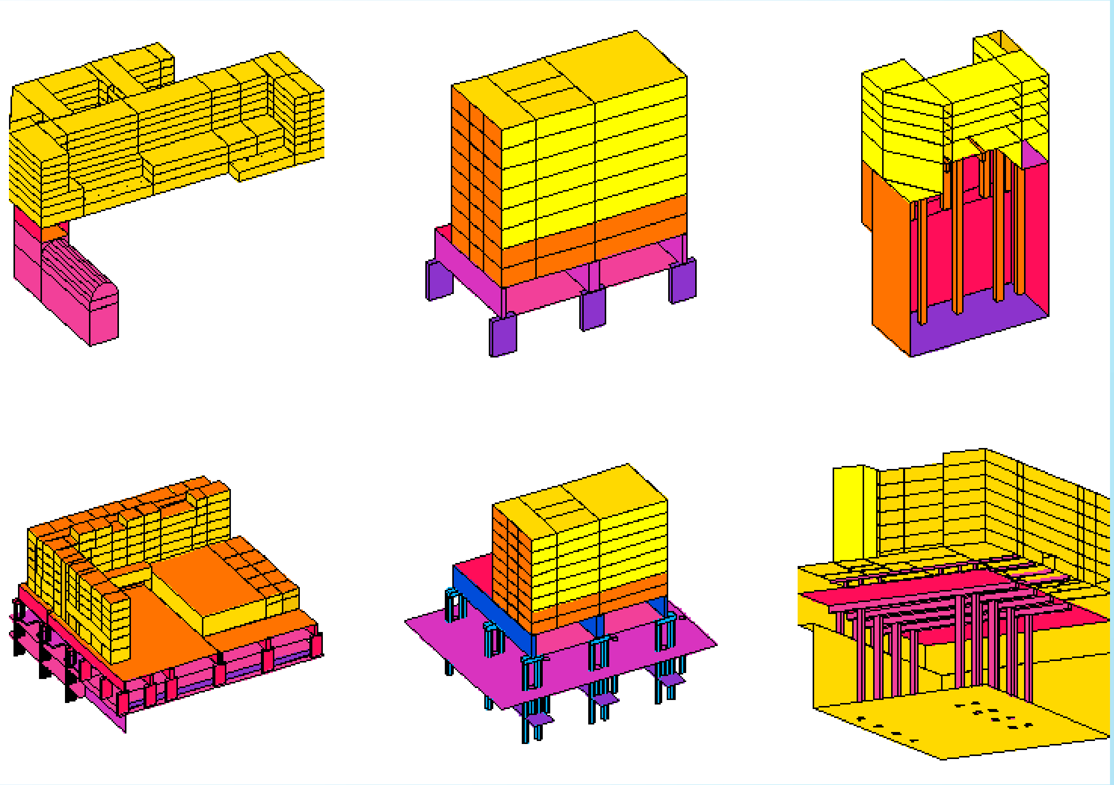
•Effect of structural modifications estimated : increase of data in empirical model (data base)

•Estimation of structure-borne vibration levels and ground borne noise levels in buildings

•Exposure descriptors for human perception included (post-treatment stage)
=> expression of a relation between annoyance and structural parameters possible

Examples of application : Large Projects in Paris

Eole

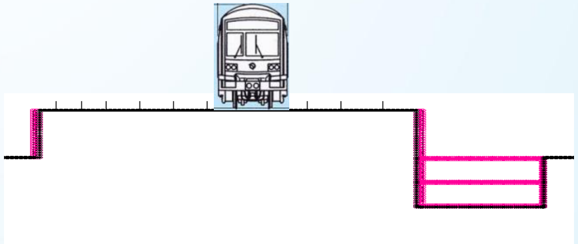


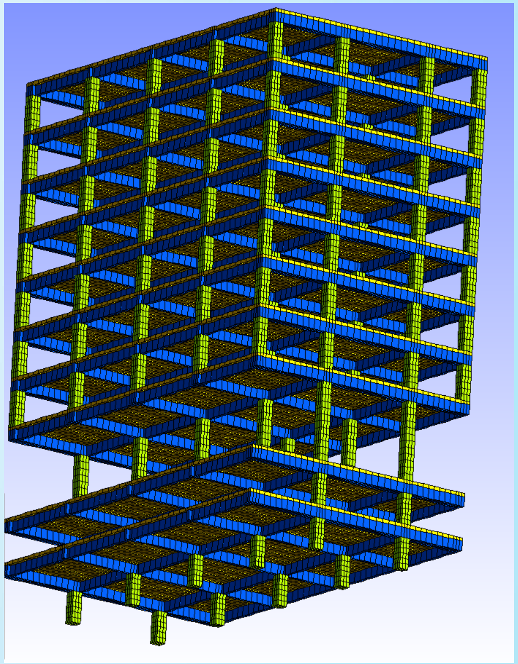
RERD

SEMAPA slab (Austerlitz)

Structures above ground	SEA
Structures above ground	dedicated models (waves/SEA)

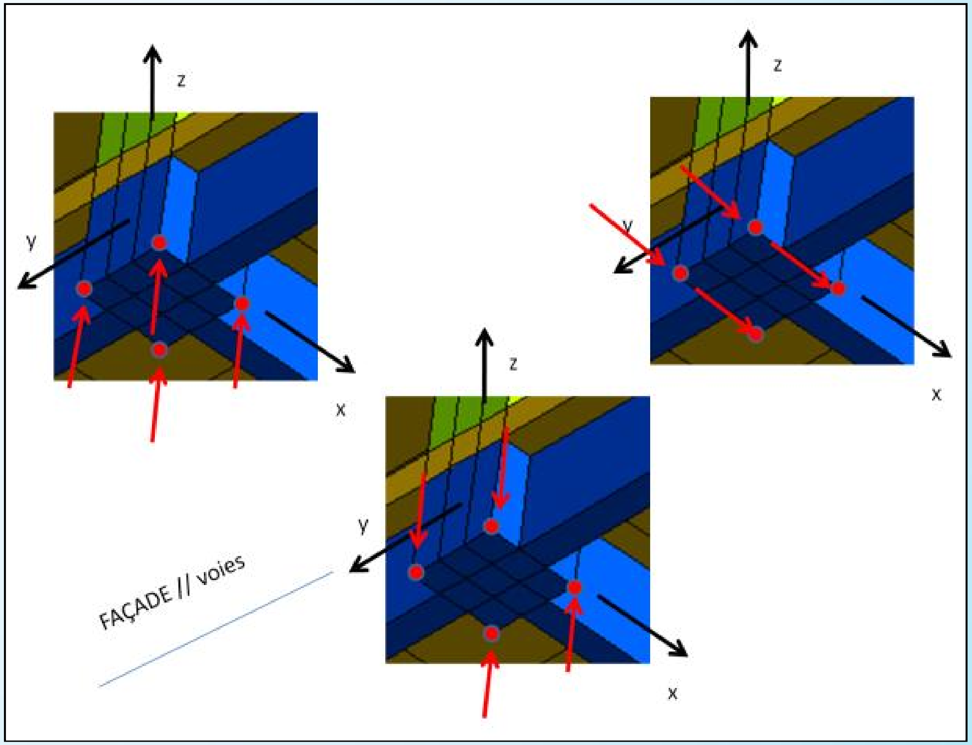
Example of application: building close to a railway station (SNCF)





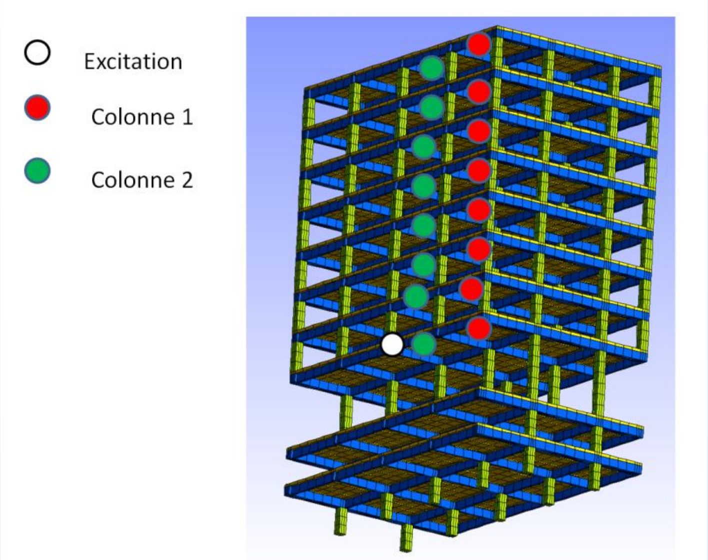
Below ground (calculs BEM) and above ground (Nastran)

Example of application: Computation of mobilities

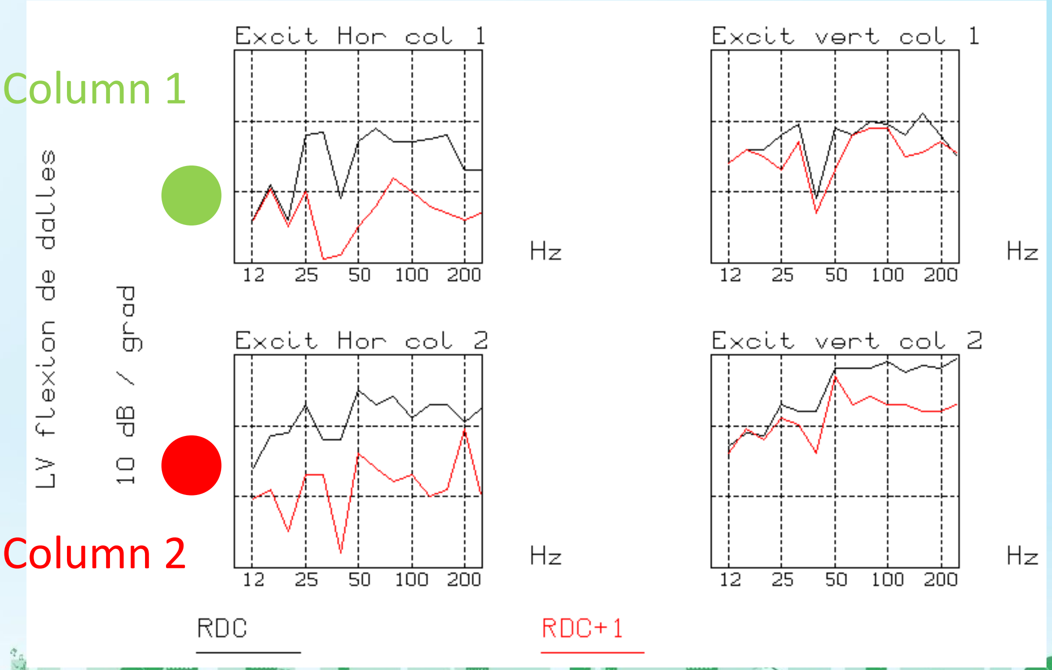


Excitation at the lower part of a superstructure to compute mobilities

Example of application: floor response (bending)



Excitation: horizontal vertical



Example of application: effect of structural modifications

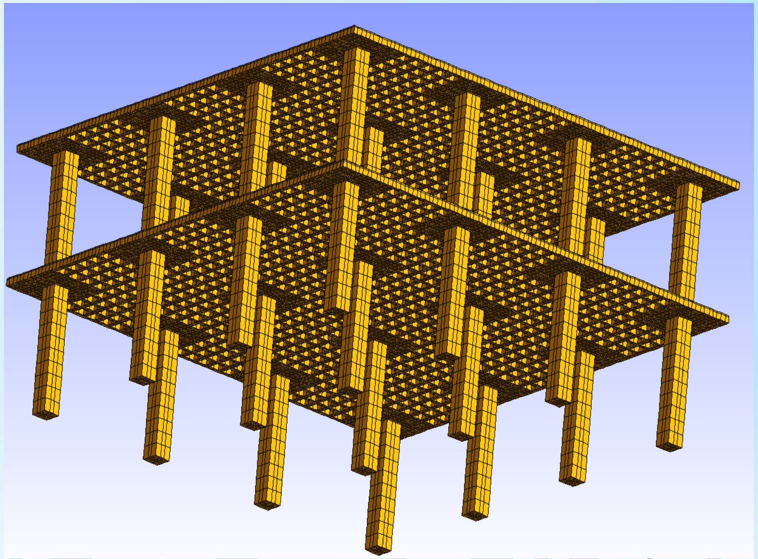
Project CSTB/ACOUPHEN

Warehouse close to existing tracks: converted into lodgings (above top slab)

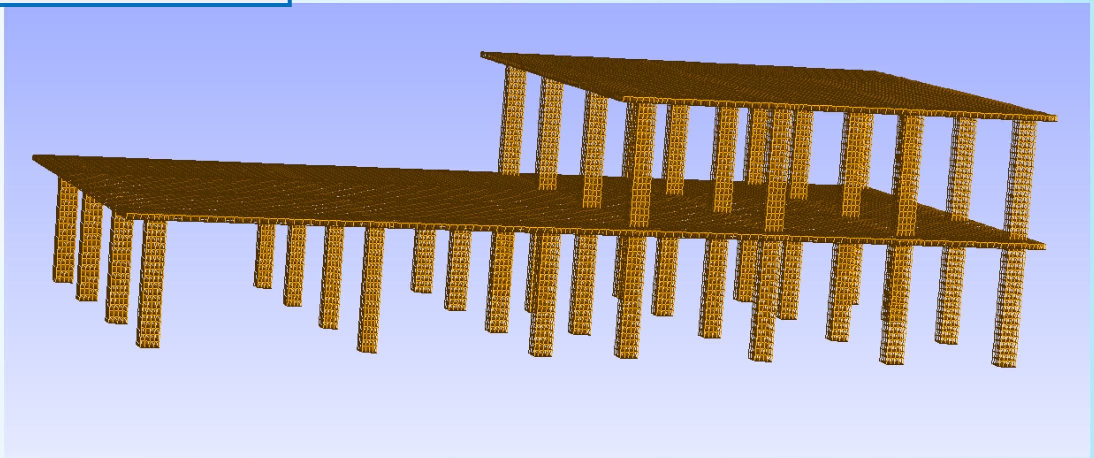
Velocity response measured: model calibration

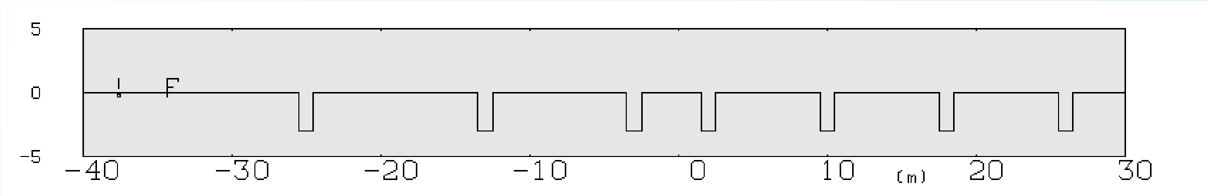
Objective: predict the influence of structure modifications

Part of the existing geometry

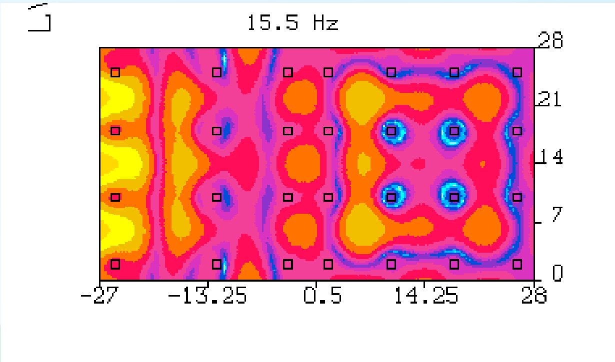


FEM model





BEM computation of Velocity at the top of foundations



Calculated Floor velocity Levels